Urban Food Production

Exploring the potential of urban agriculture for the decarbonisation of cities

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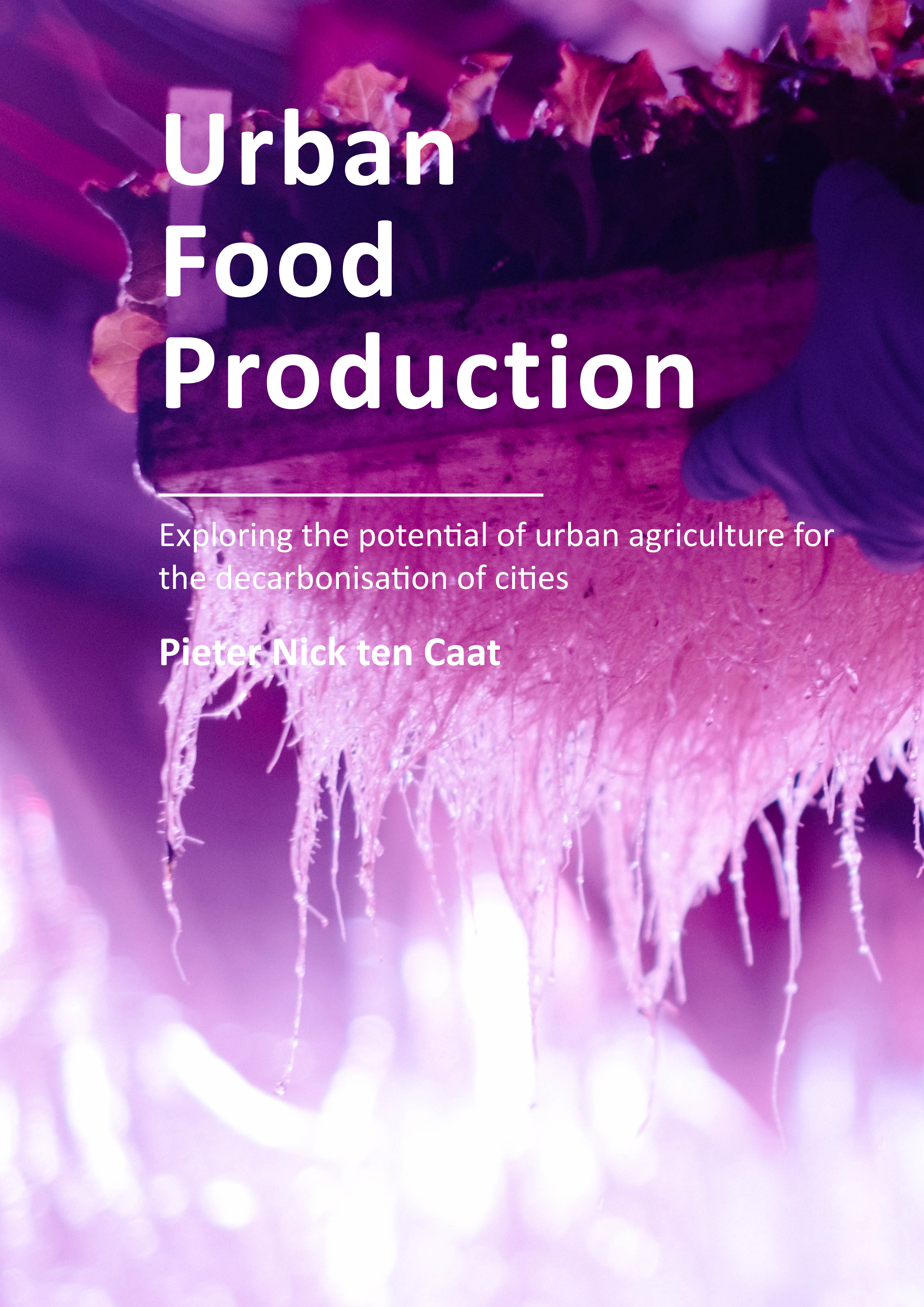

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Cover image | *Deep Flow Technology* lettuce production applied in an experimental hydroponic farming prototype at the *Recovery Park Farms* in Detroit, USA. Picture taken by Shun Nakayama in June 2019. Picture used with permission.

Urban Food Production

Exploring the potential of urban agriculture for the decarbonisation of cities

Dissertation

for the purpose of obtaining the degree of doctor

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by

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Summary

Introduction.

The anthropogenic demand for food, energy and water (FEW) resources is growing, changing and increasingly concentrating in cities due fast urbanisation worldwide. Carbon dioxide emissions associated with the FEW supply infrastructure makes cities one of the main drivers of global greenhouse gas emissions. Urban food production (UFP) could potentially mitigate city's carbon emissions by means of direct and indirect emissions cutbacks, respectively through proximity-based advantages and recirculation benefits by integration with the urban resource infrastructure. The inherent complexity and comprehensiveness of food production makes it challenging to explore this method during the urban design process and provide holistic evaluations at an early stage.

This research investigates how urbanising the production of food can mitigate the carbon emissions of urban communities. Along the principles of the *FEW nexus* approach to resource management, a method and platform have been developed that support professionals such as urban planners and designers with the exploration of urban food production in the design process. The aim of this work is to transform cities into more sustainable and resilient places to live. This work hypothesises that urbanising the production of food resources and making urban food production an integral part of the urban resources infrastructure can help the *decarbonisation* of cities. The objective of this work is to develop a protocol and platform for a non-expert, multi-disciplinary urban design team that can guide the implementation and evaluation of a food production system. The platform, which has been coined the *FEWprint*, should guide the *agro-urban designer* during the exploration phase of the design process by providing quantitative feedback on various relevant indicators. The following main research question has been formulated based on the problem statement, hypothesis, research aim and objective: How could the urban food production design process be harmonised with the FEW nexus principles in order to lower the carbon footprint of the city?

Chapter 2: Pig farming in Kattenburg - a new approach to livestock rearing

This chapter assesses the carbon implications of returning livestock, in this example pigs, to the inner-urban environment and integrating this food system with the existing fabric of urban flows. The aim of this chapter was to address the effectiveness of local food production in terms of carbon emissions reduction, by making a comparative assessment between an array of PV panels and an equally sized pig farm. With regard to the overall research, the aim of this assessment was to get acquainted with the integration aspect of urban farming, the considered resource flows and the allocation of emissions to the FEW sectors.

Chapter 3: FEWprint *assessment* component

The third chapter introduces the first part of the FEWprint platform: the evaluation of the carbon footprint of an urban residential community. Based on the established definition and published theory and methods in the field of carbon accounting of cities, a suitable scope of consideration and calculation framework is proposed. New to this carbon assessment is the evaluation of food consumption with semi-aggregated carbon indicators to establish a representative diet.

Chapter 4: FEWprint *diet shift* component

The fourth chapter describes the *Diet shift* component of the FEWprint platform. The carbon impact of food consumption is mainly dictated by the share of animal-sourced food products within the diet, as animal products present considerably higher carbon intensities compared to plant-based food. In addition, considering the high requirements of agricultural land for livestock, diets that are more inclined towards crops for their protein are more likely to be satisfied with local

produce in a space-constraint urban system. The *Diet shift* component is used to simulate dietary changes and their impact on the carbon footprint of a person whilst maintaining a similar amount of protein intake.

Chapter 5: Greenhouse solar collector - a synergistic solution

Chapter five describes exploratory research on a synergistic energy system in an inner-urban context. Compared to chapter two, this chapter limits on the scope of considered urban flows and adds weight to the integration aspect of a nexus evaluation and also increases the level of detail of calculation-accuracy, for example by adding a temporal component to the evaluation. A synergistic inter-dependent energy triad between a rooftop greenhouse, a supermarket building and residential apartment buildings was designed and evaluated. The greenhouse acts as a solar collector in this triangle. The aim of this chapter is to provide material that supports the movement on the integration of food production in the built environment.

Chapter 6: FEWprint *design UFP* component

The sixth chapter introduces and discusses the third component of the FEWprint platform: *design*. This chapter introduces the *pentalemma* of urban food production aspects—*demand, space, yield, resources* and *impact*— and elaborates how the FEWprint can be employed to systematically manipulate this pentalemma to explore food-centred design propositions for neighbourhoods. The functionality of the platform and applicability of the method are demonstrated by means of a theoretical urban redesign exercise for the Kattenburg community in Amsterdam. This chapter concludes with an analysis of the FEWprint operator-design team interaction during the workshop and proposes a refined strategy to make this collaboration more effective.

Conclusion. A non-linear *research-by-design* process, informed by indigenous values and risks, allows to navigate unconventional spatial solutions to outline new transformative pathways and create unexpected perspectives on the future of a neighbourhood. However, the diversity and inherent complexity of (urban) food production makes it difficult for non-experts to provide holistic evaluations, especially during the exploratory phase of design when performance assessment needs to keep up with rapid trial-and-error based decision-making. This research aimed to develop and disseminate a method and platform that can be used by agro-urban designers during the conceptual stage of the design process to explore the decarbonisation potential of urban food production. The method and platform have been developed along the principles of the FEW nexus theory – an integrative approach towards resource system design and assessment.

The overarching master strategy applied as the backbone of the protocol follows the steps *research*, *reduce*, *produce* and *reuse.* Step one, research, is covered in the *assessment* component of the platform. This step provides a status-quo analysis of the resource consumption and resulting carbon equivalent footprint of the urban community. Step 2, reduce, refers to community-wide dietary alterations that could reduce the food sector carbon impact. The *reduce* step is organised in the *shift* component, and simulates the effect of dietary changes without compromising the nutritional quality of the diet, in this study indicated with the total daily protein intake. Step 3, produce, is found in the *design* component of the platform. A food system can be designed by combining various food production elements from a multi-method and multi-product design toolbox until a desired proportion of the demand is met or the intended decarbonisation targets are obtained. This research highlights five inter-dependent aspects that reduces food production complexity into comprehensible elements and that can be configured during the design process to inform holistic decision making: demand, space, resources, yield and impact, coined the *pentalemma*. After composing a food system, resource circulation between the urban system and the food system can be explored - reuse**.**

Samenvatting

Introductie. De antropogene vraag naar voedsel, energie en water (Food, Energy & Water, FEW) neemt toe en concentreert zich steeds meer in steden als gevolg van de wereldwijde verstedelijking. Koolstofdioxide-emissies (CO_2) die verband houden met de FEW-infrastructuur maken steden tot een van de belangrijkste oorzaken van wereldwijde broeikasgasemissies. Stedelijke voedselproductie (urban food production, UFP) zou de CO_2 emissies van steden kunnen verminderen o.a. door kortere afstanden tussen producent en consument, maar ook dankzij FEW-circulatie d.m.v. integratie met de stedelijke FEW infrastructuur. De inherente complexiteit en uitgebreidheid van voedselproductie maken het echter moeilijk om deze kans te exploreren tijdens het stedelijk ontwerpproces en om holistische evaluaties in een vroeg stadium te bieden.

Deze studie onderzoekt hoe stedelijke voedselproductie de CO_2 footprint van gemeenschappen kan verminderen. Aan de hand van de *FEW nexus* ontwerpprincipes, is een methode en platform ontwikkeld om professionals zoals stedenbouwkundigen en ontwerpers te ondersteunen bij het exploreren van stedelijke voedselproductie tijdens het ontwerpproces. Het doel van dit onderzoek is om steden duurzamer en veerkrachtiger te maken. Het onderzoek veronderstelt dat het verstedelijken van de voedselproductie en het integreren ervan in de stedelijke FEW infrastructuur kan bijdragen aan het verlagen van de stedelijke emissies. Het doel van dit onderzoek is om een methode en platform te ontwikkelen voor een multidisciplinair ontwerpteam bij de implementatie en evaluatie van een voedselproductiesysteem. Het platform, dat de naam *FEWprint* heeft gekregen, moet de agro-stedelijk ontwerper tijdens de verkennende fase van het ontwerpproces begeleiden door numerieke feedback te geven op verschillende relevante indicatoren. De volgende hoofdvraag is geformuleerd op basis van de probleemstelling, hypothese, onderzoeksdoel: Hoe kan het ontwerpproces van stedelijke voedselproductie worden afgestemd op de principes van de FEW nexus om de CO_2 footprint steden te verlagen?

Hoofdstuk 2: Varkenshouderij in Kattenburg - een nieuwe benadering van veeteelt

Dit hoofdstuk onderzoekt de CO_2 reductie door het terugbrengen van vee, in dit geval varkens, naar de binnenstedelijke omgeving en de integratie van dit voedselsysteem met de bestaande FEW stromen. Het doel van dit hoofdstuk was om de effectiviteit van lokale voedselproductie in termen van CO_2 reductie te onderzoeken door een vergelijking te maken tussen PV-panelen en een varkenshouderij. Met betrekking tot dit proefschrift was het doel van deze studie om vertrouwd te raken met het integratieaspect van stedelijke landbouw, de meegenomen FEW bronnen en de toewijzing van emissies aan de FEW-sectoren.

Hoofdstuk 3: Het evaluatiecomponent van FEWprint

Het derde hoofdstuk introduceert het eerste deel van het FEWprint-platform: de *evaluatie* van de CO_2 footprint van een stedelijke gemeenschap. Op basis van de vastgestelde definitie, reeds gepubliceerde artikelen en methoden op het gebied van CO_2-berekeningen van steden, wordt een geschikte scope en berekeningskader voorgesteld. Nieuw in deze berekeningen is de evaluatie van voedselconsumptie met semi-geaggregeerde koolstofindicatoren om een representatief dieet vast te stellen.

Hoofdstuk 4: Omschakelingscomponent van FEWprint-dieet

Het vierde hoofdstuk beschrijft het *transitie component* van het platform. Het uitstoot van voedselconsumptie wordt voornamelijk bepaald door het dierlijke aandeel in het dieet, aangezien dierlijke producten aanzienlijk hogere CO_2 uitstoot hebben in vergelijking met plantaardige alternatieven. Bovendien, door de doorgaans grote hoeveelheid landbouwgrond benodigd voor veeteelt, zijn diëten die meer gebaseerd zijn op plantaardig voedsel voor hun eiwitten beter in staat om geproduceerd te worden in een stedelijke omgeving met beperkte ruimte. Het *transitiecomponent* van het platform kan worden gebruikt om proteïnetransities te simuleren en de daaropvolgende veranderende impact op de CO_2 footprint van een persoon te berekenen, met gelijkblijvende eiwitinname.

Hoofdstuk 5: Kas-zonnecollector - een synergetische oplossing

Hoofdstuk 5 beschrijft een verkennend onderzoek naar een synergetisch energiesysteem in een binnenstedelijke context. In vergelijking met hoofdstuk 2, limiteert dit hoofdstuk de scope van de berekende FEW resources en legt het meer nadruk op het integratieaspect van een nexus-evaluatie. Ook is er meer detailniveau en nauwkeurigheid in de berekeningen, bijvoorbeeld door een tijdscomponent aan de evaluatie toe te voegen. Er wordt een geïntegreerde energiesysteem ontworpen en geëvalueerd tussen een dakkas, een supermarkt en een portiekflat, waarbij de kas functioneert als een zonnecollector in dit systeem. Het doel van dit hoofdstuk is om kennis en ervaring op te doen voor de integratie van voedselproductie in de gebouwde omgeving en deze kennis te gebruiken bij het ontwikkelen van het ontwerp component van het platform.

Hoofdstuk 6: Ontwerpelement van FEWprint voor UFP

Het zesde hoofdstuk introduceert het derde component van het FEWprint-platform: *ontwerp*. Dit hoofdstuk beschrijft de pentalemma van aspecten van stedelijke voedselproductie - vraag, ruimte, opbrengst, resources en impact - en legt uit hoe het FEWprint kan worden gebruikt om dit pentalemma systematisch te beïnvloeden om voedselgerichte ontwerpproposities voor steden te verkennen. De functionaliteit van het platform en de toepasbaarheid van de methode worden gedemonstreerd aan de hand van een theoretische ontwerpoefening voor de Kattenburg-gemeenschap in Amsterdam. Dit hoofdstuk eindigt met een analyse van de interactie tussen de FEWprint-operator en het ontwerpteam tijdens de workshop en stelt een verfijnde strategie voor om deze samenwerking effectiever te maken.

Conclusie. Een niet-lineair *research-by-design* proces, geïnformeerd door lokale waarden en risico's, maakt het mogelijk om onconventionele ontwerpoplossingen te verkennen, nieuwe transformatiepaden uit te stippelen en onverwachte toekomstperspectieven van een stad te vormen. De diversiteit en inherente complexiteit van (stedelijke) voedselproductie maken het echter moeilijk voor niet-experts om holistische evaluaties te geven, vooral tijdens de verkennende fase van het proces. Hier moeten de systeemevaluaties bijbenen met snelle besluitvorming op basis van *trial-and-error*. Dit onderzoek heeft tot doel een methode en platform te ontwikkelen die kunnen worden gebruikt door *agro-stedelijke* ontwerpers tijdens de conceptuele fase van het ontwerpproces om het CO_2 reductie potentieel van stedelijke voedselproductie te verkennen. De methode is ontwikkeld volgens de principes van de FEW nexus theorie - een integratieve benadering van ontwerp en evaluatie van FEW systemen.

De overkoepelende masterstrategie die als ruggengraat van de methode wordt toegepast, volgt de stappen *research, reduce*, *produce* en *reuse*. Stap één, *research*, komt aan bod in het evaluatiecomponent van het platform. Deze stap biedt een status-quo analyse van het FEW gebruik en de resulterende CO_2 footprint van de stedelijke gemeenschap. Stap 2, *reduce*, verwijst naar gemeenschaps-brede dieetveranderingen die de CO_2 impact van de voedselsector kunnen verminderen. Deze stap is ondergebracht in het *diet shift* component en simuleert het effect van dieetveranderingen zonder afbreuk te doen aan de voedingskwaliteit van het dieet m.b.t. de dagelijkse eiwitinname. Stap 3, *produce*, bevindt zich in het *design* component van het platform. Een stedelijk voedselsysteem kan worden ontworpen d.m.v. het combineren van verschillende producten en productiemethoden uit een ontwerp *toolbox*, tot dat gewenste doelen worden bereikt. Dit onderzoek beschrijft 5 gerelateerde aspecten, de *pentalemma* met daarin vraag, ruimte, voedsel opbrengst, FEW resources en impact, die moeten worden geoptimaliseerd in dit ontwerpcomponent. Stap 4, *reuse*, kijkt naar circulaire mogelijkheden voor FEW management tussen stad en voedselproductie, waarvoor het platform nu twee opties aanbied. Het *reuse* component is in ontwikkeling en kan in toekomstige studies verder worden uitgebreid.

Het FEWprint platform en methode doet een eerste stap in de richting van een holistische beoordeling van stedelijke voedselproductie en heeft het potentieel om niet alleen professionals zoals stedenbouwkundigen en ontwerpers te ondersteunen, maar ook belanghebbenden te betrekken bij de besluitvorming over duurzame stadsontwikkeling.

PART I

Introduction

1. General introduction

In 2022, the projection of the world population exceeded 7.5 billion people with an increase of more than 74 million people in 2021 alone. Following this trend, this number is expected to further increase to 10 billion by year 2050 (UN DESA, 2017). Since the 20th century, urbanisation has been an accelerating happening and an undeniable reality recognised in practically every region on this planet. Particularly, in developed high-income countries, urbanisation is projected to comfortably exceed 80% by the year 2050. However, the steepest urbanisation curve for the coming decades can be observed in presently middle and upper-middle income nations (UN DESA, 2019). That said, as the global economic situation gradually improves, an increasing number of countries are moving into the world's economic middle-segment. Accordingly, the consumption patterns of individuals around the world are shifting towards standards that are more similar to Western standards. In other words, the individual demand for resources is simultaneously growing and changing, a transition that is recognised within the food consumption for dozens of countries by National Geographic[1] (2020). Overall, global food demand is expected to increase by about 60% in 2050 (FAO, 2017).

The global population growth, combined with the mass relocation of billions of people and changing consumer behaviour means that the demand for the key resources food, energy and water (FEW) is increasingly concentrating in urban areas. This phenomenon contributes to making cities one of the main drivers of global greenhouse gas emissions and one of the prime objects for improvement. At present, cities predominantly rely on global, unsustainable and linear logistics systems to provide these resources, which exhaust the earth's carrying capacity in the process. Typical examples of cross-boundary trade of food are the import of — with a degree of generalisation — grain from Ukraine, beef from Brazil or the United States, citrus fruits from tropical and Mediterranean regions, bananas from equatorial regions and fish from seas or oceans that extend beyond the horizon of the consumer. Outsourcing the food industry often means outsourcing greenhouse gas emissions associated with this system, which are a key contributor to the global warming effect (IPCC, 2018a).

This research investigates how urbanising resource management, more specifically the production of food, can mitigate the carbon emissions of urban communities. Along the principles of the FEW (food-energy-water) nexus approach to resource management, a method has been developed that supports professionals such as urban planners and designers with the integration of urban food production in their work processes.

This doctoral research is part of the M-Nex project, funded by the Belmont Forum and the EU Urban Europe Joint Programme Initiative, which was launched in May 2018 in Sydney and that was concluded with an online conference in April 2022.

[1] Explore this trend at https://www.nationalgeographic.com/what-the-world-eats/

1.1. Food, Energy & Water provision: an exhausting status-quo

1.1.1. Food, Energy & Water - the impact of resource systems

The growing and concentrating demand for the food, energy and water (FEW) resources in urban centres and the unfavourable consequences that this growth poses on the environment are, in a summarising fashion, briefly described below.

Food. On a global level, the agricultural sector was responsible for 17% of the total carbon dioxide equivalent emissions occurring at the *field-to-farm gate* stage, including LU/LUC (FAO, 2020a). As a result of relatively faster growing other economic sectors, the agriculture fraction has decreased by ±25% in 2000. However, the absolute farming emissions have stayed relatively stable during this period with around 9.5 Gton released per year. For the entire food supply chain, including the emissions occurring at the *farm-gate to fork* stage, this number increases to ±26% of the total global emissions (Poore & Nemecek, 2018).

To meet the growing requirements of society, the production of food has intensified significantly over the past century. Undergoing the first, second and third agricultural revolution allowed the world population to keep multiplying without ever reaching a global famine ceiling (Khush, 2001). Nowadays, most industrialised countries are for a part of their food requirements relying on a network of global food supply mechanisms (Geyik, Hadjikakou, Karapinar, & Bryan, 2021). Food production industry has become heavily intensified, mechanised and optimised and puts wasting stresses on the *topsoil*[2]. The contemporary crop yields obtained by the use of large scale irrigation infrastructures and the use of synthetic fertilizer and spraying pesticides have yielded their maximum impact (Herder, Van Isterdael, Beeckman, & De Smet, 2010). Due to climate change and exhaustive unsustainable farming management, food crop habitats are suffering from increasing unfavourable pressures such as water scarcity, open water and ground water pollution due to agro-chemical run-off, nutrition depletion, high ground water salinity, excessive nitrogen deposition and build-up of pesticides or soil pests. Combined with a decreasing availability of arable land, soil degradation is imposing a serious risk on food production for the generations to come. As attempts to further boost the yield by more fertilizer or pesticides are not feasible, current short-term and cheap solutions include the *horizontal*[3] expansion of farmland at the cost of existing ecosystems (Winkler, Fuchs, Rounsevell, & Herold, 2021), predominantly occurring in tropical regions (Gibbs et al., 2010).

Farmland expansion, also referred to as land use/land-use change (LU/LUC) in life cycle analysis (LCA) literature, is one of the main causes of greenhouse gas emissions in the agricultural sector (Poore & Nemecek, 2018). Converting existing ecosystems into agricultural land causes both direct and indirect greenhouse gas emissions. Burning forestland directly causes atmospheric discharge of carbon dioxide stored in biomass. Alteration of the land often includes tilling of the soil, which causes the carbon dioxide stocks stored in the soil organic matter to be released. Finally, the carbon sequestration capacity of forest is higher compared to that of cropland, meaning far less CO_2 is recaptured and stored per hectare when the land is reused for agriculture.

Within agriculture, the livestock sector is responsible for more than half of the total greenhouse gas emissions (Poore & Nemecek, 2018). The demand for livestock feed, such as soy and corn

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[2] *topsoil.* The first 20-30cm of land that is richest in minerals, soil organic matter, nutrients, water and air and is used for farming. An unconsidered use of topsoil for agriculture will exhaust or erode the earth and render it unsuitable. The availability of suitable topsoil depends on geological features and availability varies per region. Topsoil can be artificially regenerated, or naturally over a longer period of time.

[3] *horizontal expansions.* The spatial expansion of agriculture through land reclamation and land use changes from natural ecosystems.

among others, is responsible for a major part of the LU/LUC (FAO, 2006). In addition, two other major greenhouse gas sources are specific to the livestock sector. First there is the bacterial enteric fermentation process inside rudiment animals such as sheep, goats and cows (Crutzen, Aselmann, & Seiler, 1986). When carbon-containing materials decay under anaerobic circumstances, microbes produce the stronger greenhouse gas methane (CH_4, GWP=28) instead of carbon dioxide (CO_2, GWP=1). The same bacterial process can occur when manure is stored in a wet or slurry form, preventing sufficient oxygen from entering the manure decay process. The second driver behind livestock emissions is manure management. Next to methane emissions associated with manure storage, applying manure during crop cultivation causes soil-borne microbes to convert the nitrogen in manure, mainly in urine, into nitrous oxide (N_2O, GWP=298). Finally, the processing and production of livestock feed, food transportation, food packaging and retail of food products is also responsible for a part of the food sector greenhouse gasses, albeit a considerably smaller contribution to the total emissions (Poore & Nemecek, 2018).

Energy. The predominant part of our global electrical and thermal energy supply is based on a continuous provision of fossil fuels commodities, often imported from overseas nations. Since the (first) industrial revolution, societies started to rely on the easy, relatively cheap and seemingly limitless provision of these fuels for their energy, transport, products, economies, political power and technical development. Converting fossil energy carriers (predominantly crude oil distillates, natural gas & coal) into electrical energy, heat, mobility or products that are useful for human application releases carbon dioxide into the atmosphere. The emission of CO_2 goes at a much faster rate than the earth is naturally capable of sequestering, hence the composition of outdoor air that gets more and more polluted over time with increasing concentrations of greenhouse gasses, be it CO_2, NO_x, CH_4 and other gases. This altered atmospheric layer increases the retention of irradiated solar energy on earth, thus gradually increasing global temperature, resulting in various local and global climate and geography changes with undesirable to catastrophic consequences (IPCC, 2018a).

Water. The combined aspects of a rising world population, increasing per capita demand and the consequential anthropogenic climate change is putting stress on the global fresh water reserves and the ecosystems that inhabit these water masses (Matthews, 2016). The demand for water mainly originates from four main uses: agriculture, energy generation, industry and human consumption. Application in the energy and agricultural sector and human consumption are further highlighted below.

The potential energy stored in high-altitude water masses is used to drive the turbine blades of hydro-electric power plants. Indirectly, a substantial amount of water is consumed (i.e. not returned to its source) in this process due to evaporation that occurs in the artificial basins, which could have alarming consequences to downstream communities (Mekonnen & Hoekstra, 2012). A known present-day example would be the recently opened *Grand Ethiopian Renaissance Dam* that causes political tensions with downstream Egypt. Water is also applied as the primary cooling fluid in thermo-electric power plants, where liquid water is turned into pressurised steam to set the generators in motion. Even though most of the steam is condensed, treated and then reused or disposed into the water bodies it was extracted from, a considerable part of the water is lost due to evaporation or other processes, the extent of which depending on the applied power generation methods and technologies (Pan, Snyder, Packman, Lin, & Chiang, 2018).

Agriculture demand is often sustained by overexploited and inefficient irrigation networks and agro-chemical runoff is polluting life-supporting water bodies. Natural wetlands surrounding rivers and deltas are used for the expansion of cities and farmlands, forcing the water stream into a narrow artificial corridor straight into the lakes or ocean, creating issues due to the resulting lowering groundwater table and rainwater attenuation (Novotny, 2008).

Finally, the production of potable water requires energy for processing and distribution, as well as for collection and purification after use.

Food, Energy and water - three connected resources

Under current management, a growing demand for food resources causes a direct demand increase for water, energy and topsoil. An increasing demand for electricity means more water has to be withdrawn from natural reserves. Satisfying the demand for fresh water necessitates the investment of electrical energy for purification/desalination, distribution, collection and treatment. These are three examples of evident resource inter-linkages that are intelligible to conceive, yet, rather difficult to confidently quantify or model. Even more, the comprehensibility of resource inter-dependencies becomes more complicated when attempting to assess the full resource production, transportation/distribution and consumption system, especially at more detailed scales of consideration, for example at the household or neighbourhood level.

Resource provision and after-use processing infrastructure often crosses city, regional or even national borders. Through a network of many interconnected nodes, a linear chain of supply is formed from producer to consumer that is organised by various actors at different levels of governance. Identifying and mapping the relation between resources is a first step of this approach, understanding and quantifying them is a second. The FEW Nexus paradigm could offer the framework to streamline this effort, which is further discussed in section 1.2.

1.1.2. Urbanising food production to reduce carbon emissions

Adopting a biophysical perspective, it can be said that neighbourhoods are dissipative entities that use large quantities of energy and material resources (Rees, 2012). Even though residential neighbourhoods are depending on a global resource provision infrastructure outside their administrative boundaries to be able to function (Pincetl, Bunje, & Holmes, 2012), urbanisation also introduced efficiency gains through demand concentration (based on proximity benefits) and the economies of scale (lower costs through higher volumes) associated with high population density and concentration of economic activity (Moore, Kissinger, & Rees, 2013). Being at the tail-end of multiple predominantly linear supply chains, the accumulation of various forms of waste materials fosters opportunities for material conservation through circulation. The production of food resources — rooted on a metabolism that in theory could assimilate various waste flows to create new valuable output — is a circular strategy which is further investigated in this work.

Farming and marketing of food resources within the geographical boundaries of a city has the potential to mitigate the food sector emissions. A **direct** impact is achieved due to the close proximity between the consumer and the producer, which results in reduced *food miles*, i.e. the energy resource embodied in food transportation (AEA Technology Environment, 2005). In addition, inner-city or peripheral production reduces the need to expand agricultural land in existing nature area in overseas nations, i.e. the *land use/ land-use change* process (Winkler et al., 2021). Finally, shorter supply chains also lead to less food waste (Priefer et al., 2016).

The production of food goods is archetypically an industry that takes place in locations with sufficient areal potential to tap into the efficiency and efficacy of upscaling and — in a globalised system — takes place on locations with favourable climate conditions. Urbanising – and the thereby unavoidable downscaling – of food production should therefore not be considered as a mere transition of agriculture into the city. Instead, it should be approached as an incentive to identify, map out and quantify the various material and resource flows surrounding food production and to use that knowledge to design a system that is mutually beneficial for the farming *node* and the *host* urban context (Specht et al., 2014). A metabolic understanding and quantification of both the food production processes and the urban system could disclose anchor points for system integration, which would potentially allow for various opportunities for symbiotic resource management through urban *ecosystem services*[4], a potential that is brought up more often in literature (Goldstein, Hauschild, Fernández, & Birkved, 2016b; McDougall, Kristiansen, & Rader, 2019; Shah et al., 2021).

Indirect carbon emission benefits occur when urban food systems are applied as ecological services in the management of other sectors. These benefits come down to the mitigation or avoidance of waste flows and/or reducing the necessity to import resources from outside the urban borders. Even though such services are not fully emission-free due to ancillary systems that require energy, to start, one can assume that emissions are lower than conventional resource management methods. Some examples: the water retention capacity of greenspace is higher than that of *hard* surfaces, thus attenuating precipitation runoff and lowering the pressure on rain- and storm water drainage infrastructure. Especially in cities where rainwater is pre-processed before disposal, this has positive carbon implications. Wastewater can be filtered and recycled for irrigation purposes (Croce & Vettorato, 2021) and domestic organic waste can be treated and reused as fertiliser, diminishing the costs associated with waste (water) collection and processing (Ferreira, Guilherme, Ferreira, & Oliveira, 2018). Crops have the ability to control the micro-climate temperature through shading, absorption, reflection and/or evapotranspiration properties, lowering the urban heat island effect and decreasing the cooling demand for the adjacent buildings (Safikhani, Abdullah, Ossen, & Baharvand, 2014). Finally, soil and biomass used for agricultural purposes sequester and store carbon dioxide from the air.

1.1.4. Urban food production - new challenges emerge

Urban food production is increasing in popularity in urban centres among the general public, architects, urban designers and policymakers (Rothwell, Ridoutt, Page, & Bellotti, 2016). Despite the growing popularity and the realisation of countless urban food production initiatives[5], high-capacity, symbiotically integrated and holistically evaluated UFP systems that reliably account for a portion of the community's dietary needs do not yet exist in modern cities. Understandingly, such a profound overhaul of the existing food system would likely be born out of severe global instability and disruptions of the status-quo and requires incentives that go beyond the decarbonisation aim endorsed in this work. However, also the complexity of multi-sectoral holistic considerations and the comprehensiveness of a multi-method/multi-product approach could be one of the possible reasons that slow down explorations on the potentially positive impact of food production in cities on its carbon footprint.

For the reasons listed in the previous section, urban farming is quite often driven by the claim that *local* is inherently better for the environment (Enthoven & Van den Broeck, 2021). Indeed, some of the emissions occurring at the different stages along the food supply chain are nullified or mitigated. However, conversely, other stations along the supply chain might require additional input resources, for example due to missing out on favourable climate benefits at external production locations, more resource-intensive farming methods have to be applied locally to reach similar productivity, e.g. greenhouses (Brodt, Kramer, Kendall, & Feenstra, 2013; Hospido et al., 2009). In fact, Enthoven & Van den Broek aggregated and compared several LCA-based studies in their literature review and point out that local food systems trigger more (9 studies), an equal amount of (5 studies) or less (6 studies) emissions compared to their imported counterparts (2021). Finally, in a space-limited urban context, food production often operates at a smaller capacity, which requires compromises in terms of resource input efficiency and consequentially increases the footprint per kg of agricultural output - a concept coined the *ecology of scale* (Schlich & Fleissner, 2005).

[4] *Ecosystem services: goods or services (or any other positive benefit) provided by ecosystems to people. Can generally be subdivided into provisioning, supporting, regulating and cultural services.*
[5] *popular examples are Gotham Greens in New York City or DakAkker in Rotterdam*

Although under certain circumstances, local production can outperform the imported equivalents in terms of environmental impact, urban farming does not by definition mean less impactful food products. However, considering exclusively the direct carbon emission implications of urbanising food systems, meaning the changes to the food supply chain emissions, only provides an incomplete perspective of the method. A deeper consideration of the indirect impact of agriculture-based ecosystem services on resource management in the urban context could potentially add more ballast to the decarbonisation claims of urban food production.

Every urban context and its population presents its own demand for resources and its own inter-connected system of food, energy and water to satisfy this demand. As such, the driving forces behind community carbon emissions are distinctive per neighbourhood. In addition, technical opportunities and/or spatial possibilities are rarely similar between urban neighbourhoods. As such, there is no overarching method or *one solution fits all* to integrate the production of food to the (residential) urban context but rather variations of several symbiotic methods operating at different scales or capacities that best fit the local requirements, which respect local constraints or that lead to an optimal impact for that context. A *research-by-design* approach facilitates and encourages an unconstrained out-of-the-box design process needed to come up with novel urban perspectives (Roggema, 2016), including urban food production propositions. At the moment, there is no protocol available that streamlines such urban design process through feedback loops on the decarbonisation impact of integrated food systems. The next section therefore discusses the difficulties of exploring food production strategies in urban (re)design efforts.

1.1.5. Including food production in the design process

With regards to food as a material flow, the farmer holds position at the beginning of the food supply chain as the producer. The urban dweller holds position at the end of the chain in the role of the consumer. The assimilation of food production elements in the city combines knowledge from two diverging disciplines – urban design/planning and agriculture – in a collaborative effort to reimagine and reshape their respective field in order to achieve a synergistic environmental impact. The two fields are divided by a *language* or knowledge gap that must be bridged to become effective. This manuscript is written from the perspective of the urban designer-planner, who is the designer of the UFP system, often referred to as the *agro-urban designer* from here on out.

In light of the overall decarbonisation aim, the primary reason behind UFP is to reduce the community's emissions by means of substituting imported food with low-impact local alternatives. This potentially avoids part of the emissions associated with the conventional food supply chain, in other words, the **direct** implications on food related emissions. Plugging in food producing elements to the (existing) urban resource network introduces a demand for farming resources (water, electricity, heat, feed, nutrition and manure) that results in new emissions to the carbon balance of the context. In tandem, food output can be translated into *negative emissions* and subtracted from the carbon balance, provided it is consumed by the host-community.

Urban food system design is a multi-faceted challenge. First of all, the range of possible crop variations that can be grown is extensive. Secondly, urban farming can materialise in different forms (low tech - high tech) at different scales and by means of varying food production techniques (e.g. soil-based, hydroponic, aquaponics, DFT, NFT, aeroponic, stacked farming). In addition, UFP will perform differently in various climates - similar to conventional farming. The diversity and inherent complexity of (urban) food production makes it difficult for non-experts to provide holistic evaluations, especially during the exploratory phase of design when feedback needs to keep pace with trial-and-error based decision-making.

1.1.6. Food consumption changes

In addition to the increase of food demand that is in tandem with global demographic grow and the individual increase of food consumption as part of increasing economic prosperity, animal-based food is constituting a larger part of the current diet (National Geographic, 2020). Especially developing counties are currently in a catching-up process, which has been termed the *nutrition transition* by Popkins et al. (2001). As the GDP is growing, relatively monotonous diets of varying nutritional quality (depending on the indigenous food) are rapidly shifting towards modifications that are more relying on (pre-processed) food of animal origin, often within one generation (FAO, 2006). Typical routinely consumed animal-based staple foods are meat (beef, pork, lamb and mutton, goat), poultry (chicken & turkey), fish & seafood, dairy products and eggs. Practically every carbon intensity (kg_{CO2}/kg_{food}) diagram of food products/food groups, animal-sourced products are concentrated at the higher end of the charts, far above plant-based food. See for example the RIVM dataset for the Dutch situation (2020) or the global mean values determined by Poore & Nemecek (2018).

The greenhouse gas emissions related to food consumption have been studied extensively in the past decades, and so has been the impact of a diet change to mitigate food sector emissions (Aleksandrowicz, Green, Joy, Smith, & Haines, 2016; Foley et al., 2011; Scarborough et al., 2014; Springmann, Godfray, Rayner, & Scarborough, 2016). In general, it can be stated that the scientific community is in consensus on the lower environmental impact of adopting a diet that predominantly consists of plant-based food categories (Mbow et al., 2019), and the World Resource Institute has included this as one of the key steps to achieved sustainable food security in the future (WRI, 2018).

For the agro-urban designer that is in pursuit of both self-sufficiency and decarbonisation of a neighbourhood or city, or that is aiming for decarbonisation *through* self-sufficiency, the demand for food and the urban space needed for UFP to satisfy this demand are at interplay with each other. The average individual food consumption patterns [$gram_{food}$/cap*day] dictates the community-wide food demand [ton_{food}/yr]. The population density in most residential neighbourhoods is likely too high to achieve full self-sufficiency within the geographical boundaries of the context. As such, a combination of UFP and conventional food imports will become responsible to meet the demand. Taking into consideration the high *land use* [6] associated with animal-based protein production (Nijdam, Rood, & Westhoek, 2012; Poore & Nemecek, 2018), diets that are inclined towards plant-based food offer more potential in space-limited urban centres or peripheries. As such, a dietary intake shift could play a determinative role in the ratio between locally produced protein and imported protein.

[6] *land use*: land required for livestock grazing and livestock feed production.

To sum up:

- The anthropogenic demand for FEW resources is growing, changing and increasingly concentrating in cities due fast urbanisation.
- Food, energy and water supply infrastructure makes cities one of the main drivers of global greenhouse gas emissions.
- Urban food production could potentially mitigate urban carbon emissions.
- This is achieved through direct and indirect emissions cutbacks, respectively proximity-based advantages and recirculation benefits.
- A consumption-based approach to carbon analysis is required, which accounts for outer-boundary carbon emissions like food chain emissions (further discussed in section 1.3.1)
- The inherent complexity and comprehensiveness of food production makes it challenging to include in the urban design process and provide holistic evaluations.
- The FEW nexus theory can help explore UFP decarbonisation efforts.

1.2 FEW nexus paradigm

The intricate nature of food production in terms of invested resources, space demand and agricultural efficacy, make food-pivoting urban design explorations difficult to support with numerical arguments. The Food, Energy and Water nexus systems theory — in this work acronymically written as the *FEW nexus* but in literature also referred to as the WEF nexus — offers the potential framework to approach the challenge of integrating food production in the urban fabric. Chapter 1.2 further explains the theory, lists definitions and distils key principles that are relevant for the design and evaluation of UFP strategies. To start, the etymological meaning of the word *nexus*:

> *nexus* (noun). nex·us | \ˈnek-səs\, *plural* **nex·us·es**, **nex·us**. Definition of *nexus*. (1) connection; link (*also*: a causal link). (2) a connected group or series. (3) center; focus. Historic etymology for *nexus*: Latin, from *nectere*: to bind.
>
> *Merriam-Webster Dictionary.*

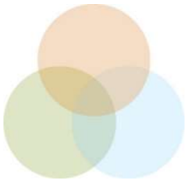

Figure 1.1: Abstract representation of the FEW nexus

The dictionary definition above can be reduced to two elementary keywords: *connection* and *centre*. In the stewardship of food, energy and water resources in cities, the two interpretations are however not necessarily interchangeable. A *nexus* approach to the management of the food, energy and water resource sectors is often conceptualised and visualised as three overlapping semi-transparent circles with intuitive colours (fig. 1.1), or in the form of a more comprehensive derivative of this. In this perfect geometrical representation, the *centre* can simply be pinpointed in the middle of the interface between the three, implying a somewhat similar meaning of *connection* and *centre*. However, a nexus assessment does not imply that each sector deserves equal, i.e. centralised, attention when designing a future-proof resource system.

A nexus-informed intervention implies a holistic evaluation, which requires a well-quantified understanding of the comprehensive and thus far under-perceived linkages between the sectors. In order to move and process flows of food, energy and water from raw (re)source to end-user / consumer products, resources have to be invested; and possibly these invested resources demand their own scaffolding resources. This system of *embodied resource* tiers is not infinite, but depending on the *final* or *driving* resource, it can be rather comprehensive to disentangle. When urban resource provision is managed through the FEW nexus lens, this system of tiers, inter-connectivity and inter-dependency of resources should be continuously considered when making design moves. One way to check if current FEW environmental impact is within or exceeding the acceptable limits, is by looking at the common indicator of *carbon equivalent emission*.

Even though the indicator has now been ‘centralised‘ in a nexus approach, the centre of gravity for system intervention priority might shift towards one sector or one bilateral relation within the FEW triad due to this new understanding of the causality between consumption and impact. Where exactly the focus of intervention should be to make an effective change, is strongly contextual as each city has developed its own infrastructure over the past centuries and each city faces its own climatological, technical or socio-economic challenges that should all be taken into account. In this research, the focus is put on the food sector.

In the next section, the concept of the FEW nexus is further explored and general principles are translated into guidelines that are useful in urban level resource management.

1.2.1. FEW nexus - definitions and principles

The areas of food, energy and water are interdependent from each other by nature and share numerous interwoven connections regarding security, environmental impact, quantity and quality. Policies or systems installed to manage resources in one sector can affect the other sectors in substantive ways. Ignoring these cross-sectoral effects can have significant effects on the quality and quantity of the resources or on the functioning of the system as a whole. On the other hand, ignoring the relationship between resources might lead to missed opportunities surrounding symbiotic impact.

Within the academic community, there is not yet a clear definition of the term nexus and it is thus far to be acknowledged in a uniform way (Endo et al., 2017). Under the absence of a commonly agreed definition or general nexus framework, various definitions of the term have emerged coming from a wide-range of organisations and authors, each with a different angle of approach (Reinhard et al., 2017). For example, Hoff, main author of the 2011 Bonn conference synopses, states that 'A nexus approach can support a transition to sustainability, by reducing trade-offs and generating additional benefits that outweigh the transaction costs associated with stronger integration across sectors' (2011, p.9). Endo et al. mention that nexus is 'interpreted as a process to link ideas and actions of different stakeholders from different sectors for achieving sustainable development' (2015, p.2). The German Gesellschaft für Internationale Zusammenarbeit (GIZ) and ICLEI state that an '[…] urban nexus solution integrates two or more systems, services, policy or operational "silos", jurisdictions or social behaviors, in order to achieve multiple urban policy objectives and to deliver greater benefits with equal or less resources' (GIZ & ICLEI, 2014.p.6). According to Leck et al., 'Nexus thinking is concerned with addressing externalities across multiple sectors, with a focus on system efficiency, rather than the productivity of isolated sectors' (Leck et al., 2015). Reinhard et al. wrote that 'a movement is needed away from a sector-by-sector approach to policy, science and practice, towards an approach that considers the interactions between water, food and energy, while taking into account the synergies and trade-offs that arise from the management of these three resources' (2017,p.6). Finally, Rees (2013) mentioned that the nexus approach is required to establish a framework of decision making that can identify cross-sectoral impacts and unintended consequences and that can explore feasible trade-offs.

All aforementioned citations accentuate the multi-sectoral way of thinking in contrast to the 'silo-thinking' that is dominating nowadays. The FEW nexus approach constitutes an integrative strategy that identifies resource links and subsequently avoids inter-sectoral and temporal problem shifting to prevent or mitigate cross-sectoral impacts of inadequate decision making. In reverse, a holistic consideration of resource management also identifies potential overlap in which feasible correlations, synergies and sharing of fluxes could be exploited for an optimised performance of the system as a whole. Some of the definitions emphasise the nexus on the governance and policy making level, where others (including this research) apply the FEW nexus to the management of *throughput*[7] resources.

[7] *throughput resources:* resources that pass through a system and do not accumulate.

1.2.2. FEW nexus - overview

Based on the various definitions, the following FEW nexus design principles are listed. These principles assume an application of the FEW nexus theory in the biophysical sphere of resource management with the aim of investigating urban food production strategies for the decarbonisation of cities:

1) **Stratification of resources**
   A FEW nexus approach to system (re)design aims to seek, identify, map and quantify the various inter-sectoral linkages and subsequently appreciates and considers these links during the conceptualisation, design and evaluation of a resource system in an urban context. Each final (i.e. end-user) resource can only be produced by first investing secondary or even tertiary resources, each presenting their own implications on the carbon balance of a city.
2) **System performance**
   The performance of the overall system, in this research the combined performance of the city and the food producing system, is prioritised above the performance of independent sectors. As such, it is possible that compromises are made within one sector that benefit linked sectors.
3) **Common currency**
   Holistic system performance assessment requires inclusion of all connected sectors. For this, an applicable, relevant and system-wide indicator should be used that can be manipulated directly with changes within one sector or indirectly with changes in another linked sector.
4) **Self-sufficiency**
   Every resource produced and consumed locally theoretically leads to less environmental pressure elsewhere on the planet.
5) **Circularity**
   Close proximity of resource provision infrastructures allows for short-distance energy or material exchange without (significant) compromises as a result of transportation costs or losses.
6) **Synergy**
   Subsystems can be connected at their interfaces to establish new inter-linkages and achieve a higher productivity and efficiency compared to two autonomously operating systems.

FEW nexus research: limitations

Two key limitations have slowed down the application of this strategy in practice: scale gap and intrinsic complexity. Both issues are further discussed in the next section.

1.3 Research gap

This work contributes to the scientific body of knowledge from two entry points. The primary gap which this work intends to bridge is the integration of food production in the urban environment; and in particular how this new approach to sustainable and resilient cities could be unified with the urban design process. The second gap pivots around the FEW nexus theory and is more implicitly discussed in this research. This work and its output adds to the void within the FEW nexus theory at the smaller scale by providing elaborated examples and a platform. The research gaps are discussed in more detail below.

1.3.1 Adding urban food production to the urban design process

In the late eighties-early nineties, policy makers in the Netherlands proposed to apply the *Trias Ecologica* (Duijvestein, 1989) or *Trias Energetica* (TE) principles (Lysen, 1996) to guide the energy part of sustainable building in their national environmental policy plan, meaning: 1) reduce demand, 2) use renewable resources, 3) use finite resources cleanly and efficiently (van den Dobbelsteen et al., 2018). After nearly two decades, statistical data showed that the progress towards renewable energy implementation and intended climate goals was lagging. Inspired by the *cradle-to-cradle* ethos (McDonough & Braungart, 2010) that started to gain momentum and the original Trias Energetica, Dobbelsteen introduced the *New Stepped Strategy (NSS),* comprised of step 0) Research the local context and potentials, 1) Reduce the demand, 2) reuse waste flows, 3) use renewable resources and ensure waste equals food (Dobbelsteen, 2008).

The 2015 Paris treaty has put national governments and thereby the cities within their borders under pressure to translate carbon emissions ambitions into actionable agendas (UNFCCC, 2015b). A new *energy transition*[8], from fossil-based energy carriers to renewable energy resources, is usually considered the overarching key transformation required in cities to achieve carbon neutrality goals. However, achieving this requires contextualised guidelines, quantifiable goals, transformative interventions and planning, translated onto a chronological roadmap, also called *energy master planning* (EMP) (Dobbelsteen, Broersma, Tillie, & Fremouw, 2014). Dobbelsteen's energy master planning approach combines the aforementioned *New Stepped Strategy*, the *Rotterdam Energy Approach & Planning* methodology, that proposes a cross-scalar (building-cluster-district-city) approach to better seize opportunities for heat exchange (Dobbelsteen, Wisse, Doepel, & Tillie, 2012; Tillie, Dobbelsteen, Doepel, Joubert, et al., 2009), and *Energy Potential Mapping*, which geo-locates and visualises (thermal) energy potentials in terms of their energetic and exergetic quality, capacity and location (Siebe Broersma, Fremouw, & Van Den Dobbelsteen, 2013; Siebre Broersma & Fremouw, 2014).

The European FP7 project City-zen applied this three-pronged EMP approach in several European cities and develop a site-specific *design charrette*-based method to produce energy transition strategies in a short period of time with a multi-disciplinary stakeholder team. In addition, the EMP approach expanded with a carbon accounting framework was first applied to substantiate the urban energy transition plan proposed for the neighbourhood of Gruz in Dubrovnik (Dobbelsteen et al., 2018). Pulselli further developed the applied accounting approach into a generic carbon accounting framework for European cities (Pulselli et al., 2019), which was then demonstrated for a neighbourhood in Seville, Spain (Pulselli et al., 2019) and finally culminated into a stakeholder-engaged condensed workshop strategy to kick-off the decarbonisation of cities (Pulselli et al., 2021).

The M-Nex study (Yan & Roggema, 2019) and this doctoral research, which informally could be seen as a derivative of the City-Zen project, takes the FEW nexus framework to redesign existing

[8] *energy transition.* An umbrella term used to describe the significant restructure of an energy system with regard to its input material. Historically, energy transitions have occurred before, for example wood > steam, or steam > coals

resource infrastructure for neighbourhoods or cities. Even though the City-Zen approach also considered energy-related emissions associated with non-energy-related urban resource provision (e.g. electricity for water), the studies were predominantly conducted under the principal theme of the energy transition. As such, in terms of carbon accounting, only scope 1 (direct/territorial) and scope 2 (extra-urban emissions due to electricity use) were included in the carbon balance. The (limited) agriculture-driven emissions measured in the town of Roeselare's (Belgium) energy master plan were coming from farming systems that were actually physically present on site and not from imported food products (Riccardo Maria Pulselli et al., 2021). The protocol and FEWprint platform developed in this research expand the carbon accounting framework with scope 3 emissions and puts the emphasis on the design and assessment of food systems in the built environment – with the similar intention of urban decarbonisation. For this, the *consumption-based* approach to carbon accounting is applied.

The consumption-based approach towards carbon footprint analysis can be used to acquire a more encompassing estimation of the footprint of a city. It states that resources-related emissions are driven by the end-user and should therefore be attributed to them by means of a full scope assessment that captures the entire life cycle of resources, goods and services (S. Chen, Long, Chen, Feng, & Hubacek, 2020; Mi et al., 2019). The scope 3 impact of food consumption by an urban population has previously been included when estimating the food footprint of cities or communities; for example, Hillman & Ramaswami (2010), Heinonen (2011) and Moore (2013) used an *aggregated data* approach to food assessment. Aggregated data is high(er) level data that consists of grouped individual data, based on a shared dominator to combine multiple data sources or to overcome missing data entries.

To make urban food production an interesting decarbonisation strategy to explore, the designer's toolbox should offer multi-product and multi-method elements to provide a certain design of freedom to navigate various design options. In addition, access to a product-level and a divergent inventory of food allows to compose a diet that is sufficiently appropriate to represent the indigenous diet and/or that is varied in its nutritional quality. Consequentially, the *disaggregated* approach towards food impact assessment is required during the status-quo analysis, in order to holistically evaluate the decarbonisation impact of an urban food system designed at the product-level. A disaggregated approach to food impact of cities has been conducted before, for example by Codoban & Kennedy (2008) and diet impact studies are usually product-specific in order to pinpoint high-impact products and inform change. This research will therefore apply the disaggregated method during the design and the assessment of urban food production.

1.3.2 FEW Nexus theory - research gap

Small scale applications

The relation between food, energy and water was introduced and emphasised at the 2009 World Economic Forum and gained further momentum at the 2011 Bonn Conference, where the FEW Nexus integrative approach emerged (Hoff, 2011). Nowadays, there have not been tangible examples in practice of urban projects that have been designed explicitly according to FEW nexus principles. Using online search engines for searching 'food energy water nexus city' reveals mostly diagrams, schemes or flow charts and practically all the top hits direct you towards scientific papers or research institutes. Pioneering examples of tangible nexus buildings, systems or neighbourhoods are non-existent. This does of course not imply that there are no projects that apply intelligent, holistic and integrated resource management systems, but it seems that there are no projects that have added nexus to their keywords. It is apparent that theory has not yet found its way into practice.

Since the emerging of the concept, research into the FEW Nexus has accelerated in various disciplines of research. The FEW nexus can be paired with multiple UN Sustainable Development Goals (United Nations, 2015), for example goal 2 (no hunger), 6 (clean water), 7 (affordable and sustainable energy) & 12 (responsible consumption and production) pivot directly or indirectly around the security and quality of food, energy and water resources. Among other factors, it has resulted in the publication of many FEW nexus publications in the social sciences. In contrast, a preliminary scientific literature survey reveals a limited amount of work on the resource nexus in the discipline of applied sciences, in particular in the field of architectural engineering or urban planning.

In the past ten years, less than a quarter of the FEW nexus publications focussed on the urban scale (Zhang et al., 2019). In addition, the urban level studies mostly do not focus on the design of the city or on urbanised and decentralised local resource productions systems. To give examples, some studies perform a retrospective assessment of a situation: Guta et al. (2017), Stevens & Gallagher (2015) and Terrapon-Pfaff et al. (2018) all look through a Nexus lens to describe the effect of decentralised energy solutions on food and water resources in remote communities in developing regions. Other studies perform a very detailed Nexus assessment at a household scale, but only discuss the bilateral water-energy relationship. Abdallah & Rosenberg (2014), for example, developed an integrated approach to model heterogeneous household water and energy use at the household level and Talebpour et al. (2014) looked at the water and energy nexus of residential rainwater tanks at an end-use level.

The scientific community acknowledges this gap and some researchers call for a downscaling of nexus research on resource production and management (Yan & Roggema, 2019). Both Rees (2013) and Leck (2015) point out that we have marginal research-based evidence on how to implement the ambitious FEW Nexus attitude in the physical realm and build real-world solutions on various scales or provide guidance to decision makers. Terrapon-Pfaff et al. (2018, p. 410) state that thus far 'the focus of WEF nexus discussions and applications has mainly been on national or global levels, macro-level drivers, material flows and large infrastructure developments.' This is acknowledged by Hang et al. and Martinez-Hernandez et al., who point out that most of the existing work addresses larger global, national or regional levels and there are only a few studies analysing the FEW Nexus at the local scale, yet it will be at the micro scale where policies and strategies turn into physical interventions (Leung Pah Hang, Martinez-Hernandez, Leach, & Yang, 2017; Martinez-Hernandez, Leach, & Yang, 2017). Even though there are concepts that focus on the level of the city, it is at the micro-administrative unit of the district or neighbourhood where policy makers can combine public, private and civic interventions in order to mitigate climate change more effectively (Gondhalekar & Ramsauer, 2017).

Each urban context is unique and presents its own demand for FEW resources and a system to satisfy this demand. Aspects like the landscape geography tend to steer local urban morphology, but also economic status, age and cultural aspects have led to an optimised, yet disaggregated FEW management system for the context. As such, opportunities, limitations and challenges surrounding system integration or symbiosis are also specific to that context. Therefore, national FEW nexus policies or goals should not be implemented or imposed on a setting without careful consideration. Contextualisation of these strategies is desirable so that aspects of it are better tailored to local conditions and targeting location-specific synergistic techno-ecological interactions is not obstructed by oblivious generic polices (Dargin, Daher, & Mohtar, 2019; Martinez-Hernandez et al., 2017; Yang & Goodrich, 2014).

Finally, scanning for nexus opportunities at the neighbourhood level reveals possibilities for symbioses as close geographical proximity between sub-systems allows for physical connections between them to facilitate resource sharing (Leung Pah Hang et al., 2017). At the neighbourhood level, inter-system distances are short and energetic investments for transporting resources, transport/conversion losses (i.e. thermal energy) and leaking losses also remain minimal. For example, the dissipative nature of thermal energy makes it inefficient for long-distance conveyance and transportation losses have to be included, which decreases the efficiency of especially high temperature systems. Close proximity of sub-systems or residential/commercial functions would makes this issue less limiting.

FEW nexus complexity leads to complex tools

The second FEW nexus theory research gap discussed and addressed in this dissertation is the intrinsic complexity of the nexus concept and the consequences of this intricacy on the functionality of tools that aim to quantify the FEW nexus or provide a nexus based evaluation of a system. The cross-disciplinary nature of the nexus concept requires the attuning of data, methods, tools and indicators in order to obtain the shared language necessary to pursue synergetic design. Effective discourse harmonisation depends on various factors, for example on the scope of the consideration, on the granularity and on the depth of the assessment, meaning how many layers of embodied resources are considered. At increasing levels of granularity, knowledge and data get more specific, more comprehensive and more difficult to organise, let alone translate into functional and generically applicable tools or indicators.

In the past years the scientific sphere has made progress in understanding nexus interlinkages and quantifying resource flows. Multiple assessment tools have been developed that can support these calculations, for example: WEAP (SEI, 2020), LEAP (Heaps, 2020), MuSIASM (Giampietro & Mayumi, 2000) and CLEWS (Howells et al., 2013). Contemporary nexus assessment or modelling tools, such as the aforementioned examples, have been extensively reviewed in the past years by various papers (Brouwer et al., 2018; Dargin et al., 2019; FAO, 2014; IRENA, 2015; Kaddoura & El Khatib, 2017). The recurring primary issues and challenges within the array of tools include limitations due to data availability and standardisations, level of integration, specific entry point, user accessibility, complexity, and scale or boundary constraints.

As of 2019, there are only two publicly available tools that can be used to model and assess a local integrated resource production system: the WEF Nexus tool 2.0 (Daher & Mohtar, 2015) and the NexSym (Martinez-Hernandez et al., 2017). The WEF Nexus tool 2.0 is an inclusive and multi-scalar input-output model that defines and quantifies several interconnectivities between food, energy and water. The modelling tool supports the development of integrative FEW strategies and planning for the future of these resources (Daher & Mohtar, 2015). Even though the platform offers an accessible interface and the tool's structure is generically applicable by inserting contextual data, scenario building is conducted with five general scenario inputs, the output data is unspecific and it does not provide the design toolbox needed to explore UFP at the local level (which is also not the intended goal). NexSym is the acronym for Nexus Simulation System. The tool addresses the need for understanding and assessing the water-energy-food nexus at the local scale and supports the user to design their own local FEW production system. One of the novel features is that the tool provides the option to insert geographical and climatological data relevant to the local context. As the tool uses the Visual Basic Application in an Excel digital space, the tool has a reduced accessibility for unskilled users and its interface remains rather abstract.

The all-embracing challenge that is complicating current tools is the extensive amount of data input required to build models, run simulations or perform evaluations. Simplification of the assessed resource interlinkages and dependencies can partly overcome the problem of data constraints, however this goes at the cost of output accuracy (Kaddoura & El Khatib, 2017). Public databases like FOASTAT, EuroStat, UNSD or national statistics bureaus provide readily available data for national or transnational nexus assessments. However, granular data is often not collected and stored by a particular centralised agency and/or data management tends to be sectorally organised. Furthermore, the data needed to assess a neighbourhood is collected at varying scales defined by the geographical, ecological, jurisdictional, and operational extents of the city, as will also be shown in chapter 3.2. In general, data aggregation is unavoidable, but at increasing aggregations levels, situational applicability of data at the neighbourhood scale is compromised. Complications with paywalls or data sensitivity obstruct researchers from retrieving important data (McGrane et al., 2018). Finally, the scope or resource integration varies and not all tools evaluate the FEW trilemma but are limited to a bilateral relationship only, as becomes clear in the overview of the Food and Agricultural Organisation of the United Nations (FAO, 2014).

The accessibility and user friendliness of a tool is affected by several factors, but mainly holds close ties with data input requirements. Existing nexus evaluation tools are not designed as simple, user-friendly tools for quick and early appraisal of design moves but generally have significant data needs and are resource intensive in terms of time, capacities or financing (IRENA, 2015). The final limitation, and most relevant to this research, is the absence of micro-scale/local level nexus decision support tools. Despite the wide array of developed evaluation tools, most of them provide a perspective at the (supra)national or at best regional scale and only give a primitive consideration of the effects at the local level (Hake et al., 2016). A tool and framework is lacking that operates at the neighbourhood scale, requiring minimal public data input. In addition, tool output should be expressed in units that are relatable and relevant to urban policy makers, designers and/or researchers.

To sum up:

This dissertation addresses the research gap from two entry points

urban food production

- Urban food production is not yet used as a decarbonisation strategy for cities of neighbourhoods.
- The consumption-based accounting approach is required to include the food sector impact and subsequently be able to evaluate UFP strategies
- The platform should find a balance between comprehensibility and user friendliness. Level of data and input aggregation is thereby key.

FEW nexus paradigm

- Thus far the FEW nexus converse has predominantly prevailed at the regional, national or supra-national scale.
- The inherent complexity of the FEW nexus is reflected in the suitability of FEW nexus tools to analyse the FEW triad
- FEW nexus tools often do not give a perspective at the local level. The ones that do have a limited design toolbox or are challenging to comprehend.
- No FEW nexus tools have been developed to support the design and evaluation of urban food production strategies.

1.4 Research Aim and Objective

The demand for resources is concentrating where people are concentrating: the city. When addressing the environmental impact of this resource demand through the *consumption-based approach* (see 3.2.2), cities are the drivers behind the global greenhouse gas emissions associated with the provision, use and end-of-life processing of these resources. In other words, the residential areas of cities are one of the main carbon-emitting spatial functions worldwide.

The aim of this work is to transform cities into more sustainable and resilient places to live. Since in this manuscript *sustainability* is expressed and measured in terms of carbon dioxide emissions equivalents, the aim can also be expressed as the *decarbonisation* of cities. This does not only imply the energy transition from using fossil energy resources to renewable energy sources, but also entails a reconfiguration and *urbanisation* of food, water and waste management in order to regain control over the emissions occurring in these sectors.

1.4.1. Hypothesis

The stewardship of FEW resources should be reconsidered to move away from the linear resources provision model that is prevailing in practically all of the industrialised cities and to transition to a circular model. This model is designed around the principles of demand reduction, local resource production and resource recirculation. Through the lens of carbon assessment, a circular model lowers the import of resources from external production systems, hence avoiding extra-urban emissions at these locations and avoiding emissions associated with resource transportation or transportation/storage losses. Secondly, waste materials are recycled within the systems boundary of the city, avoiding emissions associated with the end-of-life processing of these materials, which are typically landfilling or incineration for domestic waste products.

This work hypothesises that urbanising the production of food resources and making urban food production an integral part of the urban resources infrastructure can help the decarbonisation of cities. Agricultural systems turn raw input (fertiliser, water, nutrients, energy) into valuable goods: food crops or animal feed[9]. This way, farming constitutes an important and sustainable ecosystem service to cities surrounding organic waste management, water management and food production. In order to explore this decarbonisation strategy, the principles of the FEW nexus theory can be used to frame this research-by-design effort.

1.4.2. Research objective

Using urban food production to curtail the total carbon footprint of a community, implicitly implies that the food system is operating at such a capacity and scale that a considerable portion of the daily community's food demand can be met with local yield. Even though in principle every single piece of produce grown and consumed in the backyard of a community member possibly emits less emissions per kilogram than its externally produced and supermarket-bought sibling, this work intends to explore more radical interventions at the neighbourhood level and transform them into food-centred communities. Research-by-design exercises with a multi-disciplinary design team of local actors and stakeholders, supported by academic experts are an effective way to explore the UFP strategy during the conceptual, unconstrained, path-independent and explorative phase of urban redesign (Roggema, 2016).

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[9] *Agriculture used to produce energy crops, cotton or other materials for specific industries is excluded as possible functions of farming in this work.*

Depending on the chosen method, a farming system requires space and the resources energy and water as input in order to become productive[10]. Simultaneously, food and organic waste flows are outputs of the system. This *agricultural metabolism* is unique for each combination of farming method and product, is affected by the ambient growing climate, the scale of the farm, and management practice and it can be manipulated by various farming parameters controlled by the farmer. This in- and output of resources has an impact on the carbon balance of the community, either in the form of additional (+) emissions due to farm's resource demand and/or in the form of *negative emissions* (-) due to local production replacing imported food or other avoided emissions by means of farm-city synergies.

To demonstrate the complexity of UFP design, the following situation is described: when an *agro-urban* design team is guided by food yield targets and is not constrained by embodied resources or carbon reduction goals, composing a system of various farming elements that together produce the intended quantities of food crops is a relatively clear assignment. Provided that the farming output data is readily available, designing an UFP system is a matter of gradually scaling up all the required farming elements until there is no more surface area available. However, exploring food production with the ambition of maximising its decarbonisation impact is difficult to keep organised as the input-output implications and consequential carbon impact has to be re-assessed after each design move, whilst ensuring that a varied composition of food crops is produced and the space-budget is not exceeded.

The objective of this work is to develop a protocol and platform for a non-expert, multi-disciplinary urban design team that can guide the implementation of a food production system and evaluate this system according to the principles of the FEW nexus. The platform, which has been coined the *FEWprint*, should guide the agro-urban designer during the exploration phase of the design process by providing quantitative feedback on various relevant indicators. The FEWprint should avoid the pitfalls that have limited existing tools and systems that aim to provide a perspective on the nexus between food, energy and water. In order to be useful during an urban redesign assignment, the granularity of the output data should be detailed enough to inform building-level design moves yet not swamp the user with incomprehensible input requirements.

1.4.3. Research backbone

The backbone of this study, and thereby the developed protocol, is based on the *New Stepped Strategy* (NSS) framework. The framework has been developed in response to the slower than anticipated energy transition in the seventies, eighties and nineties in the Netherlands, which was based on the commonly accepted *trias energetica* principles as guidelines. Based on the emerging, circularity-based, *cradle-to-cradle* movement in the early 2000s, the added *reuse* and (renewable) *production* steps potentially mitigate or even prevent that a part of the energy demand is still covered by finite energy resources. However, the urban and building level energy delivery systems have to be considerably redesigned and reconfigured for this, for example described in Tillie et al. (2009) and the City-zen projects (Dobbelsteen, Martin, et al., 2018; Riccardo Maria Pulselli et al., 2021).

This work applies an adaptation of the NSS framework as the macro-strategy for the protocol, in which the essential steps *reuse* and *produce* are switched with each other and organised under the *design* component of the FEWprint (figure 1.2 on the next page). This research discusses the integration of food systems in the urban context. In order to exploit inter-system resource exchange in this framework, an agricultural metabolism should first be established; hence the steps reuse and produce are switched. Finally, it should be emphasised that both the NSS and the

[10] *nutrients* are another key resource to farming (mainly nitrogen, phosphorus, and potassium), acquired through fertilisation with organic (manure) or synthetic fertiliser. Fertilisation is however not further discussed in this work nor a part of the developed platform.

adapted framework guide the design of systems and infrastructure required to supply the resources and are not a manual to handle the resources as is. For example, both food and energy cannot be reused for a similar purpose as they are both subject to the 2nd law of thermodynamics and surrender their exergy to entropy when used.

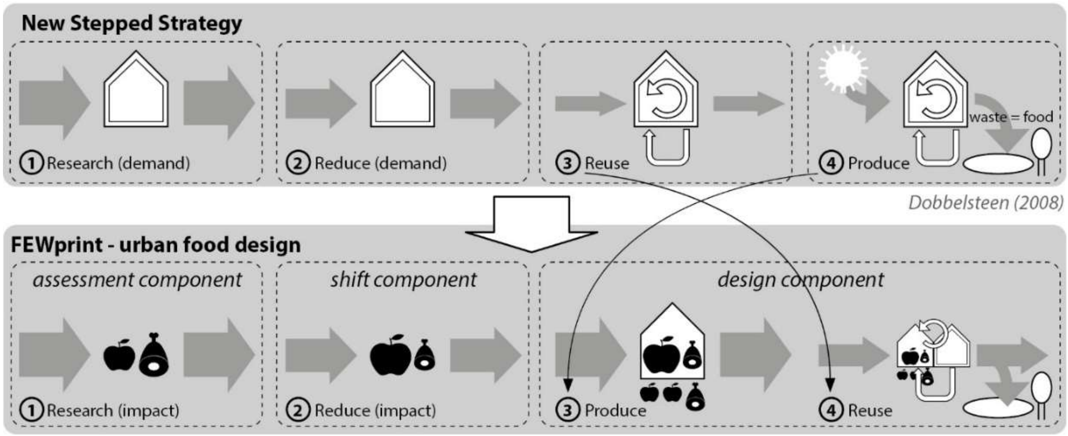

Figure 1.2. *An adaptation of the energy master planning framework New Stepped Strategy (Dobbelsteen, 2008) forms the backbone of this dissertation, following the subsequent steps of 1) research, 2) reduce, 3) produce and 4) reuse.*

In the order of the adapted version, the following purposes or meanings are attributed to each step. For comparison, both the NSS and the FEWprint approach are briefly described.

1. **Research** (operated in the assessment component)
   NSS: analysis of the present energy demand and sustainable (local) potentials to exploit.
   FEWprint: carbon assessment of the present situation, also called *status-quo* or *business-as-usual* scenario.
2. **Reduce** (operated in the shift component)
   NSS: this step implies reduction of the demand for energy resources with interventions at both the building and the urban levels. In addition to energy conserving measures, this step more importantly refers to *passive building design measures* that do not require auxiliary energy.
   FEWprint: reduce implies a cutback of the carbon footprint by opting for more sustainable alternatives to high-impact food products (usually prioritising plant-based food above meat products). It does not imply an actual reduction of food commodities.
3. **Produce** (operated in the design component)
   NSS: the production of renewable energy (e.g. PV, solar collectors, PVT, hydro-electricity)
   FEWprint: the production of food in the urban environment and estimate direct carbon implications.
4. **Reuse** (operated in the design component)
   NSS: internal recycling of waste, building-level collection and semi-central processing, waste material reuse for secondary purposes (external recycling), use of residual thermal energy across scales
   FEWprint: coupling of the urban and the farming metabolisms and estimate indirect carbon implications.

For a detailed description of the NSS steps and case study examples, please refer to Dobbelsteen et al. (2008).

1.5 Research Questions

The following main research question has been formulated based on the problem statement, hypothesis, research aim and objective:

> How could the urban food production design process be harmonised with the FEW nexus principles in order to lower the carbon footprint of the city?

This main question is complemented three sub-questions:

(1) *quantification*

How could a representative carbon emissions profile of urban resource use be made that includes the activities of urban food production?

This research question pertains to the evaluation component and is discussed in chapter 3. The scaffolding chapter 2 is supporting to this chapter.

(2) *shift*

How could the demand for food be swayed in order to reduce the accompanying carbon emissions?

This research question pertains to the diet shift component and is discussed in chapter 4.

(3) *design*

How can the fields of urban design-planning and food production design be bridged?

This research question pertains to the UFP design component and is discussed in chapter 6. The scaffolding chapters 2 and chapter 5 are supporting to this chapter.

1.6. Methods & Materials

1.6.1. Research context

This doctoral research titled *Urban Food Production - Exploring the potential of urban agriculture for the decarbonisation of cities* is conducted in conjunction with the *SUGI/M-Nex* research project.

The M-Nex project, an acronym for *Moveable Nexus: Design-led urban food, water and energy management innovation in new boundary conditions of change*, is one of fifteen *Sustainable Urban Global Initiative* (SUGI) research projects initiated and co-funded by the *Belmont Forum* and the *Joint Programming Initiative Urban Europe* to bring together the fragmented research and expertise across the globe to address FEW nexus challenges. The M-Nex consortium consists of six partner universities across the globe (principal investigator): Queens University Belfast (prof. Greg Keeffe), Qatar University (prof. Sami Sayad), Michigan University (prof. Geoffrey Thün), University of Sydney (prof. Rob Roggema), KEIO University (prof. Wanglin Yan) and Delft University of Technology (prof. Andy van den Dobbelsteen). These academic parties work together with the Institute for Global Environmental Strategies (Bijon Kumar Mitra) and the MacCreanor Lavington architectural office (Kevin Logan).

M-Nex aims to transform urban areas into centres of innovation and technology through co-design of urban space. Through stakeholder engagement and living lab research methods, a team of varying disciplinary expertise has been assembled for collaboration to redesign existing neighbourhoods into sustainable urban resource production systems. M-Nex is a design-research effort (applied research) that has been divided into 3 research pillars: design, participation and evaluation. TU Delft and Michigan University are responsible for the evaluation pillar.

The M-Nex team applied a *Living Lab* strategy in the host-cities of each of the aforementioned partner universities. In each city, one neighbourhood or community was chosen to serve as the case study. Through co-design with local professional stakeholders, governmental entities, students and the residing community, design workshops have been organised in order to arrive at a future-proof (re)design of the neighbourhood (Yan & Roggema, 2019). Results and experience acquired in each workshop produced new knowledge that fed back into the three emerging research platforms: design, evaluation and participation. At the end of the project, a FEW nexus design strategy was developed, reinforced by iterative rounds of testing, scientific publications, Living Lab demonstrations and theoretical examples.

The TU Delft has been responsible for the construction of the *FEWprint* tool. This tool is the key output of the evaluation platform and has come to shape through several rounds of testing during the previously mentioned living labs. Three chapters of this dissertation describe the development of this platform and have been published as journal articles or are currently under review. The FEWprint platform has been made available to the general public on the project website [www.m-nex.net].

1.6.2. Research Methods & Outline

This doctoral research pivots around the development of the FEWprint decision support platform and framework, which aligns with the objectives of the *evaluation* work package in the M-Nex study. The FEWprint consists of three linked components:

1. *assessment*
   Carbon emission accounting of urban communities based on end-user consumption data;
2. *shift*
   Testing the impact of dietary changes on the carbon emissions of a dweller or community;
3. *design*
   Streamlining the urban food production design process.

Overall, de tool is developed following the envisioned platform's order of component application, starting with an assessment of the status-quo, followed by experimentation surrounding food demand change and finally exploring the impact of a food production system which establishes a *new* scenario to which the status-quo scenario can be compared. Throughout the development of the platform, inter-component integration is constantly monitored and secured. As such, the design of each successive component will not be fully conducted in a linear fashion but rather semi-parallel to each other, see figure 1.3. Adjustment might be made according to new insights, for example based on experiences during the M-Nex living labs or other trial-applications. To each component one *core* chapter is devoted in this dissertation.

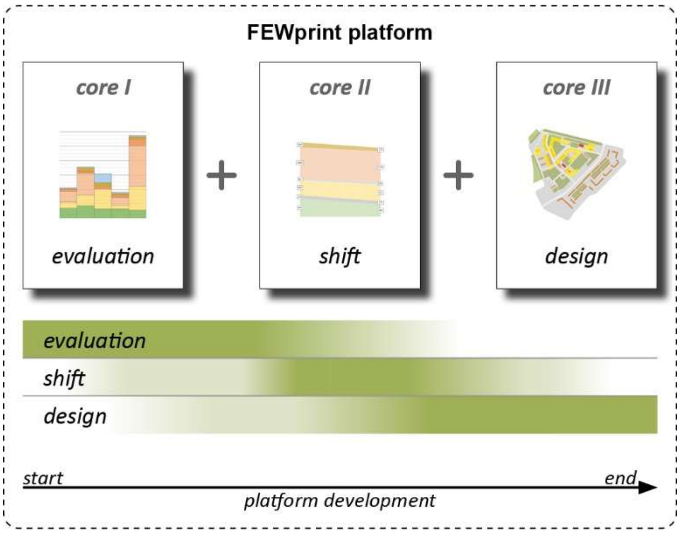

Figure 1.3: *Development of the three-pronged platform.*

The backbone of this dissertation consists of three *core* chapters and two *scaffolding* chapters, shown in figure 1.4. The three core chapters each introduce, explain and demonstrate one of the components of the FEWprint platform — assessment, shift and design — and together form the main *corridor* of this doctoral research. Two scaffolding chapters reinforce this corridor with two exploratory studies, the outcomes of which informed the development of the platform. The first scaffolding chapter presents a full FEW-scope assessment of an integrated urban pig farming facility. The second scaffolding study describes a detailed analysis and carbon assessment of using a rooftop greenhouse as a solar collector for the underlying residential buildings. The structure of the dissertation is visualised with the orange line. Inter-chapter bridging sections connect the main chapters together into one cohesive story. This introduction chapter is counted as chapter one.

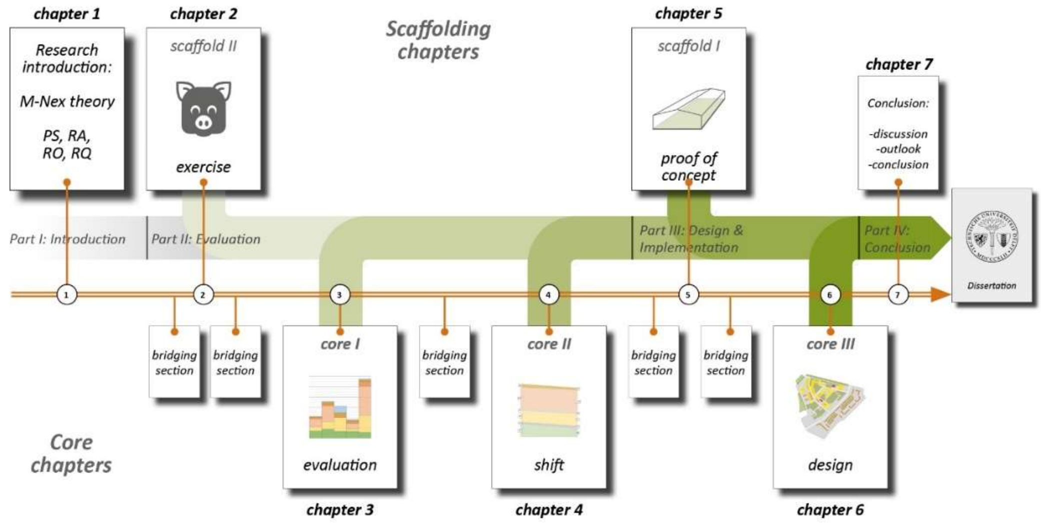

***Figure 1.4**. Research outline of the dissertation.*

Chapter 2: Pig farming in Kattenburg - a new approach to livestock rearing

The **second** chapter assesses the carbon implications of returning livestock, in this example pigs, to the inner-urban environment and integrating this food system with the existing fabric of urban flows. The aim of this chapter was to address the effectiveness of local food production in terms of carbon emissions reduction, by making a comparative assessment between an array of PV panels and an equally sized pig farm. The capacity of the farming system, meaning the maximum number of animals at any time, was based on the daily domestic organic waste available in the residential neighbourhood that could serve as animal feed. In return, the farming system provides (a part of) the pork demand in the neighbourhood. Depending on the configuration of the PV-array, the livestock system is 6-11 times more effective in avoiding greenhouse gas emissions per m^2 of occupied urban space. With regard to the overall research, the aim of this assessment was to get acquainted with the integration aspect of urban farming, the considered resource flows and the allocation of emissions to the FEW sectors.

Chapter 3: FEWprint *assessment* component

After the introduction, the **third** chapter introduces the first part of the FEWprint platform: the evaluation of the carbon footprint of an urban residential community (figure 1.5). Based on the established definition and published theory and methods in the field of carbon accounting of cities, a suitable scope of consideration and calculation framework is proposed. New to this carbon assessment is the evaluation of food consumption. In order to demonstrate the – usually considerable – portion of food-related emissions of a community or neighbourhood, the developed strategy and accompanying tool are applied to the case studies of all six consortium partners. This demonstration entails a calculation of a *FEWprint* profile for each community, and a calculation of the carbon mitigating impact of a theoretical community-wide dietary shift.

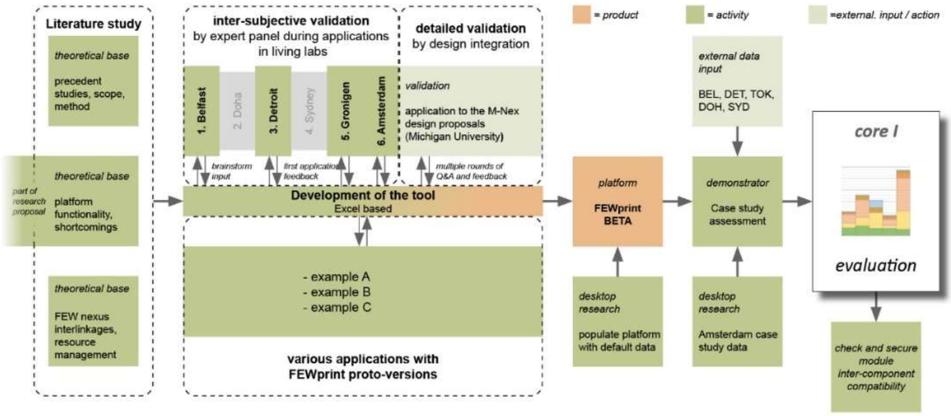

Figure 1.5: Research plan for the 'Assessment' component, chapter 3 in this manuscript.

Chapter 4: FEWprint *diet shift* component

The **fourth** chapter describes the *Diet shift* component of the FEWprint platform. As was discussed in the problem statement of this introduction, the carbon impact of food consumption is mainly dictated by the share of animal-sourced food products within the diet as animal products present considerably higher carbon intensities compared to plant-based food. In addition, considering the high requirements of agricultural land for livestock, diets that are more inclined towards crops for their protein are more likely to be satisfied with local produce in a space-constraint urban system. The *Diet shift* component is used to simulate dietary changes and their impact on the carbon footprint of a person whilst maintaining a similar amount of protein intake. Chapter five introduces and explains the component and provides the relevant theory surrounding protein as a nutritional indicator and the comparability of plant and animal protein in terms of nutritional quality. The component is demonstrated by assessing five rigorous diet scenarios, ranging from the present diet to a full vegan diet, for the M-Nex cases in Amsterdam, Detroit and Belfast and reveals that a diet transition in Amsterdam is most impactful when the full FEWprint is considered. See figure 1.6.

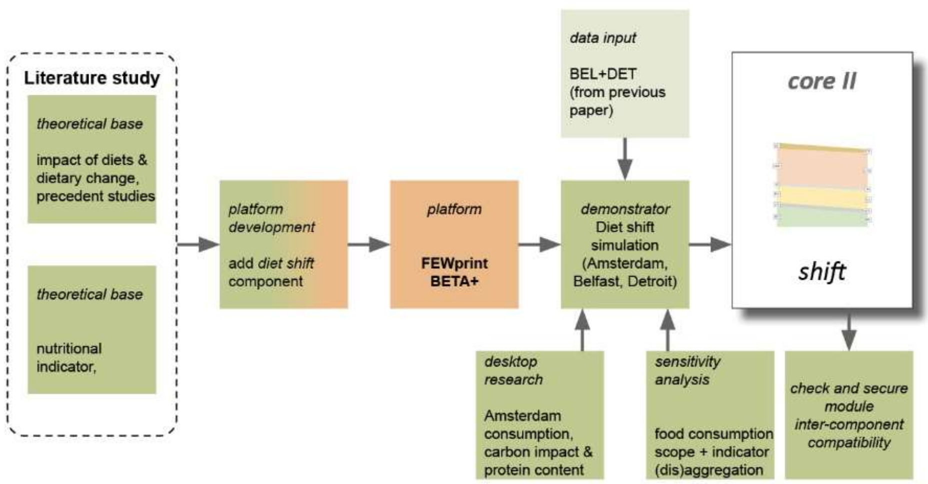

Figure 1.6: Research plan for the 'Diet shift' component, chapter 4 in this manuscript.

Chapter 5: Greenhouse solar collector - a synergistic solution

Chapter **five** describes exploratory research on a synergistic energy system in an inner-urban context. Compared to chapter two, this chapter limits on the scope of considered urban flows and adds weight to the integration aspect of a nexus evaluation and also increases the level of detail of calculation-accuracy, for example by adding a temporal component to the evaluation. This As part of a research collaboration with *Lidl Holland* (supermarket chain), a synergistic inter-dependent energy triad between a rooftop greenhouse, a supermarket building and residential apartment buildings was designed and evaluated. The greenhouse acts as a solar collector in this triangle. Through the use of accurate, hourly-based profiling of the simultaneous and mismatched discrepancies between thermal energy excesses and demands, direct and delayed energy exchange was simulated and the resulting carbon implications were assessed. The aim of this chapter is to provide material that supports the movement on the integration of food production in the built environment.

Chapter 6: FEWprint *design UFP* component

The **sixth** and final core chapter introduces and discusses the third component of the FEWprint platform: *design*. This chapter introduces the *pentalemma* of urban food production aspects—*demand, space, yield, resources* and *impact*— and elaborates how the FEWprint can be employed to systematically manipulate this pentalemma to explore food-centred design propositions for neighbourhoods. The five aspects are briefly explained. The chapter further describes the design protocol and methods to simplify the engineering behind (urban) food production design to harmonise the field with the activities of urban designers / planners. The functionality of the platform and applicability of the protocol are demonstrated by means of a theoretical urban redesign exercise for the Kattenburg community in Amsterdam. For this design workshop, a student-expert panel was composed to come up with a food-centred redesign proposal within one day, based on the M-Nex design scheme. This chapter concludes with an analysis of the FEWprint operator-design team interaction during the workshop and proposes a refined strategy to make this collaboration more effective. See figure 1.7 below.

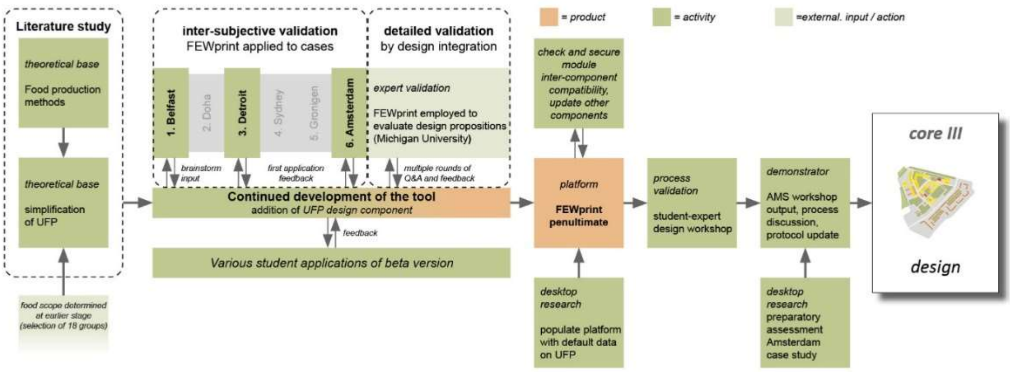

Figure 1.7: Research plan for the 'Design UFP' component, chapter 6 in this manuscript.

1.7 Supplementary information

The following background information is provided to this introduction to enhance the readability of this doctoral research.

- This manuscript uses carbon dioxide equivalents, or CO_2eq, as the metric to assess the urban context, evaluate urban redesigns and/or urban food producing systems. Where throughout this manuscript the words *(carbon) emissions, CO_2, carbon dioxide, greenhouse gases* is used, carbon dioxide equivalents are meant unless specified otherwise. Carbon dioxide equivalents is a metric used to compare different greenhouse gases based on their global warming potential, or GWP (World Resources Institute, 2014). Carbon dioxide has a GWP of 1 and is used as the reference gas to which other gases are compared. The full list of greenhouse gases is long and contains complex chemicals in the hydrofluorocarbons or perfluorocarbon groups that show far greater GWPs than carbon dioxide. There are however three main greenhouse gasses relevant to include in urban/UFP greenhouse gas analysis: carbon dioxide (CO_2, GWP =1), methane (CH_4, GWP=28 and nitrous oxide (N_2O, GWP=298). Since the content of the chapters is not amended before inclusion in this manuscript, the explanation above is repeated in some chapters.
- Where in this manuscript the acronym *FEW nexus* or only *FEW* is used, it generally includes not only the key resources of food, energy and water, but also includes the resource management sector domestic waste and resources related to personal mobility, i.e. car fuel.
- *FEWprint* and FEWprint. This term has a double meaning throughout the manuscript. When written in italic font, the word is referring to the *FEWprint* platform and when written in regular font, FEWprint is referring to the aggregated carbon footprint of the community, usually expressed in kg/cap*yr.

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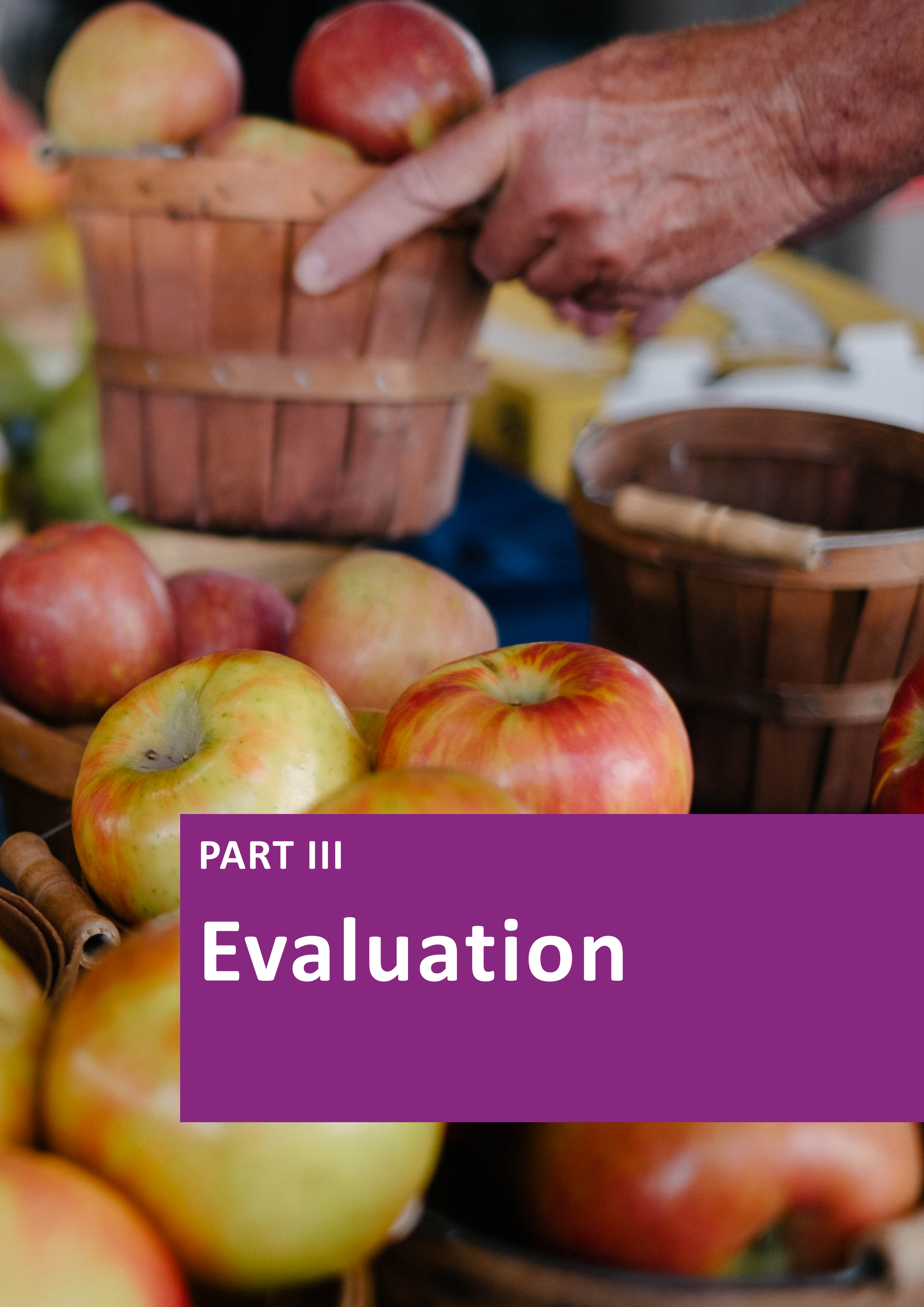

PART III

Evaluation

2

Pig farming vs. Solar farming

Exploring novel opportunities for the energy transition

Nick ten Caat, Nico Tillie and Martin Tenpierik

This opening chapter elaborates a hypothetical urban farming proposition in which a small livestock system is added and integrated into the built environment to foster a circular and synergistic resource management system. The capacity, and thereby the consequential productivity of the farm, is dictated by the amount organic waste that is rejected by the community. The aim of the following chapter is two-fold. First, it aims to identify, map and quantify material and energy flows of resources in a residential neighbourhood and to pinpoint methods of resource circulation for new purposes. The second aim is to perform a preliminary and narrower nexus assessment of the environmental impact and translate the experience into a comprehensive method that can be consolidated in the FEWprint platform for generic application. To address the ecological potential of adding food production to urban context, a comparison is drawn with the performance of a photovoltaic (PV) system in terms of avoided carbon emissions per square meter - hence the title of this chapter.

The chapter start off with an introduction of the energy transition challenges in Amsterdam and the current strategy to overcome these challenges. The benefits of circular farming and urban animal husbandry are discussed in sections 2.2.1 and 2.2.2, followed by an analysis of the conventional pork production chain 2.2.3. After discussing the system boundaries, scenarios, scope and functional units in 2.2.4 to 2.2.7, a detailed elaboration on the daily operations of a local pig farming system is provided 2.2.8. Since a comparison is made between the effectiveness of a livestock system and a PV system in terms of avoided carbon emissions, section 2.2.9 provides an estimation for PV panels in the Netherlands. The performance and added value of local livestock farming is discussed in the results section 2.3.

2

Pig farming vs. Solar farming

Exploring novel opportunities for the energy transition.

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Aside from layout changes and minor textual changes to improve readbility, this paper has not been amended for uptake in this dissertation.

2. Pig farming vs. Solar farming: exploring novel opportunities for the energy transition

Abstract

Amsterdam aims to bring down its carbon footprint by 55% in 2030 and by 95% in 2050. For the built environment, plotted pathways towards carbon neutrality primarily revolve around the reduction of fossil-based energy demand and the transition towards renewable energy production strategies. The consumption of food resources, and its significant corresponding carbon footprints, remain up to this day outside the scope of the city's carbon accounting. At the interface of the building sector and the agricultural sector, under-explored possibilities for synergistic and sustainable resource management come to light. For a more holistic and veracious evaluation, this research expands the carbon accounting inventory of the urban dweller with the food category and then explores, by means of a theoretical case in an Amsterdam neighbourhood, an unconventional strategy for the decarbonisation of the built environment: urban pig farming. The farming system is added to an urban context and coupled with the existing local resource flows, allowing for new output-input links. The capacity of the farm, i.e. the maximum number of animals at any time, is determined by the daily food waste output of the neighbourhood. To put the carbon mitigation effect of this method into perspective, a comparison is drawn with a conventional method for the energy transition: photovoltaic energy, for which two common PV array configurations are assessed. The three scenarios are evaluated on three aspects relevant to the energy transition of the built environment: avoided carbon emissions, produced thermal energy and produced electrical energy, normalised per square meter surface area occupied by the system. Carbon accounting shows that an integrated pig production facility of 495 m^2, holding 79 animals, can potentially reduce the carbon emissions of the neighbourhood by 218 tons (-5.6%) a year, i.e. 441kg CO_2 per square meter. The solar farm has a net impact of 42 $kg/m^2/yr$ if the panel array configuration is based on optimal panel angle and 77 $kg/m^2/yr$ if the configuration is based on optimal ground surface area cover. This study intends to spark further discussion on urban farming by showing that an integrated pig farm can potentially avoid between 6 - 10 times more carbon emissions compared to a solar farm.

Keywords

urban farming, energy transition, renewable energy, carbon footprint, Amsterdam

2.1 Introduction

Gradual depletion of fossil fuel supplies and anthropogenic climate change necessitate a transition towards renewable energy solutions in cities (IPCC, 2018b; UN Habitat, 2014). In the city of Amsterdam, the designated city for this study, around 30% (~1.325 kton) of the carbon emissions can be attributed to the city's residential and commercial natural gas demand alone (Gemeente Amsterdam, 2016). Both national and local governments committed themselves to the Europa 2020 agreements and to the global UNFCCC Paris 2015 climate agreement. For the Amsterdam metropolitan area, this leads to stringent CO_2 emission targets: a reduction of 55% by 2030 and 95% by 2050 (relative to 1990 levels) (Gemeente Amsterdam, 2019b).

In order to become free of fossil energy, cities are compelled to undergo an *energy transition* towards renewable energy sources as well as to better manage demand and supply (Solomon and Krishna, 2011). This implies a progressive disconnection from fossil-based energy resources and an increasing reliance on a combination of renewable electrical and thermal sources, such as photovoltaics, wind power or biogas. Amsterdam has conceived a roadmap towards (near) fossil energy freedom (Gemeente Amsterdam, 2019b). At the moment, conventional strategies mainly include expanding the photovoltaic surface area, increasing the wind turbine capacity at the perimeter of the city, expanding the existing high temperature district heating grid and setting high standards for the energy performance of future and retrofitted buildings (Gemeente Amsterdam, 2015). One of the milestones the municipality has set for itself is to fully abandon natural gas use in the built environment by 2040 (Gemeente Amsterdam, 2019b).

The carbon footprint of Amsterdam's dwellings can initially be allocated to the use of electricity and natural gas for domestic heating. However, the carbon footprint of the urban dweller extends beyond energy consumption of merely its housing and is topped up by, but not limited to, emissions related to 1) the production, distribution and treatment of water, 2) personal and public mobility, 3) the processing of domestic waste and 4), the production and transportation of food.

This study describes the hypothetical introduction of an organic pig farm into the residential neighbourhood of Kattenburg, Amsterdam. Such a farming system is not an autarkic entity and will put additional demands on the existing energy, water and waste infrastructure, subsequently implicating changes to the overall carbon footprint of the neighbourhood. Simultaneously, the global warming potential (GWP) of pork produced in this urban setting cannot be calculated with life cycle analysis (LCA) data of conventional farming practices since an alternative and unconventional method is used to feed the animals and different farm management applies.

Urban farming is co-incentivized by the idea that food chain carbon emissions (and other environmental burdens) are mitigated or even avoided due to more sustainable farming practices at a closer proximity to the consumers. However, to which extent this intended positive impact on the carbon balance outweighs the negative impact due to the increased demand for water and energy should be studied and calculated per case. Therefore, this study expands the scope of urban carbon accounting by adding pork consumption to the inventory. This integrated carbon profile –energy, mobility, water, waste and food- acts as the initial condition for the appraisal of urban food strategies and allows for a holistic assessment of the contribution of urban agriculture (UA) to the decarbonisation of the city. The aim of this research is to spark reconsiderations on urban livestock farming by demonstrating the decarbonisation potential of deploying a pig farm as an energy transition strategy.

2.2 Materials and Method

2.2.1 Sharing waste flows

For many centuries, the scale of a city was determined by the amount of food its arable belt could produce and how quickly this food could be transported to the markets (Steel, 2008). Innovations in ocean bulk transportation and the expansion of railway networks in the 19th century allowed cities to expand this belt and the agriculture to areas where space was abundant. Innovations in preservation and refrigerated transport lead to the global food system we rely on today (Hackauf, 2015). Livestock farming has changed over the last decades into a bio-industry, it has become more specialised, intensive, effective, large-scale, mechanised and less labour is involved in agricultural practices. Urban agriculture is 'the production, processing and marketing of food and related products and services in urban areas, making use of urban resources and waste' (Veen, Breman and Jansma, 2012, p.4). A farming system could act as a nexus within the network of urban waste, nutrient, water and energy flows. The farm receives urban output, converts it into crops or animal protein, creating new value out of waste, and circulates it back to the city. This lowers the use of virgin or imported materials and offers ecological and environmental benefits at various stages of the food production chain. A second ecological key benefit of UA is the reduction of carbon equivalent emissions due to a reduction of food miles, as food products or animal feed are no longer imported/exported to overseas countries but directly brought onto the local market (Van Timmeren and Hackauf, 2014).

This study theorises that Kattenburg's organic waste output becomes valuable farm input and the farm's output becomes valuable city input in the form of pork products and biogas. As such, the capacity of the farm is determined by the availability of organic waste generated within the neighbourhood. In other words: pig feed is not imported from external sources but produced onsite.

2.2.2 Urban livestock farming

Urban livestock farming, the raising of domesticated animals for the production of human food within or at the perimeters of cities and villages, used to be an ordinary practice in the beginning of the 20th century. After the 2nd world war, however, the growing global population led to an increasing demand for pork meat that could only be met though modernisation and upscaling. Therefore, in major pork exporting counties like the Netherlands and Denmark, the total number of individual pig farms decreased while the average number of pigs per farm increased considerably (Wageningen UR, 2019a; Willems et al., 2016).

Not including neighbourhood petting zoos, there are no initiatives in the Netherlands where pigs are kept within the urban context, let alone for the purpose of meat production. Online research reveals that (design) studies on the idea of commercial urban pig raising are limited. In 2001, MVRDV proposed *Pig City*, a radical re-imagination of organic and humane pig farming in The Netherlands. The design concept highly valued pig wellbeing and comfort while at the same time maintaining an animal concentration high enough to remain economically feasible (MVRDV, 2011). In the design- studio 'City Pig' , figure 2.1, the benefits and challenges of urban pig production are explored by proposing a series of urban integrated reimaginations of pig farms (Hackauf, 2015).

Figure 2.1: *One of the out-of-the-box farming concepts Copyright: The Why Factory (Delft University of Technology)*

Though various studies have researched the environmental impact of livestock production in general, there is less quantitative information available about livestock farming in (peri)urban environments (S. Wei et al., 2016). The debate against the return of pigs to cities revolves around the impacts of manure (mis)management, inadequate farming facilities that attract rodents and insects, risks around zoonosis, pollution of local water bodies due to polluted rainwater runoff and nuisance due to odour, noise, dust or fine particulate matter (Mfewou and Lendzele, 2018; Ström et al., 2017). Also, an inner-city farm would, even though expected to be smaller in production capacity, increase incoming and outgoing truck and tractor transport movements in the locality. Yet, it should be addressed that these disadvantages are more common in small-scale unregulated farming methods. Technologically advanced closed production systems, meeting stringent health, environmental and safety regulations with well-organised manure management are less likely to impose the mentioned burdens on their direct environments.

2.2.3 Import, export and carbon footprint of pork

Over the past decades, the distance between the consumer and the farm has increased, as did the distance between the animal and the farm that produces its feedstock. Nowadays, subsistent farming has made place for virtually landless pig farms. Grain, generally the main component of a regular slaughter pig's diet is for 90% imported from countries like France and Germany (Willems et al., 2016). Waste products of the food industry, like wheat bran, supply only part of the pig feed (±13%). Recycling valuable manure nutrients in an environmentally friendly way depends essentially on the total manure produced by all the livestock in an area and the amount of available arable land in the proximity of the farm (S. Wei et al., 2016). The EU Nitrates directive installed limitations (170 kg/hectare) on land spreading of manure to avoid (ground) water eutrophication by nitrogen and phosphorus wash off (EU Commission, 1991). The total manure production tends to exceed this limitation, forcing Dutch farmers to export about 90% of their (pasteurised) excess manure to other farmers or even across borders (Willems et al., 2016).

In order to draw a comparison between the local pork and the regular pork, Life Cycle Assessment results are analysed to determine the global warming potential (GWP) of the various stages in the pork production chain. In the Netherlands, three pork production methods can be distinguished: a *global* system - pig feed imported from abroad, meat exported abroad, *semi-local* - feed imported, meat sold locally and *local* -local feed, local market (Rougoor et al, 2015). The LCA assessment was performed for the five main stages in the pork production chain (shown in figure 2.2). Even though there are national concerns about sustainability and animal welfare, the majority of pork meat is still produced on large scale intensive farms tied to a global pig feed supply network. The Netherlands is market leader on the international pork meat market: with a self-sufficiency rate of 330% in 2019 (Wageningen UR, 2019b), the majority of pork produced is exported to neighbouring European countries. Still, this study assumes the *semi-local* scenario for the pork meat consumed in Kattenburg: pig feed is supplied with a global system, animals are slaughtered and processed centrally in the region and meat is sold within the Netherlands. This corresponds with a GWP of 2,78 kg CO_2/ kg carcass weight (CW) (Rougoor et al., 2015). The carbon emissions occurring at the slaughter, retail and consumer stage (in total 0,14 kg CO_2/kg_{CW}) are also included in the theoretical Kattenburg pig farm, without alterations.

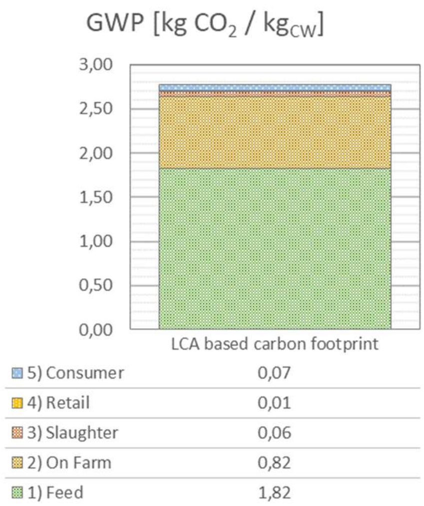

Figure 2.2 *Carbon equivalent footprint of Dutch pork meat (semi-local option), divided in the 5 main stages of production, results in 2,78 kg CO_2 per kg pork produced. Graph based on the research by Rougoor et al. (2015).*

2.2.4 Kattenburg, Amsterdam

Kattenburg is a high-density residential neighbourhood and former industrial harbour zone located in the city centre of Amsterdam, see figure 2.3 below. As of 2019, Kattenburg has 1801 residents divided over 1061 households (OIS Amsterdam, 2019).

Figure 2.3 *Kattenburg, East-Amsterdam (source: ©Google Earth)*

2.2.5 Scenarios

Two alternative scenarios are calculated and compared to the status-quo:

- *Status quo*. The existing condition assumes no existing urban interventions that support the energy transition with a major impact and represents a conventional system regarding the production and management of FEW resources.
- In s*cenario 1* an organic pig farm is introduced and positioned in the neighbourhood resource network. The new farm, further elaborated in section 2.2.8 and schematically drawn in figure 2.4, is imagined as an archetypical pig farm and fitted with a *feed station*, where domestic organic waste is sorted and converted into pig feed. This station includes the bio waste collection service by an electric vehicle. Additionally, the pig farm is equipped with a *waste station,* that includes an anaerobic digester (AD) and cogeneration plant (CHP) for manure management and energy generation to use onsite. In this station the digestate processing and bio gas upgrading also takes place. Excess biogas is shared with the adjacent residential buildings in the Kattenburg neighbourhood.
- In s*cenario 2* photovoltaic solar collectors (PV) are installed in the neighbourhood. PV panels are a widely accepted system of solar electricity generation and have made their way to the Dutch consumer market for many years now. Two *sub-scenarios* are taken into consideration: 2a) a South oriented PV array configuration based on maximal solar gain and 2b) a East-West PV array configuration based on optimal ground/rooftop surface coverage.

2.2.6 Scope

Carbon accounting is applied to assess the impact of the farming system on the emissions of the neighbourhood. The consumption of food, energy and water and the production of household waste within the Kattenburg boundaries result in upstream, territorial and downstream emissions of greenhouse gasses (World Resources Institute, 2014). In this comparitive study, only carbon emission drivers that can be allocated to Kattenburg's activities and that are directly affected by the proposed interventions are considered for evaluation. To give an example: the pig farm has an impact on Kattenburg's energy provision since excess green gas is directly shared with the adjacent dwellings, leading to a decrease in the demand for natural gas. The remaining digestate, even though rich in nutrients and a potential substitution for mineral based fertiliser, does not have a direct link with any of Kattenburg's activities and potential avoided carbon emissions are therefore not subtracted from the total carbon footprint. On the contrary, the on-site produced pork meat can virtually substitute imported pork meat on a one to one basis, subsequently lowering the carbon emissions of imported pork. The integrated footprint of Kattenburg is trimmed down to include consumed resources that are relevant to this study only, an overview is provided in table 2.1.

Table 2.1. Current per capita resource consumption/production of Kattenburg. Selection of the consumed resources relevant to this comparative analysis.

sector + component	product/activity	PCC / PCP(1)	*unit*	(source)/note
Food, meat	Pork meat	36,5	*kg/yr*	(Dagevos et al., 2017) Dutch national average.
Energy, electrical	National grid mix	1614	*kWh/yr*	(Liander, 2019) Neighbourhood specific data
Energy, thermal	Natural gas	549	*m^3/yr*	(Liander, 2019) Neighbourhood specific data
Water, consumption	centralised production	107	*L/day*	(Waternet, 2016) Regional average consumption of household water
	centralised treatment	107	*L/day*	Assume water demand = water processed.
Waste, processing	Domestic waste production	492	*kg/yr*	(Rijkswaterstaat, 2017) Dutch national average value
	organic fraction, 32%	157	*kg/yr*	(Rijkswaterstaat, 2017) Dutch national average fraction

organic fraction, waste-to-incineration	100	%	All organic waste is currently incinerated.

[1)] PCC: Per Capita Consumption, PCP: Per Capita Production.

Table 2.1 shows the per capita consumption (PCC) of the five assessed components of an average Kattenburg resident. Annual pork meat consumption is assumed to be similar to the Dutch national average consumption of 2017, which includes all types of (treated) meat products (i.e. fresh meat, frozen meat, meat products) but not meat added to secondary products (e.g. canned soups) (Dagevos, et al., 2017). Energy consumption is divided in electrical energy and fuel consumption to meet the thermal energy demand. For reasons of simplicity, incidental electrical energy generation on household level (e.g. private PV systems) are not included and it is assumed all households are connected to the national gas grid. Energy consumption data is provided at the household level (Liander, 2019). Domestic water consumption is retrieved from the district supplier (Waternet, 2016). Annual domestic waste produced per capita and its organic waste fraction (GFT) are retrieved from an online database (Rijkswaterstaat, 2017). Since the municipality of Amsterdam does not administer the organic waste fraction, national values are applied. Apart from a handful of small bottom-up initiatives and local pilots, there has not yet been a municipality-wide centralised bio-waste collection and processing service in Amsterdam (Van Zoelen, 2016). There is a lack of unambiguous data available that describes the processing method of separated organic fraction in the future. For these reasons it is assumed all the domestic bio waste is treated as domestic residual waste and is incinerated by the AEB waste incineration plant.

2.2.7 Functional units and carbon emissions factors

The pig farm and the two PV configuration options are assessed on three performance indicators:

1. Avoided carbon dioxide emissions [kg $CO_2eq/m^2/yr$] (all scenarios)
2. Net electrical energy generated [$MJ_e/m^2/yr$] (scenario 2a and 2b)
3. Net thermal energy generated [$MJ_t/m^2/yr$] (scenario 1)

Urban interventions proposed within the framework of the energy transition tend to aim for carbon-neutrality as the critical objective (Dobbelsteen et al., 2018; Pulselli et al., 2019). The environmental impact of the built environment is assessed as the footprint of carbon dioxide equivalents (CO_2e), corresponding to the three main greenhouse gasses released into the atmosphere, multiplied by their 100 year GWP, i.e. carbon dioxide (CO_2, GWP=1), methane (CH_4, GWP=28) and nitrous oxide (N_2O, GWP = 265). The GWP measures the potential greenhouse effect of an emitted gas relative to an equivalent mass of carbon dioxide, measured over a period of 100 years after its release into the atmosphere (World Resources Institute, 2014). Table 2.2 on the next page gives an overview of the applied carbon footprint indicators applied in this work.

Avoided CO_2e is normalised for the surface area the urban intervention occupies hence CO_2e/m^2*yr is used to describe the impact of the intervention. Additionally, net produced electrical energy [kWh/m^2*yr] or net produced thermal energy [$MJ/m^2/yr$] are calculated, where *net* implies that the energy demand resulting from the farm system is subtracted from the gross energy yield.

Table 2.2 Inventory of greenhouse gas emissions (GHG) of relevant components of the three scenarios

Sector	Component	Product/Activity	CF	Unit	Note
Food	Meat	pork meat production	2,7800	kg CO_2e/kg	(Rougoor et al., 2015) , LCA Dutch Pork meat
Energy	Electrical	grid mix	0,5260	kg CO_2e/kWh	(Otten and Afman, 2015), Country Specific value
	Electrical	solar: PV system	0,0000	kg CO_2e/kWh	No direct emissions occur [b].
	Thermal	natural gas	1,8900	kg CO_2e/m^3	(Zijlema, 2018), Country Specific value
	Thermal	biogas	0,0000	kg CO_2e/m^3	See table footnote [1,2]
Water	Consumption	centralised production	0,3600	kg CO_2e/m^3	(Frijns, Mulder, and Roorda, 2008), GWP - country specific value
	Consumption	centralised treatment	1,0700	kg CO_2e/m^3	(STOWA, 2008), GWP - country Specific value
Waste	Processing	waste-to-energy	0,6520	kg CO_2e/kg	(R. Pulselli et al., 2019) European average values

[1)] The combustion of biogas or green gas (predominantly methane) releases CO2 into the atmosphere. However, since the biogas originates from agricultural biomass that has sequestered this carbon dioxide earlier in the season (i.e. short carbon cycle), the net emission is zero. Carbon emission reductions are possible if the biogas substitutes natural gas.

[2)] Energy is invested for the production of the PV modules and the anaerobic digester systems, generally coined embodied energy. Invested energy is left out of the calculations in this study.

2.2.8 Kattenburg Farming system

The pig farm is divided into three stations: feed station, farming station and waste station. See the schematic representation of the farm and the system boundaries in figure 2.4 below.

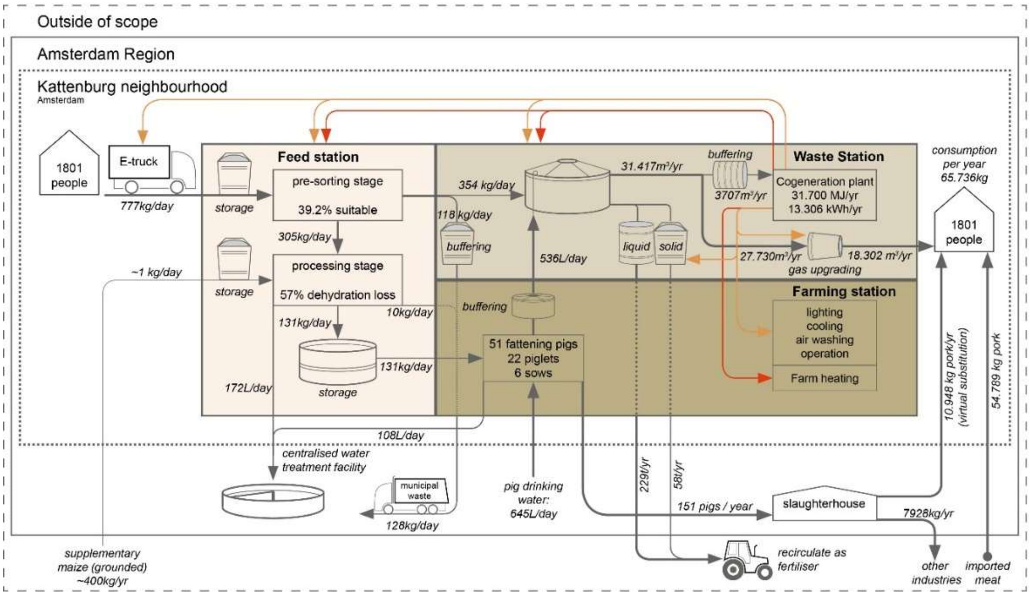

Figure 2.4: *The Kattenburg integrated pig farm with three stations. Some flows are given in daily quantities due to daily cycles (e.g. pig food consumption) and others per annum. Some small rounding errors may occur.*

Feed station

Food waste is archetypical pig feed and has historically been applied as such in Europe until 2002, when a farmer in the U.K. illegally fed uncooked food waste to pigs, igniting the foot-and-mouth disease epidemic (Salemdeeb et al., 2016). This caused the EU to ban the use of food waste for animal feed. This legislation steers away from a large saving potential on the environmental impact of pig raising. A potential land saving opportunity of around 1.8M hectares of agricultural land in Europe can be estimated if the European Union would change its legislation on the use of food waste for pork swill (Ermgassen et al., 2016). Salemdeeb et al. (2016) compare the application of food waste for pig feed with conventional anaerobic digestion and composting food waste management methods on 14 environmental and health impact points. Food waste processing into wet pig feed scored best on 13 out of 14 these indicators. In countries such as Japan and South-Korea food waste is still converted into pig feed (called *Ecofeed* in Japan), under the condition that manufacturers are subject to stringent regulations and obligations by the food safety law (Sugiura et al., 2009).

According to the Ministry of Infrastructure and Water Management, an average Dutch person produces 492 kg of domestic waste per year. Around 32% of this total amount is biodegradable waste equivalent to 157 kg/cap/yr (Rijkswaterstaat, 2017). For the sake of this study it is assumed all of Kattenburg's 1801 residents are consciously participating in the necessary semi-centralised waste separation program and that the new local waste collection and management system is operating without significant losses, hence a biowaste flow of 777 kg/day is theoretically possible.

Not all biodegradable waste is suitable to serve as pig feed and pre-processing filtration separates the unsuitable biomass from the suitable matter. This study applies the suitability coefficient of 39.2% (Ermgassen et al., 2016) which leaves 305 kg/day available for processing. The rejected bio waste can be fermented in an anaerobic digester to serve as biofuel. Suitable bio waste is fed into a shredder and filtered for solid contaminants. The hygienisation process includes partial dehydration before the wet residue is heat-treated on a temperature of 100°C for sterilisation. Before storage, grounded maize is added. One ton of suitable domestic organic waste results in 430 kg of pig feed (Kim and Kim, 2010; Salemdeeb et al., 2016). This wet pig feed can substitute conventional pig feed on a one to one basis (Salemdeeb et al., 2016). The amount of pig feed that can theoretically be generated from Kattenburg's biowaste flow is calculated with equation [1]:

$$F = \frac{W_{bio} * r_1 * r_2 * N_{KB}}{365} \qquad [1]$$

where:

F [kg/day], is the daily wet pig feed produced from bio waste.

W_{bio} [kg/cap/yr], represents the annually produced bio-degradable waste per capita.

r_2 [-], notes the assumed part of bio waste suitable for further conversion (0.392)

r_2 [-], notes the waste-to-food conversion rate of 0,430 (0,405 + 0,025 maize)

N_{KB} [-], represents the total population of Kattenburg

Farming station

The productivity of the pig farm is based on the food conversion ratio and the number of pigs sent to slaughter each year. For this study it is assumed no bulk feed is imported from outside the system. Sows are artificially inseminated, which excludes boars from the farm. Based on the average life stage duration of the pigs and assuming a continuous and steady breeding cycle, we calculate that for every one piglet (42 days life stage, see table 2.3) there are 3,28 fattening pigs

(138 days) present at any time. Incorporating this ratio, the average daily feed intake of one animal (C_{pig}) on this farm is 1,62 kg/day and is calculated with equation [2]. The calculation is based on the average daily feed intake of a piglet (0,9 kg) and of a fattening pig (1,92 kg) combined with the before mentioned animal life stage ratio. The maximum number of animals on the farm is determined by the available bio waste based pig fodder and can be calculated with equation [3].

$$C_{pig} = \frac{(1*0,9)+(3.28*1,9)}{4.28} = 1.62 \text{ kg/day} \qquad [2]$$

$$\sum N_{pig} = \frac{F}{c_{pig}} \qquad [3]$$

The minimum number of sows required to sustain the farm's pig population can be using equation [4]. The farm keeps its own sows to produce piglets so that no weaning pigs are imported from external breeding farms. It is assumed that one sow can produce 28 piglets per year (Zu Ermgassen et al., 2016). The number of piglets (PL) and fattening pigs (FP) can be calculated with equations [5] and [6].

$$N_{sow} = \frac{\sum N_{pig} * (365/LC_{pig})}{28} \qquad [4]$$

$$N_{fp} = (1 - \frac{LS_{pl}}{LS_{fp}}) * (\sum N_{pigs} - N_{sow}) \qquad [5]$$

$$N_{pl} = \sum N_{pigs} - N_{fp} - N_{sow} \qquad [6]$$

The maximum number of animals at any time on this farm is represented by $\sum N_{pig}$. The number of piglets (PL), fattening pigs (FP) and sows are represented by N_{PL}, N_{FP} and N_{sow}. The duration of *piglet* life stage (LS_{PL}) and *fattening pig* life stage (LS_{FP}) is respectively 42 and 138 days, or 180 days in total.

The annual pork yield of this farm is described by M_{farm} [kg/yr] and depends on the number of animals the farm delivers, the life weight (kg_{LW} [kg/pig]) of a slaughter pig (table 12.3) and the amount of consumable meat that can be retrieved from the carcass, indicated by m_{pig} [%] (Vion, 2017, p.19). Also sows are brought to slaughter at the end of their intended life cycle (LC_{sow}).

$$M_{farm} = \frac{N_{sow}}{LC_{sow}/365} + \frac{N_{fp} + N_{pl}}{(LS_{PL}+LS_{FP})/365} * kg_{LW} * m_{pig} \qquad [7]$$

The equations above point out that, based on the food waste revenue, the maximum number of animals that can be kept at any time in the farm is 79 (namely 6 sows, 22 piglets and 51 fattening pigs), which means that the farm could theoretically deliver 151 slaughter pigs per year when a normal life span of 180 days is applied. This study assumes the animals are slaughtered at conventional large scale facilities, where 58% of the full body weight can be retrieved for human consumption (Vion, 2017). Assuming a life weight of 125 kg_{LW} per animal and an edible meat fraction of 58%, this farm can generate 10.948 kg of pork meat per year. The remaining pig products are used in other industries but are not carbon accounted for in this study.

Table 2.3. Technical data of pork production chain and spatial specifications pig farming.

pork production specifics	*unit*	piglet (PL)	fattening pig (FP)	sow	note / source
Life stage length	*days*	42(1)	138(2)	730 (2yr)(5)	Total life cycle animal $[LC_{pig}]$ = 180 days.
Feed intake	*kg/day*	0,71(3)	1,92(4)	1,92(4)	(Rougoor et al., 2015) assume sow = FP
Water cons. / slurry produced	*ton/pig/yr*	2,98 / 2,48	2,98 / 2,48	2,98 / 2,48	Indicative values for calculations.(6)
Water exhaled/lost otherwise	*ton/pig/yr*	0,50	0,50	0,50	Own calculation. Assume sink = WWTF
Carcass weight / Life weight	kg_{CW}/kg_{LW}	n.a. / n.a.	102 / 125	102 / 125	(Rougoor et al., 2015) assume sow = FP

Min space: pig pen / free roaming	*m²/animal*	0,6 / 1,0	1,3 / 1,0	2,5 / 1,9	(SBLk, 2018)
No of animals	*[-]*	22	51	6	Own calculations. Equation 4-6.
total space required	*m²*	35,2	117,3	26,4	Own calculations.

1) (SBLk, 2018). Piglets should stay a minimum of 42 days with the sow according to 3-star organic farming standards.

2) (Rougoor et al., 2015, table 4 in source) final weight slaughter pig [kgLW] / average growth rate [kg/day] = 125/0,9 = 138 days.

3) Life span sows vary per farming method. We assume 2 years/720 days

4) (Rougoor et al. 2015) total feed intake [kg]/life span [days] = 30/42 = 0,71 kg/day

5) (Rougoor et al. 2015) total feed intake fattening pig [kg]/life span [days] = 265/138 = 1,92 kg/day

6) (Schiavon et al. 2016). Exact values depend on many parameters (i.e. farm typology, climate, pig life phase). Mentioned values are for fattening pigs with a life weight of 120 kg that are on a wet feed diet (water-food intake ratio = 4:1). Assume floor is partially slatted. For simplicity we assume the fattening pig, piglet and sow are equal

Waste station

The pig farm is heated and cooled to maintain a comfortable environment for the animals and electricity is required for farm lighting, ventilation, air cleaning and other on-farm processes (see table 2.5). The farm generates its own thermal and electrical energy by means of anaerobic digestion (AD) and combined heat and power generation (CHP). The annual biogas yield is sufficient to meet the energy demand of the electric waste collection vehicle, the feed station, the pig farm, the AD and the biogas upgrading station. Excess biogas is cleaned and upgraded in a water scrubber, after which it is suitable to be mixed with the natural gas grid.

Pigs produce manure or slurry, which can be valuable for crops as it contains large amounts of Nitrogen (N), Phosphorus (P) and Potassium (K), but can pose an environmental threat if managed poorly (Loyon et al., 2016). Slurry produced by the pigs is collected through the partially slotted floor and buffered in a closed storage tank. Together with the rejected biowaste, the manure serves as input for the AD. Depending on the fermentation speed in the AD, the manure is mixed with shredded biowaste and the resulting substrate pumped into the AD tank, ensuring a continuous production of biogas. In the AD tank, the co-digestion process of pig manure and food waste occurs under zero-oxygen conditions, resulting in the production of methane, carbon dioxide and small amounts of incondensable gasses like N_2, O_2 and H_2 (Chen et al., 2015). The temperature of the AD substrate is kept within the mesophilic range (35-45°C), speeding up the digestion process. The biogas output of the AD co-depends on the substrate typology and on the solid fraction of that substrate (Table 2.4) (SGC, 2012). The biogas yield of this farming system is calculated to be 96,7 m³ per ton input, resulting in 31.437 m³ of biogas per annum. After the anaerobic digestion process a mineral rich and odourless digestate remains in the reactor vessel, which is centrifuged to separate the liquid and solid fraction and then stored. Mass balance calculations are used to determine the amount of liquid and solid digestate produced, based on the feedstock characteristics (Table 2.4), biogas composition (63% methane, 37% carbon dioxide) and component densities. The digestate could potentially substitute mineral fertiliser on the crop field, but this is left out of this study.

The produced biogas fuels an on-site combined heat and power plant (CHP) to generate the electricity required by the feed station, the pig farm, the AD and the electric collection vehicle (table 2.5). Excess biogas is cleaned and upgraded, which means that the carbon dioxide concentration is reduced and unwanted trace elements are removed before mixing with the gas grid (X. Y. Chen et al., 2015). There are several methods for biogas upgrading that all come with various advantages and disadvantages. High Pressure Water Scrubbing (HPWS) seems to be most suitable for small scale applications, is cheap and can handle fluctuating capacities (Baena-moreno et al., 2019; Wylock and Budzianowski, 2017). Upgraded biogas is called *green gas* and can be shared with the adjacent residential buildings, where it can substitute conventional natural gas on a one-to-one basis.

Removed carbon dioxide cannot be collected and repurposed with this technique and is left out of the carbon emission evaluation. For simplicity, it is assumed no methane is lost during the scrubbing process.

Table 2.4. Substrate properties (SGC, 2012) and biogas yield AD

AD input	Quantity [ton/yr]	Mix ratio [kg/ 1000kg]	Solids [%]	Solids in mix [kg/1000kg]	Biogas content [m^3/1000kg]	Biogas yield [m^3/1000kg]	Gas yield V_{prod} [m^3/yr]
Pig Slurry	195,9	603	8	48,2	26	15,7	-
Bio waste	129,0	397	33	131,0	204	81,0	-
total	325,1	1000		179,2	-	96,7	31.437

Table 2.5. Life cycle inventory of various system components and other parameters

n.	Comp.	Description	Value	Unit	Note/Source
1	Feed station	Electricity demand feed processing	13,9	MJ_e/1000kg	(Kim and Kim, 2010)
2		Thermal energy demand feed processing [a]	105,7	MJ_t/ 1000kg	(Kim and Kim, 2010) See foot note a.
3		Wastewater production during feed processing (r_2)	564	L/ 1000kg	(Kim and Kim, 2010)
4		Supplementary grounded maize added	25	kg/1000kg	(Kim and Kim, 2010)
5		Screenings produced during feed processing	30	kg / 1000kg	(Kim and Kim, 2010)
6		Accepted bio waste in pre-processing (r_1)	392	kg / 1000kg	(Zu Ermgassen et al., 2016). i.e. 39.2% is suitable
7		Electricity demand food waste collection vehicle	460	kWh/yr	Estimation, see [d]
8	Farming station	Electricity demand pig farm	87,8	MJ_e/animal delivered	Based on 19,5 kWh/100kg_{LW} (Dalgaard, Halberg, and Hermansen, 2007).
9		Energy demand pig farm	29,9	MJ_T/animal delivered	Based on 23,9 MJ / 100kg_{LW} (Dalgaard et al., 2007a).
10		Water demand pig / manure production pig	-	-	See table 2.3
11	Waste station	Electricity demand A.D. process	7,20	MJ_e/1000 kg input	(Nguyen, Hermansen, and Mogensen, 2010)
12		Energy demand A.D. process	46,8	MJ_t/1000 kg input	(Nguyen et al., 2010)
13		Fraction of rejected bio waste suitable for AD	75	%	Assumption.
14		Digestate production A.D. process	886	kg/1000kg input	Own calculation [c]
15		Liquid fraction in residual digestate	79,8	%	Own calculation [f]
16		Solid fraction in residual digestate	20,2	%	Own calculation [f]
17		Volumetric loss during conversion biogas > green gas, conversion value	0,746	-	Own calculation [e]
18		CHP: efficiency (η_{CHP})	90	%	Standard efficiency, 10% is lost to the system.
19		CHP: Thermal energy produced	11,5	MJ_t/m^3	50% of fuel input, standardized calculation value.
20		CHP: Electricity energy produced	9,2	MJ_e/m^3	(Wylock and Budzianowski, 2017) 40% of fuel input
21		Electricity demand solid-liquid separation digestate (centrifugal method)	9,00	MJ_e/1000kg digestate	(Timonen, Sinkko, Luostarinen, Tampio, and Joensuu, 2019).
22	Misc.	Electricity required for biogas upgrading (e_{up})	0,90	MJ_e/Nm^3	(Baena-moreno et al., 2019) Conservative value.
23		Energy content biogas (q_{bgas})	23,00	MJ/m^3	(SGC, 2012) Lower caloric value, 67% CH_4.
24		Energy content natural gas / green gas	31,65	MJ_t/Nm^3	(Zijlema, 2018)

[a] Source mentions diesel. Calculatio: 2,91 L^{-1} Diesel / 1000kg food waste = 105 MJ/t (assuming Diesel = 36 MJ/L^{-1}). Converted to biogas this gives (23 MJ/m^3): 4,55 m^3/1000kg food waste.

[c] CH_4 concentration biogas = 63% (SGC, 2012). Density CH_4/CO_2 = resp. 0,72 / 1,96 kg/m³ (Timonen et al., 2019). This gives a biogas density of 1,179 kg/m³. The biogas yield of this substrate composition is 96,7m³/ 1000kg substrate (table 12.4) , i.e. 114 kg of biogas is removed from the reactor vessel, leaving 886 kg of digestate. Biogas trace elements like H_2O, H_2, N, H_2S and O_2 are ignored for this calculation for simplicity due to their small concentrations.

[d] Assumed vehicle type: Goupil G4 electric freight cart. Lithium battery with 7,2 kWh capacity offers 85km driving range (vehicle brochure). Assume 15km/day = ~5500 km/year. This comes down to roughly 65 full charges / year, or 460 kWh/yr.

[e] Methane concentration should be increased from 63% to 97% (+34%) to make *green gas*, i.e. 0,34 x 1,96 = 0,67 kg /m³ CO_2 is removed from the biogas. This conversion leads to a volume reduction for the green gas (at equal pressure) of 1/1,34 = 0,756. The *green gas* density after upgrading is 0,756 kg/m³ (3% CO_2, 97% CH_4).

[f] Total solids in substrate is 179,2kg /1000kg (table 12.4). We assume this amount remains the same for the digestate, but the biogas yield should be subtracted. This makes 179,2 kg / 886kg digestate, or ~20% of the digestate.

2.2.9 Solar Farm

In order to put the performance of the urban integrated pig farm into perspective, a comparison is drawn with the carbon emissions mitigation potential of a PV field, expressed per square meter of occupied surface area. Since PV panels or arrays can be clustered, oriented and distributed throughout the urban context in essentially unlimited manners, two key setups are further elaborated:

- Setup A is installed according to the optimal angle relative to the solar trajectory in the Netherlands (figure 2.5, left, top): respectively 36° and 180° South for most optimal angle for the altitude and azimuth. A consequence of this method is the required free space between two panels in a PV field to avoid inter-panel shading, leading to a larger ground surface area per panel and a less efficient use of the available space. The minimal distance between two panels within a solar array is calculated with a rule of thumb, suitable for a context in the Netherlands: 2,7 x panel height.

- Setup B is based on an optimised use of the available surface area and proposes an east-west panel orientation under a lower panel inclination: respectively 10° and 90° East/270° West. As such, the panels no longer shade each other but the yield per panel is reduced. A maintenance corridor of 50 cm is applied (figure 2.5, left, bottom)

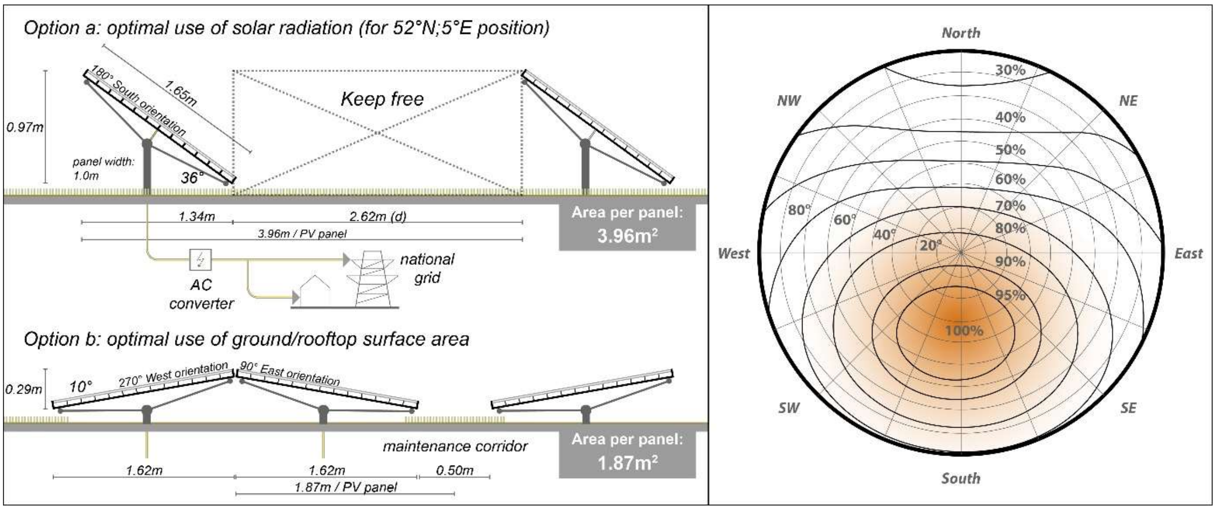

*Figure 2.5 Left, top: Panel setup A, oriented to the South. **Left, bottom**: Panel setup B, oriented to the East and West. **Right**: Diagram displaying the optimal panel inclination and azimuth for a panel in the Netherlands: respectively 36° and +/-180°.*

Electrical output

The annual electricity yield of one PV panel can be calculated with equations [8-11]:

$$PV\ yield\ (E_{sys}) = A_{sys} * \eta_{PV} * \eta_{other} * \int_0^t G_M(t) * dt \quad [8]$$

A_{sys} [m^2], Surface area of the panel. This study applies the standard dimensions of 1,00 x 1,65m.

η_{PV} [-], is the efficiency of the PV module and is given by the manufacturer. Set to 18%.

η_{other} [-], represents the combined efficiency of all the other factors (e.g. thermal losses and inverter losses) and is set to 0,9, a suitable value for the city of Amsterdam (RVO, 2014).

$\int_0^t G_M(t) * dt$ [Wh/m^2] is the total irradiation incident on the surface of the PV module and depends on the solar irradiance (DNI, DHI, GHI) and the sun's position at a specific moment (*t*). Hourly time steps are calculated for one full year. Equation 10 calculates the relative orientation between the panel surface and the sun at moment t ($AOI(t)$) and assumes that no obstructions are shading the PV modules.

$$G_M(t) = DNI(t) * \cos(AOI(t)) + DHI(t) * SVF + GHI(t) * (1 - SVF) * \alpha \quad [9]$$

where

$$\cos(AOI(t)) = \sin\theta_M * \cos(a_s(t)) * \cos(A_M - A_S(t)) + \cos\theta_M * \sin(a_S(t)) \quad [10]$$

$$SVF = \frac{1+\cos\theta_M}{2} \quad [11]$$

DNI [-], Direct normal irradiance. Retrieved from Meteonorm (2019) for position 52°N

GHI [-], Global horizontal irradiance (Meteonorm, 2019).

DHI [-], Direct Horizontal irradiance (Meteonorm, 2019).

A_S/a_S [°], Respectively solar azimuth and solar elevation at (*t*) (Meteonorm, 2019)

θ_M/A_M [°], Respectively panel tilt and panel azimuth. Set on 36°/180° for scenario A (ISSO, 2017) and 10°/ 90°, 270° (East/West) for scenario B.

SVF [-], Sky View Factor. Calculated with equation 11.

α [-], Albedo factor. Depends primarily on the (ground) surfaces in the direct vicinity and is set to 0,2 for this inner-city location.

At 52°N,5°E there is a small (less than 1%) dissimilarity between the electricity yield of the East-facing panel and the West-facing panel, which is neglected in this study.

2.3 Results

2.3.1 Green gas production

Produced excess biogas can be upgraded, pressurised and pumped into the gas network, offering a renewable alternative for natural gas for domestic heating or cooking purposes. Equations 12-14 are applied to calculate the net production of biogas in this farming system. All the energy flows considered in this study are represented in figure 2.6. Approximately 8% of the produced biogas is required to run all the processes within the farming system, leaving 28.656 m^3 of biogas available for upgrading. This purification process from biogas into green gas requires another 26.300 MJ_e and leads to a volumetric reduction of 34%, as almost all the carbon dioxide is scrubbed from the gas mix (see table 2.5). On an annual basis the pig farming system could export 18.301 m^3 of green gas to the adjacent dwellings, which is about 2% of Kattenburg's present natural gas demand, or roughly the average annual use of 33 Kattenburg residents.

$$V_{exp} = (V_{prod} - V_{syst} - V_{up}) * (1 - 0.34) \quad [12]$$

where:

$$V_{syst} = \frac{\sum(E_{PF}+E_{FS}+E_{WS})*\frac{1}{n}}{q_{b.gas}} \quad [13]$$

$$V_{up} = \frac{(V_{prod}-V_{syst})*e_{up}}{q_{biogas}} \quad [14]$$

V_{exp} [m^3/yr], The net produced green gas pumped into the local gas grid.

V_{prod} [m^3/yr], Notes the biogas produced in the anaerobic digester (see table 2.4).

V_{sys} [m^3/yr], Represents the biogas needed to energise the feed-, pig- and waste station.

V_{up} [m^3/yr], Describes the biogas demand to energise the gas upgrading process.

η_{CHP} [-], Represents the efficiency of the CHP plant is and is set to 0,9 in this study

q_{bgas} [MJ/m^3], Notes the caloric value of biogas: 23 MJ/m^3

e_{up} [MJ/m^3], Denotes the electricity demand of the biogas upgrading process

$E_{FS,PS,WS}$ [MJ_{E+T}/yr] Energy demands of feed station, pig station and waste station and are calculated with the conversion data mentioned in table 2.5.

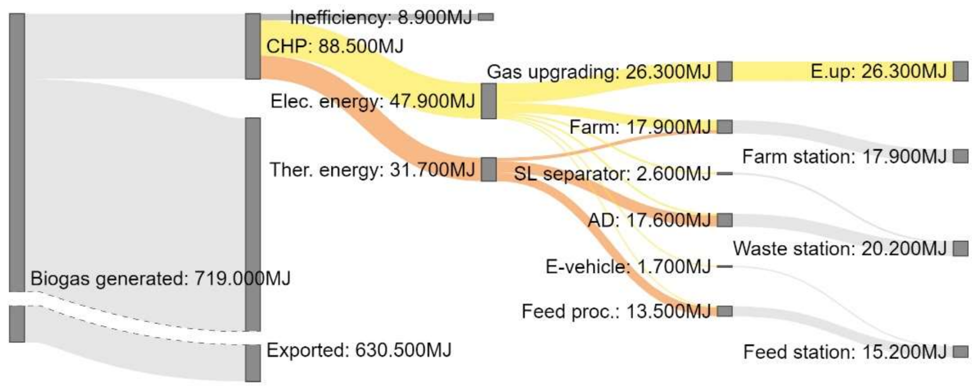

Figure 2.6 *Energy flows within the pig farm. Exported biogas is shared with the adjacent dwellings.*

2.3.2. Energy yield per square meter

One PV panel oriented according to optimal solar irradiation (setup A) can produce 314 kWh_e/yr. A panel oriented according to optimal use of available surface area can generate 272 kWh_e/yr. The electricity yields of the two panel setups are normalised per square meter of ground area occupied. Basic goniometric formulas are used to determine the total space demand for one panel and point out that setup A requires at least 3,96 m^2 (including free zone) and setup B at least 1,87 m^2 (including maintenance corridor) land area per panel, drawn in figure 2.5.

- *Setup A* yields 314 kWh_e annually per panel, or 79 kWh (286 MJ_e) per square meter of land area , shown in the graph of figure 2.7.
- *Setup B* yields 272 kWh_e per year per panel, or 147 kWh_e (529 MJ_e) per square meter of land area, figure 2.7.

Pig farm: The farm can pump 18.301m^3 green gas into the national gas grid. Table 2.6 shows a breakdown of the considered functions of the farming system and the (estimated) minimal space required. Per square meter of farm, 37 m^3 of green gas is produced, or 1170 MJ_T.

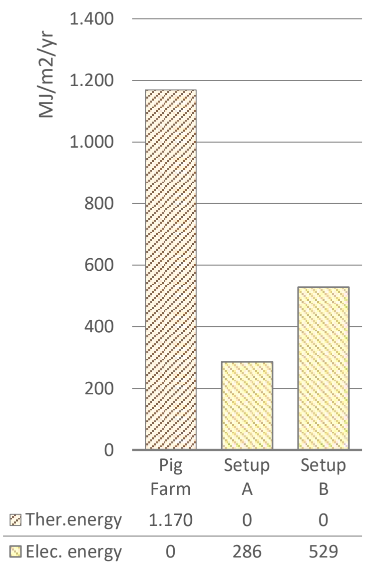

Figure 2.7 *Energy yield and corresponding avoided carbon emissions per m^2*

Table 2.6. Spatial breakdown of farm. Most values represent educated estimations.

Station	Space function	[m2]	Note
Pig station (PS)	pig production space (3 star animal well-being)	178,9	Also see table 2.3
	maternity pens	15	2 x 7,5m^2 / sow
	other (e.g. sick pen, installations, office, storage)	100	
	traffic zone	90	Assume 0,5x PS
Feed station (FS)	waste processing (e.g. expedition, parking, sorting, processing)	30	
	waste storage / pig feed storage / maize storage	10	
	traffic zone	20	Assume 0,5x FS
Waste station (WS)	rejected food waste storage + mixing vessel	10	
	anaerobic digester + auxiliary systems	10	
	biogas storage	4	
	SL separator	4	
	Solid digestate storage	6	
	Liquid digestate tank	6	
Gas upgrading	high pressure water scrubber	12	
total		**495**	

2.3.3 Avoided carbon emissions

Figure 2.8 shows the carbon profile of both Kattenburg's status quo and the scenario with the pig farm integrated. The CO_2e footprint of Kattenburg could theoretically drop with 218 ton, or 5.6% per year. The two most significant contributors to this decarbonisation effort are the avoided emissions related to the substitution of imported pork and the avoided emissions corresponding to incineration of biodegradable waste. The farm puts additional pressures on the existing water system: around 235.000 liter of drinking water is needed to hydrate the animals and for farm processes, of which 131.000 liter is pumped to the central wastewater treatment facility after use. This increase does not lead to a significant rise in carbon emissions in the *water* sector: around 200 kg of additional CO_2e emissions are added to the carbon profile. There are no changes in the electricity related carbon emissions as excess energy is not exported as electricity but as green gas. About 18.301 m^3 of natural gas can be substituted with green gas, resulting in a decarbonisation impact of almost 35 ton/yr. Of the total waste flow, 48 ton is converted into pig feed, 103 ton is directed to the AD and due to dehydration 63 ton is removed from the system as wastewater. From the initial 284 ton of organic waste, 46 ton (16%) still has to be incinerated, leading to a carbon emission decrease of 155 ton/yr. Finally, about 11.000 kg of pork (from 151 animals delivered) is produced on this urban farm, which can virtually replace about 17% of the current imported meat consumed, leading to a reduction of 29 ton CO_2e per year. All mass flows entering and leaving the farming system are represented in figure 2.9.

The graph on the right side in figure 2.8 shows the avoided carbon emissions for the pig farm (KB+Farm) and the two PV setups. With regard to carbon emissions, the urban pig farm is roughly 6-10 times more effective, depending on the chosen PV setup.

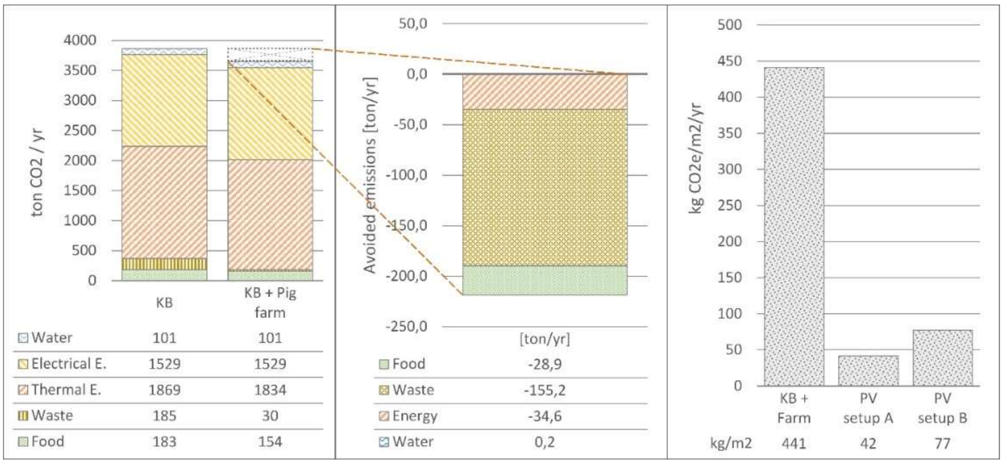

Figure 2.8 *Left: carbon footprint of KB status quo (left column) and after the addition of the pig farm (right column). Middle: breakup of the avoided carbon footprint. Right: avoided carbon emissions per square meter Keep in mind that this footprint does not represent the full integrative CO_2 footprint of Kattenburg since only a selection of relevant resources are assessed for this study.*

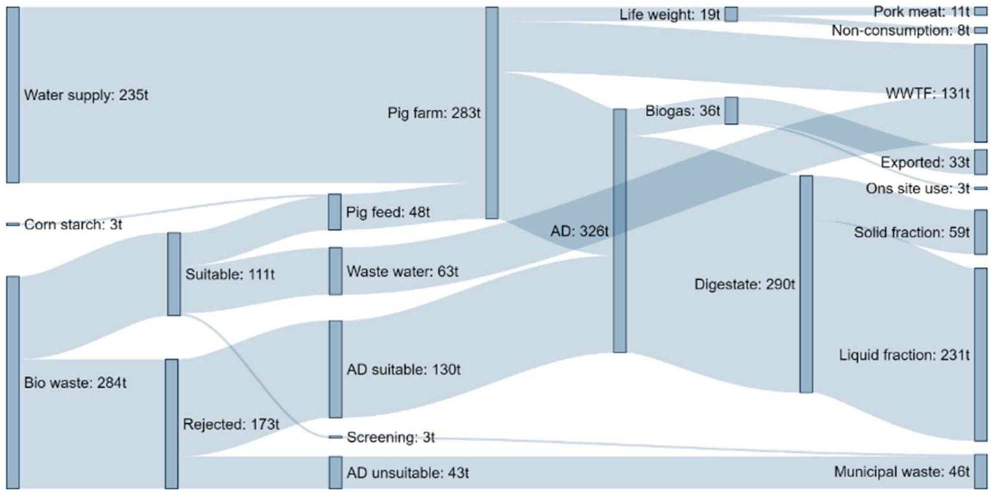

Figure 2.9 *Mass flow diagram of the pig farm system.*

2.4 Discussion

This study was performed to gain insight into the decarbonisation impact of urban pig farming. Carbon accounting of a theoretical urban pig farm in Kattenburg reveals that it is almost six times more effective compared to a space efficient PV array. However, there are limitations, assumptions and uncertainties surrounding this performance, which are discussed below.

2.4.1 Limitations and assumptions

There is no golden standard for the raising and fattening of pigs. The number of animals the farm can deliver depends on variables like the practised animal well-being standards, pig species, food diet and nutritional value, food accessibility, animal weight at slaughter and other variables a farmer can or cannot not control. The production specifications used in this study are based on a combination of Dutch pork production LCA values and organic farming conditions. These values are assumed to be representative for an exploratory carbon accounting study, yet it is important to mention that any alterations affecting the food conversion ratio, will have knock-on effects on succeeding elements like AD biogas production, delivered animals and eventually the avoided CO_2e/m^2.

A similar uncertainty applies to the physical scale of the pig farm. Based on realistic organic farming standards, it is possible to give a reliable indication on the required surface area of the pig station. However, the area of the feed and waste station in this study are based on conservative estimations and in practise spatial requirements may deviate. If the project would be realised according to the principles proposed in this study, the required space will be co-determined by the constraints of the physical context and architectural design of the facility, possibly increasing the surface area. However, due to stacking of functions, underground storage rooms and efficient combining of processes in the same room, also a lower surface area could be possible.

Taking into consideration the various parameters and assumptions, it must be noted that the calculated performance of 441 kg $CO_2/m^2/yr$ is not a concrete outcome but likely remains at the positive side of an unspecified range.

2.4.2 Outlook

The productivity of this farm is entirely coupled with the neighbourhood biowaste flow of Kattenburg and supplementary imported pig feed is excluded, emanating in a farm that produces around 151 animals per year, or 17% (11.000 kg) of the total pork demand of this neighbourhood. The number of animals at the farm could be increased if additional (local) food sources are addressed, e.g. food waste from supermarkets, small retail or waste from canteens in the commercial sector or waste from adjacent neighbourhoods. General farming tendency goes in the direction of upscaling and intensifying and producing 151 animals annually, even with an organic label, is unlikely to be sufficient to run an economically feasible farm. However, this should be investigated with additional research.

Further research should uncover the possibilities for symbioses with crop production as a way of manure management, which in this study is still exported to outside the system boundaries and left out of the carbon accounting scope.

CO_2eq emission is chosen as the KPI of this study. There are however other environmental impacts surrounding the production, distribution and processing of pork (Salemdeeb et al., 2016). Carrying out additional LCA studies on environmental and health impacts, such as embodied water, eutrophication potential, particle matter emission and land use, could produce outcomes that are in support of UA.

2.4.3 Alternative system design

There are alternative system designs/configurations possible to the one proposed in this study, that conceivably lead to different carbon performances. To provide one example: instead of exporting green gas as a substitute for natural gas, it could also fuel a CHP plant tied to a local district heating grid. Generated thermal and electrical energy would be shared with Kattenburg, subsequently arriving at different amounts of avoided CO_2.

This study shows a comparative analysis between urban pig farming and PV panels with regard to the avoided carbon emissions per square meter of surface area. In practice, the successive design move would naturally be to place the panels on top of the farm building, achieving the best of both methods. Due to endless possible variations in farm design and by that PV configurations, we did not add as third possible scenario. However, for indicative purposes, we can estimate that a farm structure of 18x28m (504 m^2), with a 10° pitched roof facing East and West similar to PV setup B in this study, could in theory hold 270 PV panels (2 arrays of 5x27 panels). This generates about 73.440 kWh_e of renewable solar energy a year, potentially avoiding another 38.6 tons of carbon emission, roughly 1% of the total emissions of Kattenburg.

2.5 Conclusion

This study explored the potential of organic urban pig farming as a method for the energy transition of the residential Kattenburg neighbourhood in Amsterdam. It was paramount to expand the carbon inventory of the dweller with the food sector to perform a holistic evaluation on the impact of farming in the urban context. Integrating a pig farm into the neighbourhood could potentially lead to a carbon emission decrease of 218 ton per year (-5.6%). Calculations pointed out that at any time, about 79 animals can be sustained with the biowaste produced by Kattenburg's 1801 inhabitants, yielding almost 11.000 kg of pork meat each year. It is estimated that the farm would require a ground surface area of 495 m^2, which translates to a carbon avoiding potential of 441 kg $CO_2e/m^2/yr$. Compared to the carbon emissions mitigation potential of PV panels, this pig farm is about ten times more effective than a panel array based on highest solar gain and about six times more effective than an array based on optimal surface coverage. Most of the avoided carbon emissions can be allocated to the reduction in incinerated biomass (-155 ton CO_2e/yr), followed by substituting natural gas with green gas (-35 ton) and virtually replacing imported pork meat with local produced meat (-29 ton).

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3

Towards fossil free cities

Emission assessment of food and resources consumption with the FEWprint carbon accounting platform

The FEW nexus integrative approach offers a framework and principles for sustainable resource management in cities and can be used to holistically evaluate the implications of urban food production. However, at the local urban scale, suitable design and evaluation tools thus far remain limited or are inadequate, mainly due to complexity issues or comprehensive data input required to operate the systems.

This chapter introduces the FEWprint platform and elaborates the first of its three main components: carbon emissions *evaluation* of (urban) communities. The development of this component builds upon knowledge and experience gained with the explorative urban livestock study described in the previous chapter. The aim of this chapter is to determine the resource scope for carbon analysis, to investigate a mutually suitable approach towards carbon accounting for both urban communities and urban food production and to define a representative food inventory within the food sector emissions.

To demonstrate the *evaluation* component, this spreadsheet-based platform is employed to calculate the consumption-based carbon equivalent footprint consequential to food consumption, thermal and electrical energy use, personal mobility, potable water production and treatment and domestic waste processing. Six diverse urban communities with a varying population in the cities of Amsterdam, Belfast, Tokyo, Detroit, Doha and Sydney are used as the cases.

In the introduction section 3.1, two aspects of the present literature gap regarding FEW nexus assessment tools are addressed. The materials and methods section opens with a description of general functioning of the FEWprint platform (section 3.2.1), following by theory on carbon accounting of urban communities (3.2.2). It describes the analysis scope (3.2.3) and the food inventory (3.2.4), it explains the calculation framework (3.2.5) and closes with an short introduction of the six cases (3.2.6). The present-day carbon footprints of the six M-Nex case studies are discussed in the results and discussion section. The chosen *semi-aggregated* and *limited scope* food inventory is compared with a full-scope, disaggregated inventory at the end of this chapter in a sensitivity analysis.

3

Towards fossil free cities

Emission assessment of food and resources consumption with the FEWprint carbon accounting platform

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Aside from layout changes and minor textual differences, the content of paper has not been amended for uptake in this dissertation.

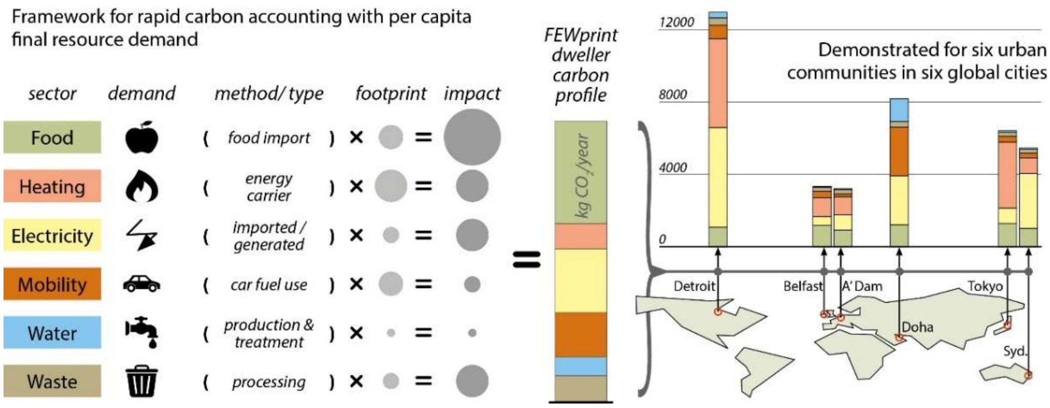
3. Towards fossil free cities – Emission assessment of food and resources consumption with the FEWprint carbon accounting platform

Abstract

Current urbanization rates concentrate the growing demand for food, energy and water (FEW) resources particularly in cities, making them one of the main drivers of global greenhouse gas emissions. The FEW nexus integrative approach offers a potential framework for sustainable resource management in cities. However, existing nexus evaluation tools are limited in application and often inadequate. This is primarily due to the FEW nexus intricacy, the tools' operational complexity and/or the need to input comprehensive data that is often unavailable to users. Having outlined these current gaps, this paper introduces the FEWprint, an integrated carbon accounting platform that provides an accessible process for FEW nexus-based evaluations of urban areas. This spreadsheet-based framework is employed to calculate a consumption-based footprint derived from food consumption, thermal/electrical energy use, car fuel demand, water management, and domestic waste processing. A comparative assessment between six different communities reveals significant differences in total annual emissions. The food sector impact shows emissions ranging between 993 kg/cap*yr and 1366 kg/cap*yr in Amsterdam and Tokyo respectively, but is also the least deviating from all considered resource sectors. This holistic carbon footprint and considered food inventory will serve as a baseline for future integrated urban farming strategies and urban design proposals to be tested.

Keywords

Nexus, Carbon accounting, Sustainable cities, Urban food production, Assessment model, Carbon emissions



Graphical Abstract

3.1. Introduction

The world population of approximately 7.5 billion people is anticipated to increase to around 10 billion in 2050 (UN DESA, 2019). With the expected global population growth, the demand for food, energy and water resources continues to grow in parallel. By 2050, food demand is expected to increase by about 60% (FAO, 2017) and fresh water demand by 20–30% (WWAP, 2019) and global energy demand by 40% in 2030 (EIA, 2019). In 2018, 54% of the world's population lived in cities and urbanisation is expected to climb to 68% in 2050 which equals roughly 6.8 billion people (UN DESA, 2019). These figures predict that the demand for the key resources food, energy and water (FEW) will increasingly concentrate in and around cities, making them – under unchanged policy – the main emitter of greenhouse gases globally. In an increasingly urbanised world, with a rising population under the threat of global climate change, the urgency to develop sustainable FEW management solutions at the level of the city is growing.

The demand for food, energy and water in cities generates emissions of greenhouse gases along the entire life cycle chain of these resources. Greenhouse gases can be expressed in carbon emission equivalents (World Resources Institute, 2014), which are also simply referred to as carbon emissions or CO_2eq throughout this work. Carbon emissions are commonly applied to measure the environmental impact of the built environment as they are a key contributor to the global warming effect (IPCC, 2018b). Earlier research that applied a carbon accounting framework is the City-zen project, in which an urban energy transition strategy was proposed for the neighbourhood of Gruz in Dubrovnik (Dobbelsteen, Martin, et al., 2018). Pulselli further developed the applied accounting approach into a generic carbon accounting framework for European cities (R. Pulselli et al., 2019), which was then demonstrated for a neighbourhood in Seville, Spain (Riccardo M Pulselli et al., 2019) and finally culminated into a stakeholder-engaged consolidated workshop strategy to kick-start the decarbonisation of cities (Riccardo Maria Pulselli et al., 2021). The aim of this study, the decarbonisation of the urban environment, is similar to the aforementioned studies but it expands the scope with a thorough and context-based consideration of food consumption.

The areas of food, energy and water management are interdependent and share numerous interwoven connections regarding security, environmental impact, quantity and quality (Hoff, 2011). Therefore, policies or physical infrastructure installed to manage resources in one sector, can have knock-on implications in the other sectors. The FEW nexus system's theory, introduced at the 2009 World Economic Forum in Germany (Hoff, 2011), appreciates, considers and accounts for this interlinkage when assessing, evaluating or (re)designing a resources system.

Within the academic community, no clear definition of the term nexus has yet been developed and it is therefore far from being acknowledged in a uniform way (Endo et al., 2017; Reinhard et al., 2017). In the absence of a commonly agreed definition or conceptual nexus framework, various interpretations of the concept have emerged from a range of organisations and authors. For example Hoff (Hoff, 2011) [p.9], main author of the 2011 Bonn conference synopses, states that 'A nexus approach to managing and achieving security in the water, energy, food and environment sectors will support a transition to sustainability by reducing trade-offs […] that outweigh the transaction costs associated with a paradigm shift to stronger integration across sectors.' Endo et al. mention that 'nexus is internationally interpreted as a process to link ideas and actions of different stakeholders from different sectors for achieving sustainable development.' (Endo et al., 2017) [p.2]. The German GIZ and ICLEI state that '[…] an Urban NEXUS solution integrates two or more systems, services, policy or operational "silos", jurisdictions or social behaviours, in order to achieve multiple urban policy objectives and to deliver greater benefits with equal or less resources.' (GIZ & ICLEI, 2014)[p.6]. Reinhard et al. (Reinhard et al., 2017) [p.6] wrote that 'The water, food and energy nexus is an approach to consider the interactions between water, food and energy, while taking into account the synergies and trade-offs that arise from the management of these three resources, and potential areas of conflict.'

Finally, Rees (J. Rees, 2013) mentioned that the nexus approach is required to establish a framework of decision making that can identify cross-sectoral impacts and unintended consequences and explore feasible trade-offs.

The cited interpretations of the nexus concept all accentuate a multi-sectoral approach to FEW management in contrast to the silo-thinking that has thus far been more prominent, and all interpretations hint towards avoiding (unintended) trade-offs whilst exploiting potential correlations for a synergistic impact on resource security, production efficiency or environmental footprint.

In the past ten years, less than a quarter of the FEW nexus publications focused on the urban scale (Zhang et al., 2019). The scientific community acknowledges this gap and researchers call for a downscaling of nexus research to urban resources production and management (Yan & Roggema, 2019). Rees (J. Rees, 2013) and Leck et al. (Leck et al., 2015) both point out that we have marginal research-based evidence on how to implement the ambitious FEW Nexus attitude in the physical realm and build real-world solutions across various scales or provide guidance to decision makers. Terrapon-Pfaff et al. (Terrapon-Pfaff et al., 2018) state that the past and contemporary focus of FEW nexus discussions and applications has mainly been on national or global levels, discussing macro-level drivers, material stocks and flows and large infrastructure developments. This is acknowledged by Leung Pah Hang et al. (Leung Pah Hang et al., 2017) and Martinez-Hernandez et al. (Martinez-Hernandez et al., 2017), who point out that most of the existing work addresses larger global, national or regional scales and there have only been a few studies analysing the FEW Nexus at the local scale. However, it is at the micro scale -meaning building to neighbourhood level- where policies and strategies inform physical interventions (Leung Pah Hang et al., 2017; Martinez-Hernandez et al., 2017).

Several assessment tools have been developed that help to comprehend the complexity of the FEW nexus, for example: WEAP (SEI, 2020), LEAP (Heaps, 2020), MuSIASM (Giampietro & Mayumi, 2000) and CLEWS (Howells et al., 2013). Despite the considerable array of developed evaluation tools, most of them provide a perspective at the (supra) national or at best regional scale and only give a primitive consideration of the effects at the local scale (Hake et al., 2016). Contemporary FEW nexus assessment or modelling tools, such as the aforementioned examples, have been extensively reviewed in the past years by various studies. The recurring issues and challenges within the array of tools include limitations due to data availability and standardisation, comparability of results, short-term analysis, level of integration, specific entry point, user accessibility, stakeholder involvement, perception of complex synergies posed by various urban systems and defining the system scale/boundary (Brouwer et al., 2018; Dargin et al., 2019; FAO, 2014; IRENA, 2015; Kaddoura & El Khatib, 2017).

The overarching challenge is the extensive amount of data input required to build models, run simulations or perform evaluations. Simplification of the assessed interconnectivity of resources can partly overcome the problem of data constraints; however, this could compromise output accuracy (Kaddoura & El Khatib, 2017). Public databases like FOASTAT, EuroStat, UNSD or national statistics bureaus provide readily available data for national or transnational nexus assessments. However, granular data is often not collected and stored by a particular centralised agency and/or data management tends to be sectorally organised. Furthermore, the data needed to assess a neighbourhood, is collected at varying scales defined by the geographical, ecological, jurisdictional, and operational extents of the city. This will be made evident in the case studies, elaborated later in this article. Finally, complications with paywalls or data sensitivity obstruct researchers from retrieving important data (McGrane et al., 2018). A tool and framework is lacking that operates at the neighbourhood scale, requiring minimal public data input. In addition, tool output should be expressed in units that are relatable and relevant to urban policy makers, designers and/or researchers.

Community farms and urban food production have gained the interest of the general public, urban planners, architects, students and researchers in the past decade. A farm can be considered a materialization of the food, energy and water nexus concept: food, energy, water, nutrients and topsoil (space) are assimilated and processed into food or feed, various forms of waste products and greenhouse gases. On a higher scale-level of consideration, a neighbourhood or city is another example of a nexus: resources enter the city-system as inputs and waste and greenhouse gases are disposed of as outputs. But what is considered a waste product for one entity can be considered a valuable resource for the other through principles of circularity. Further, new connections could be established when the two systems are in close proximity to each other (Leung Pah Hang et al., 2017). As such, a synergetic assimilation of food producing systems within the urban resources systems can potentially mitigate the environmental footprint of the farm as well as that of the city (Goldstein et al., 2016b).

A nexus-informed urban intervention, like the integration of a food system and a city system, requires a quantified understanding of the comprehensive and thus far under-perceived linkages and interactions between the involved sectors. Only with this new knowledge, can the cross-sectoral resource implications of urban food production (UFP) systems be quantified and urban (re)design proposals be holistically evaluated.

This work introduces the Food, Energy and Water integrated carbon footprint accounting tool, or FEWprint. The FEWprint is a three-pronged urban food production (UFP) evaluation platform that consists of an 1) evaluation, 2) shift and 3) design component. The evaluation component is further elaborated in the Method & Materials section and applied in this work. Briefly, it offers the framework to rapidly calculate a carbon footprint profile of urban communities on the aspects of food, energy and water (FEW) demand and waste processing by using publicly available data. This is demonstrated by calculating and comparing the business-as usual (BAU) or baseline carbon profiles for six urban neighbourhoods that differentiate in terms of scale, context, population and societal factors. The case studies are: Amsterdam (Kattenburg), Belfast (Inner-East), Detroit (Oakland Avenue Farming Community), Doha (Qatar University Campus), Tokyo (Tamaplaza) and Sydney (West Sydney).

3.2 Methods

This chapter discusses the approach and scope of the urban community carbon accounting framework and platform and introduces the six case studies used in this work. Special attention is given to the assessment of food consumption.

3.2.1 General purpose and operation

The platform operates as a scenario comparison tool. This means that after establishing a baseline scenario, alternative solutions to urban resource management can be tested by redefining the quantity, sources or management practices of the consumed resources, which establishes the new scenario, schematised in Figure 3.1. The spreadsheet-based tool is divided into several themed tabs where average end-user consumption data is inserted: (1) Food, (2) Energy, (3) Water, (4) Waste and (5) Mobility. General information about the context (e.g. demographics) is inserted in the info tab. Each time resource input is changed into a (renewable) alternative, the FEWprint tool responds by recalculating the carbon footprint. This process should be iteratively repeated for all relevant resource demands to gradually reduce the community footprint until desired targets are met. The FEWprint does not auto-generate solutions according to user-defined emission targets or policies, but rather facilitates a trial-and-error workflow to assess options. A step-by-step explanation is added to each of the aforementioned tabs to guide the user through the platform.

To account in the comparative analysis for projected long-term demographic changes (population change, national electricity grid mix changes and non-situational developments surrounding mobility), the FEWprint tool offers three timestamps to which the expected development can be anchored. The long-term development of these three externalities is different for each context and most likely will remain speculative when taken into consideration. Therefore, the platform does not provide default data for future scenarios and requires the user to define such future projections. In order to assess the effect of urban FEW management changes without including these long-term developments, a present option is offered in which the before mentioned factors remain similar to the baseline scenario.

3.2.2 Carbon accounting approach

This study applies the consumption based accounting approach, or CBA (Mi et al., 2019). CBA allocates resource use related emissions to the consumers, subsequently making carbon emission mitigation an effort of user behaviour changes and resource demand reduction at the end-user level. A (residential) urban environment, like the case studies considered in this work, often import their throughput resources from outside the geographic boundaries, sometimes across nations or even continents, subsequently outsourcing the production related emissions to these other locations (Bai, 2007). Consumption-based indicators include the entire supply chain emissions in infrastructure and non-infrastructure goods but excludes chain emissions related to the urban production and export of (excess) resources to outside the boundary (S. Chen et al., 2020).

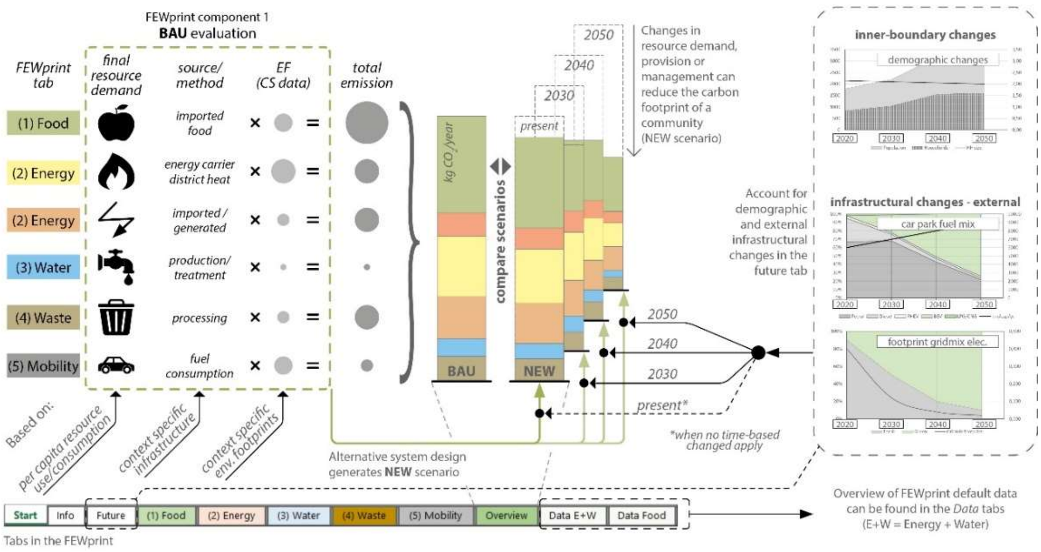


Figure 3.1. *Schematic representation of the FEWprint's evaluation component. NEW scenarios can be tested for three different future time stamps. The default years are 2030, 2040 and 2050, but any year can be entered to define timelines.*

A workable protocol for organising community carbon accounting boundaries of territorial and exo-urban emissions is the Global protocol for Community-Scale Greenhouse Gas Emission Inventories, that distinguishes urban-driven emissions into three scopes in order to prevent double counting (World Resources Institute, 2014). Scope 1 accounts for emissions coming from fuel combustion from within the urban boundary. Scope 2 addresses cross-boundary emissions occurring consequentially to the urban demand for grid-supplied electricity and district heating and/or cooling. Scope 3 notes all other greenhouse gas emissions outside the urban boundary as a result of activities and resource demands from within the city boundary. Limiting the carbon inventory to territorial emissions (scope 1), leads to a deficient depiction of the community's contribution to the global warming effect (Feng, Hubacek, Sun, & Liu, 2020; Fry et al., 2018). The CBA indicator therefore considers scope 1–3 emissions driven by final resource consumption at the level of the individual user. Figure 3.2 on the next page is an adaptation of the WRI framework to better fit the intended application scale of the FEWprint platform.

The FEWprint platform assesses the carbon footprint of a community, defined by their shared geographic area and extents. The interpretation and conditions of a community within its neighbourhood can differ across nations and various stakeholder discourses. For this reason, this research adheres to the following definition: the community considered is a multiplication of n users in an urban context, that represent the average consumption of routinely used throughput resources specific to that urban context. This definition excludes (heavy) industry or other urban functions where the resource consumption of one urban entity (for example a swimming pool) does not reflect the every-day consumption patterns and behaviour of the individual. Simultaneously, the assessment is not limited to urban dwellers, but for example also allows for application to student-communities within university campuses. The intended scale of application is the neighbourhood; however, application is possible from building scale to city scale.

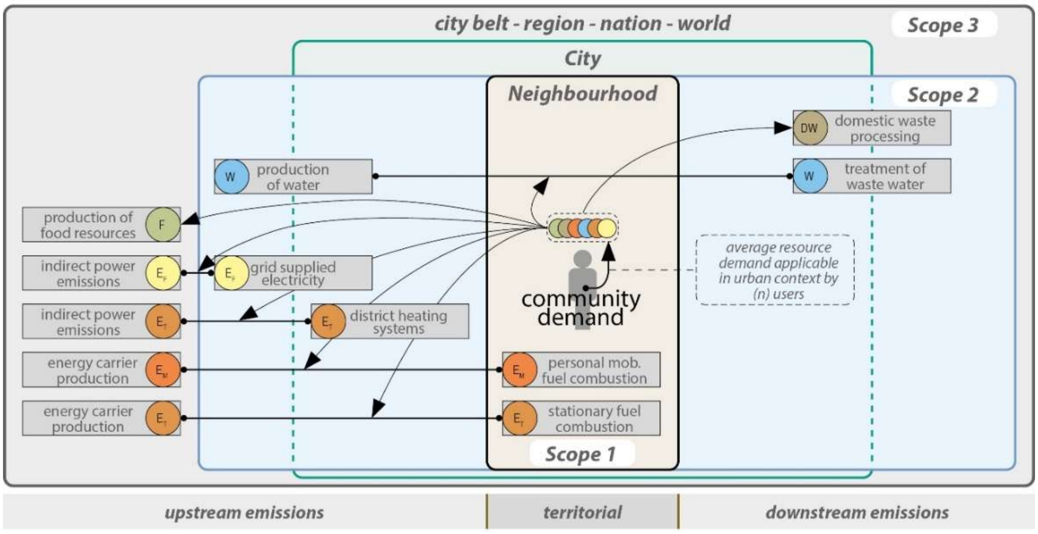


Figure 3.2. *Adaptation of the WRI carbon accounting scopes framework that addresses the neighborhood as the smallest area of consideration, as opposed to the city level in the WRI framework.*

3.2.3. Carbon assessment scope

The resource assessment scope of the FEWprint covers the provision and management of throughput resources that are commonly identifiable in an urban community. These are: food, electrical energy, thermal energy (energy carriers), fuel for mobility, drinking water, the management of waste- and rainwater and the processing of domestically produced waste. Resource demand that pertains to the working place or to the public domain, i.e. any other domain than the considered urban context, are not accounted for in this assessment. As such, it should be noted that the outcomes of this work do not outline the broader impact of an individual person, but rather of a dweller/user in the community domain. In addition, this scope does not contain the full range of emissions that can be ascribed to the urban dweller and certain omissions apply. The use of public transportation services is not accounted for. Embodied emissions of building construction materials or other urban infrastructure in the public domain are excluded. Emissions occurring during the manufacturing, transportation and end-of-life of procurement are not accounted for (e.g. cars, household inventory, delivery services or other utensils). Finally, carbon sequestration by existing biomass in the considered context is left out of the scope. These omissions could constitute a significant portion of the total emissions of a person. However, aside from the complexity of embodied carbon assessment and its integration in a user-friendly platform, we believe that insight in the omitted carbon sources would not contribute to the umbrella purpose of the FEWprint platform: the appraisal of urban food strategies during the conceptual stage of the design process.

3.2.4. Carbon accounting of food

To clarify methodological decisions of food consumption carbon accounting, the overall purpose of the FEWprint platform needs to be briefly explained. The key function of the platform is to support designers during the design of urban food producing systems, which will be further discussed in the discussion chapter. To accomplish this function, the FEWprint is divided into three integrated components: evaluation, shift and design. This article only discusses the evaluation component. The development of a three-pronged platform involved finding a functional balance between inter-component integration and achieving a comprehensive scope while securing simplicity and user-friendliness. In this conceptual triangle of platform values, prioritising one inherently diminishes the other(s). By setting certain limitations for the considered food inventory, inter-component integration is enhanced and food system design remains intelligible; however, this goes at the expense of food consumption carbon assessment comprehensiveness.

3.2.4.1. Food inventory

The FEWprint combines consumption data for 18 food groups to compose a representative diet profile for a community (Table 3.1). All groups represent staple foods, meaning that the food is eaten routinely and in such quantities that it constitutes a dominant portion of a standard diet of a community. The food inventory is limited to unprocessed or semi-processed food only and liquids are excluded. The exceptions of these are cheese and milk: processed food groups that generally have considerable carbon footprints and are consumed in high amounts in certain cultures. The exclusion of processed food and beverages is done for two purposes. First, it increases comparability between the results as data on processed items becomes increasingly difficult to interpret, process and assign to a food group, especially when six case studies need to be aligned. Second, the food production chain of processed items is difficult to grasp and requires an industry that is not easily conceivable in an (inner) urban context as part of an urban food production strategy.

3.2.4.2. Food footprint data

This study's assessment makes use of categorical carbon footprint indicators that are either provided as such by the data source or are formed by grouping footprints of individual products. This method is much less time consuming in terms of gathering, interpretation and data insertion of the required figures and data gaps of individual products are easily overcome by applying the food group figure. However, the method is a compromise to outcome accuracy as it is less of a reflection of reality, which is further discussed and assessed in a sensitivity analysis in chapter 3.4.4.

In this paper, country-specific Life Cycle Inventory assessment of food carbon footprints are gathered and used for the case studies, where available. Per case study, the taxonomy of the source's dataset has been analysed and aligned as much as possible with the categorisation used in this work in order to acquire a group carbon footprint that contains as many sub-products as possible. Situational carbon footprint data are not available in Sydney, Tokyo and Qatar, for which global average indicators calculated by Poore & Nemecek is used as a substitute (Poore & Nemecek, 2018).

Finally, we want to underline that, even though carbon equivalent emissions encompasses various greenhouse gas emissions that are responsible for climate change implications world-wide, resource demand or agricultural practises can also impose destructive and irreversible damage in the local environment. Such climate implications can be equally, if not more pressing to address for a specific context. For example, biodiversity destruction, eutrophication, acidification, water and air pollution or others forms of ecological exhaustion.

3.2.5. Carbon accounting equation framework

The sum of the sectoral emissions constitutes the FEWprint profile (CF_{tot}) and is composed of the separate sectoral footprints of food consumption (CF_F), electrical energy use (CF_{EE}), thermal energy use (CF_{TE}), the use of car fuel for mobility (CF_{ME}), water production, treatment and rainwater management (CF_W) and the processing of domestically produced waste (CF_{DW}), as shown in equation (1). All sectoral footprints are in [kg/cap* yr] and equation (1) is applicable for both the BAU scenario as well as new scenarios. The equation framework and all the sub-components used in the FEWprint are further discussed in detail in Appendix 3E.

$$CF_{tot} = CF_F + CF_{EE} + CF_{TE} + CF_{ME} + CF_W + CF_{DW} \quad [1]$$

3.2.6. Case studies

In order to demonstrate the evaluation component of the FEWprint platform, six urban communities have been selected for carbon assessment. These communities are located in the cities of Amsterdam (community population = 1721), Belfast (pop. = 32,834), Detroit (pop. = 427), Tokyo (pop. = ~84,850), Doha (student + staff population = ~24,000) and West-Sydney (projected pop. 1,000,000). An extensive description of the cases, demographic data and the resource demand by the community can be found in appendix 3D.

All of the FEWprint calculations are based on average per capita final resource demands. For the six urban communities assessed in this study, all of the consumption data was retrieved from public databases. Public data registrations generally release average consumption data at different scales of aggregation. The data can either be based on a bottom-up population survey, grouped per geographical area (the average of many individuals) or based on top-down collections at higher levels (measured total consumption divided by the population). The first method cultivates an accurate representation of the community's resource use, whereas the latter approach might produce figures that deviate considerably from local reality. Figure 3.3 below gives an overview of the aggregation levels of data sources for the case studies used in this study. As the exact definition of an aggregation level can vary between nations, the figure therefore displays a more general stratification of levels. The consumption data of the six case studies and the data sources utilized are further elaborated in appendix 3D. Bottom-up survey data is used to fill in the food consumption of the 18 groups, listed in table 3.1. Appendix 3C shows the breakdown of the food groups into sub-items for a better understanding of the considered food inventory.

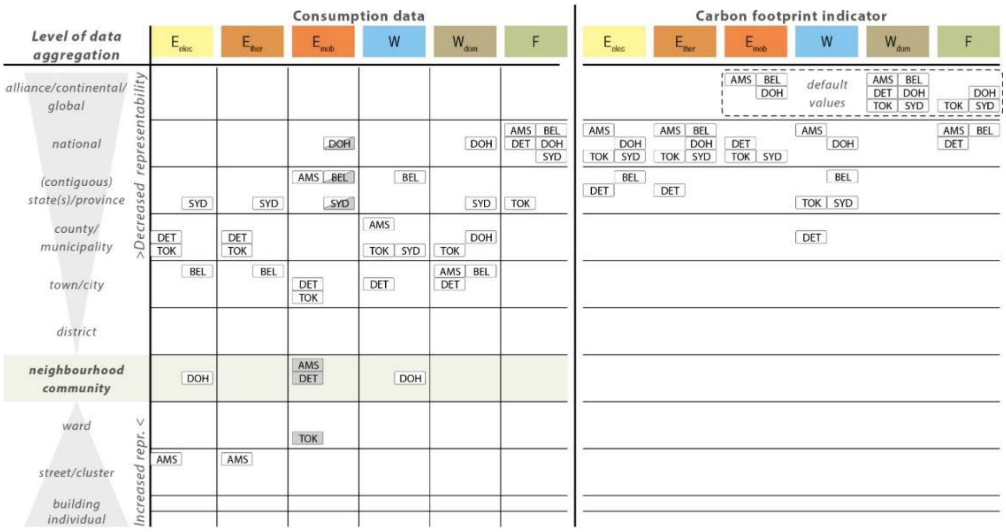


Figure 3.3. Data aggregation levels of end-user resource consumption data for the 6 case studies. Mobility labels represent the average distance driven per year (white hatch) and car ownership (dark

hatch). The position of the carbon footprint labels (right) indicates the scale of operation/service of the assessed resource infrastructure.

Carbon footprint indicators of resources or services [kg CO_2eq/unit] can vary considerably between case studies due to differences in for example management practises, types of primary energy carriers or because system operate at different scales or capacities. To increase the representability of the FEWprint output, it is recommended to apply context specific carbon footprint (CF) values as much as possible. For the assessment of the six case studies, situational carbon indicators have been collected where available and an overview is provided in Appendix 3A. Not all countries release accessible, accurate or unambiguous data for all six sectors that could be used for carbon assessment. In order to overcome these data gaps, the platform offers a set of default data, listed and explained in appendix 3B.

Table 3.1. Dietary intake of the 18 food groups [*PCC(n),* Per Capita Consumption, [gram/cap*day] and the associated carbon footprints [CF, kg CO_2eq/kg food]. The applied contextualisation parameters r_{hal}, r_{car} and r_{add}[%] are explained in Appendix 3E. Where available, country specific environmental footprints are applied; if unavailable, world average default (D) footprint data is used, provided by Poore & Nemecek (2018). The value between the brackets denotes the number of food products combined within the food group to produce an averaged representative value. n.d. = no data available or not mentioned as a separate food group but logged under other group.

		Global	Amsterdam, Kattenburg		Belfast, Inner-East		Tokyo, Tamaplaza		USA, Oakland Av.		Doha, Qatar Uni. Campus		Sydney, Western-Sydney.	
	r_{hal}[%]	*n.a.*	*15%*		*0%*		*0%*		*3%*		*0%*		*0%*	
	r_{car}[%]	*n.a.*	*20%*		*20%*		*0%*		*22%*		*20%*		*0%*	
	r_{add}[%]	*n.a.*	*15%*		*15%*		*0%*		*15%*		*15%*		*0%*	
•	**Food group**	**CF**	**PCC**	**CF**	**PCC**	**CF**	**PCC**	**CF**	**PCC**	**CF**	**PCC**	**CF**	**PCC**	**CF**
1	Vegetables	0.40	131.0	1.82 (31)	92	1.77 (3)	283		99.7	0.48 (57)	209		110.5	
2	Fruits	0.40	113.8	1.53 (18)	114	0.90 (1)	108		77.5	0.57 (32)	187		142.3	
3	Legumes & pulses	0.90	4.5	2.53 (3)	3	3.40 (2)	63		11.6	0.80 (18)	41		8.8	
4	Grains	1.40	138.3	1.32 (12)	106	1.00 (2)	103		150.8	0.46 (14)	211		131.9	
5	Rice	4.00	0.0	1.71 (2)	15	3.90 (1)	291		n.d.	1.73 (4)	184		32.2	
6	Starchy roots	0.60	72.2	0.92 (1)	93	0.40 (1)	46		57.7	0.25 (3)	59		61.1	
7	Beef (& veal)	60.0	12.6	30.82 (6)	21	68.8 (1)	14		51.8	32.85 (1)	7		18.9	
8	Pork	7.00	13.0	13.73(4)	31	7.90 (1)	45		39.4	5.56 (1)	n.d.		6.0	
9	Sheep/Goat	24.0	0.6	24.0 (D)	5	64.2 (1)	-	Default values	0.7	34.75 (1)	53	Default values	7.2	Default values
10	Poultry	6.00	16.6	12.21(2)	36	5.40 (1)	32		75.1	3.20 (3)	119		25.6	
11	Fish	3.00	12.9	8.61 (19)	22	5.40 (1)	66		8.2	7.70 (6)	46		29.9	
12	Cheese	4.50	32.6	11.28 (5)	18	4.50 (1)	4		34.2	9.97 (1)	n.d.		11.4	
13	Dairy & Milk	21.0	254.3	2.31 (11)	262	1.90 (2)	130		138.6	1.33 (2)	232		209.4	
14	Eggs	3.00	12.7	4.32 (1)	15	4.90 (1)	38		27.3	3.75 (1)	32		6.6	
15	Pasta (durum)	n.d.	47.1	1.52 (1)	14	1.00 (1)	12		n.d.	n.d.	n.d.		16.2	
16	Nuts & Seeds	0.30	6.3	4.16 (8)	5	2.00 (1)	n.d.		13.9	1.89 (13)	n.d.		6.5	
17	Meat replacements	2.00	1.5	2.00 (D)	n.d.	2.00 (D)	n.d.		n.d.	2.00 (D)	n.d.		1.2	
18	Dairy replacements	0.90	8.4	0.76 (1)	n.d.	0.90 (D)	n.d.		n.d.	0.53 (2)	n.d.		7.9	
	total		**878**		**852**		**1235**		**787**		**1380**		**833**	

[1] (Poore & Nemecek, 2018)

[2](RIVM, 2017)

[3] (RIVM, 2020b)

[4] (DEFRA, 2020a)

[7] (Scarborough et al., 2014)

[6] (MHLW, 2018)

[7] (USDA ERS, 2017)

[8] (Heller, Willits-Smith, Meyer, Keoleian, & Rose, 2018)

[9](MME Qatar, 2020)

[10] (ABS, 2014)

[spacer]

Table 3.2. Overview of the resource demand/use for the six case studies and other relevant data to complete a carbon assessment with the FEWprint platform. More information about the end-use consumptions and references are provided in Appendix 3D. Terms (equation) refer to the equation framework in Appendix 3E.

Sector	Component	term	Product/Activity/Note	demand	Unit
Kattenburg, Amsterdam (population: 1721, household size 2.2)					
Food	Various	CF_F	Selection food groups (specified in detail in table 1)	~321	kg/cap/yr
Energy	Electrical	CF_{EE}	grid mix electricity	1614	kWh_e/cap/yr
	Thermal	CF_{TE}	natural gas, centrally provided	549	m^3/cap/yr
	Mobility	CF_{ME}	Car ownership / distance driven per year	313 / 5800	#/1000hh, km
			petrol (80%), assumed efficiency: 1:15[1]	44,0	L/cap/yr
			diesel (15%), assumed efficiency: 1:18[1]	6.9	L/cap/yr
			electric (5%), assumed efficiency: 1:15[1]	2.8	kWh/cap/yr
Water	Domestic use	CF_{pw}	centralised production (110L/cap/day, ext: surface water)	40	m^3/cap/yr
	Waste water prod.	CF_{ww}	centralised treatment (110L/cap/day, ext.: conv. sewage treatm.)	40	m^3/cap/yr
	Rainwater management	CF_{rw}	Annual rainfall specific to region	871	mm/m2/yr
			Surface area: permeable / non-permeable	8.0/3.0	ha
			Pre-treatment of rainwater before disposal?	No	-
Waste	Processing	CF_{DW}	total domestic waste produced	377	kg/cap/yr
			Waste-to-Recycle	0	%
			Waste-to-energy / Waste-to-Landfill / Waste-to-Compost.	100/0/ 0	%
Inner-East, Belfast (population: 32,834, household size 2.15)					
Food	Various	CF_F	Selection food groups (table 1)	~311	kg/cap/yr
Energy	Electrical	CF_{EE}	grid mix electricity	1395	kWh_e/cap/yr
	Thermal	CF_{TE}	natural gas, centrally provided	524	m^3/cap/yr
	Mobility	CF_{ME}	Car ownership / distance driven per year	667/6368	#/1000hh/ km
			petrol (57%), assumed efficiency: 1:15	75.1	L/cap/yr
			diesel (42%), assumed efficiency: 1:18	46.1	L/cap/yr
			electric (1%), assumed efficiency: 1:15	1.3	kWh/cap/yr
Water	Domestic use	CF_{pw}	centralised production (145 L/cap/yr, ext: surface water)	53	m^3/cap/yr
	Domestic prod	CF_{ww}	centralised treatment (145L/cap/yr, ext.: conv. sewage treatm.)	53	m^3/cap/yr
	Rainwater management	CF_{rw}	Annual rainfall specific to region	930	mm/m2/yr
			Surface area: permeable / non-permeable	1000/322	ha
			Pre-treatment of rainwater before disposal?	Yes	-
Waste	Processing	CF_{DW}	total domestic waste produced	416	kg/cap/yr
			Waste-to-Recycle	24	%
			Waste-to-energy / Waste-to-Landfill / Waste-to-Compost.	26/52/22	%
Tamaplaza, Tokyo (population: 84,850, household size 2.43)					
Food	Various	CF_F	Selection food groups (table 1)	~451	kg/cap/yr
Energy	Electrical	CF_{EE}	grid mix electricity	1954	kWh_e/cap/yr
	Thermal	CF_{TE}	City Gas (=natural gas)	1387	m^3/cap/yr
	Thermal	CF_{TE}	Light oil products	173	L/cap/yr
	Thermal	CF_{TE}	LPG	381	L/cap/yr
	Mobility	CF_{ME}	Car ownership / distance driven per year	704/7231	#/1000hh/km
			petrol (80%), assumed efficiency: 1:15	111.7	L/cap/yr
			diesel (17%), assumed efficiency: 1:18	19.8	L/cap/yr
			electric (3%), assumed efficiency: 1:15	4.2	kWh/cap/yr
Water	Domestic use	CF_{pw}	centralised production (220L/cap/day, ext: surface water)	80	m^3/cap/yr
	Waste water prod.	CF_{ww}	centralised treatment (220L/cap/day, ext.: conv. sewage treatm.)	80	m^3/cap/yr
	Rainwater management	CF_{rw}	Annual rainfall specific to region	1688	mm/m2/yr
			Surface area: permeable / non-permeable	125/707	ha
			Pre-treatment of rainwater before disposal?	yes	-

Waste	Processing	CF_{DW}	total domestic waste produced	312	kg/cap/yr
			Waste-to-Recycle	23	%
			Waste-to-energy / Waste-to-Landfill / Waste-to-Compost.	77/1/ 22	%
Oakland Av. Urban Farms, **Detroit** (population: 427, household size 2.2)					
Food	Various	CF_F	Selection food groups (table 1)	~287	kg/cap/yr
Energy	Electrical	CF_{EE}	grid mix electricity	6301	kWh$_e$/cap/yr
	Thermal	CF_{TE}	Propane (thermal)	1565	m^3/cap/yr
	Thermal	CF_{TE}	Natural gas (thermal)	1206	m^3/cap/yr
	Mobility	CF_{ME}	Car ownership / distance driven per year	753/14.2K	#/1000hh, km
			petrol (96.7%), assumed efficiency: 1:15	313.7	L/cap/yr
			diesel (2.9%), assumed efficiency: 1:18	7.7	L/cap/yr
			LPG (0.35%), assumed efficiency: 1:7	1,9	L/cap/yr
			electric (0.04%), assumed efficiency: 1:15	0.1	kWh/cap/yr
Water	Domestic use	CF_{pw}	centralised production (219.5L/cap/day, ext: surface water)	80.1	m^3/cap/yr
	Waste water prod.	CF_{ww}	centralised treatment (219,5 L/cap/day, ext.: conv. sewage treatm.)	80.1	m^3/cap/yr
	Rainwater management	CF_{rw}	Annual rainfall specific to region	787	mm/m2/yr
			Surface area: permeable / non-permeable	19.7/17.0	ha
			Pre-treatment of rainwater before disposal?	yes	-
Waste	Processing	CF_{DW}	total domestic waste produced	432	kg/cap/yr
			Waste-to-Recycle	1	%
			Waste-to-energy / Waste-to-Landfill / Waste-to-Compost.	71/23/5	%
Qatar University Campus, **Doha** (population: 24.000, household size n.a.)					
Food	Various	CF_F	Selection food groups (table 1)	~504	kg/cap/yr
Energy	Electrical	CF_{EE}	grid mix electricity	4612	kWh$_e$/cap/yr
	Mobility	CF_{ME}	Car ownership / distance driven per year (also see appendix D)	n.a./22K	#/1000hh, km
			petrol (80%), assumed efficiency: 1:15	102.6	L/cap/yr
			diesel (19%), assumed efficiency: 1:18	20.3	L/cap/yr
			electric (1%), assumed efficiency: 1:15	1.3	kWh/cap/yr
Water	Domestic use	CF_{pw}	centralised production (249L/cap/day, multi Stage flash meth.)	91	m^3/cap/yr
	Waste water prod.	CF_{ww}	centralised treatment (249L/cap/day, ext.: conv. sewage treatm.)	91	m^3/cap/yr
	Rainwater management	CF_{rw}	Annual rainfall specific to region	76	mm/m2/yr
			Surface area: permeable / non-permeable		
			Pre-treatment of rainwater before disposal?		
Waste	Processing	CF_{DW}	total domestic waste produced	514	kg/cap/yr
			Waste-to-Recycle	8	%
			Waste-to-energy/Waste-to-Landfill/Waste-to-Compost.	4/91/5	%
Wester Sydney, Sydney (population: 1.000.000), household size 2.6)					
Food	Various	CF_F	Selection food groups (table 1)	~304kg	kg/cap/yr
Energy	Electrical	CF_{EE}	grid mix electricity (appliances & other)	3818	kWh$_e$/cap/yr
	Thermal	CF_{TE}	Jemena gas (=natural gas)	455	m^3/cap/yr
	Mobility	CF_{ME}	Car ownership / distance driven per year	536/8700	#/1000hh, km
			petrol (72,7%), assumed efficiency: 1:15	86.9	L/cap/yr
			diesel (25,6%), assumed efficiency: 1:18	25.5	L/cap/yr
			LPG (1,7%), assumed efficiency: 1:7	3.0	L/cap/yr
Water	Domestic use	CF_{pw}	centralised production (301 L/cap/day, ext: surface water)	110	m^3/cap/yr
	Waste water prod.	CF_{ww}	centralised treatment (301 L/cap/day, ext.: conv. sewage treatm.)	110	m^3/cap/yr
	Rainwater management	CF_{rw}	Annual rainfall specific to region	1213	mm/m2/yr
			Surface area: permeable / non-permeable	323K/485K	ha
			Pre-treatment of rainwater before disposal?	No	-
Waste	Processing	CF_{DW}	total domestic waste produced	550	kg/cap/yr
			Waste-to-Recycle	22	%
			Waste-to-energy/Waste-to-Landfill/Waste-to-Compost.	0/73/27	%

[1] A similar value for fuel efficiency (also called fuel economy) is used for all cases. E.g. 1:15 implies that is takes 1 unit of fuel to move the vehicle 15 km. Applied values are assumptions and fuel economy can be different between nations due to differences in car fleet.

3.3 Results

Figure 3.4 depicts the annual sectoral carbon emissions per capita [kg/cap*yr] for each of the six case studies. The communal carbon footprint of Kattenburg, Amsterdam (AMS) and Inner-East, Belfast (BEL) are in the same order of magnitude and show a comparable percentile distribution. The Qatar University campus, Doha (DOH), West-Sydney, Sydney (SYD) and Tamaplaza, Tokyo (TOK) present considerably higher emissions mainly due to more emissions associated with water management, mobility and domestic energy use. The CO_2eq emissions of the Oakland Avenue community (DET) exceed the other communities by far, predominantly due the combined effect of high demand for energy resources and high carbon footprint indicator values. Table 3.3 provides an overview of the sectoral emissions and lists some of the important situational factors that determine the carbon footprint of a sector. This table is used for inter-city comparison and supports the interpretation of the outcomes, which is briefly discussed in section 3.3.1.

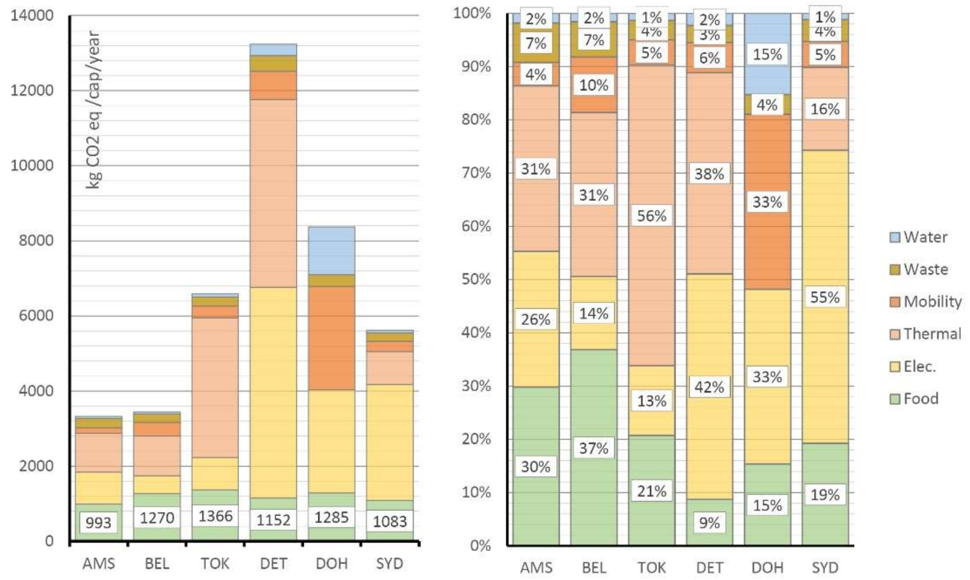


***Figure 3.4a**: (left) Sectoral emissions of the six case studies, total [kg/cap*yr] and **Figure 3.4b**: (right) percentile distribution [%].*

3.3.1. Emissions analysis

Energy. Doha relies completely on electrical energy for the indoor temperature control of dwellings; hence no emissions are noted under thermal energy. In Belfast, Amsterdam, Tokyo and Sydney, natural gas is mainly used for domestic heating. In Detroit, both electricity and natural gas are used for space heating. The combination of an elevated energy demand and a high carbon footprint for grid mix electricity amounts to a considerable impact in the energy sector in Detroit. This is coupled with a legacy of a poorly performing housing stock, making the residents of the Oakland Avenue community the largest emitters among the assessed case studies.

Water. Doha relies on electricity intense desalination methods to produce potable water. Combined with a large household demand for drinking water, this sector constitutes a significant part of the total emissions for the Doha community. In Amsterdam, Doha and Sydney, rainwater is not processed and is immediately directed out of the neighbourhood and/or city. In Tokyo, Belfast and Detroit, captured rainwater from non-permeable surfaces is pre-treated centrally by means of conventional sewage treatment before it is disposed of in natural water flows. However, it is only in Detroit where this pre-treatment leads to considerable additional emissions.

Mobility. The sectoral impact of mobility is affected by the combination of five parameters: car ownership, car typology based on fuel input, annual driving distance, fuel footprints and car fuel use efficiency. The efficiency is assumed similarly for all cases in this study (see Table 3.2) and car fuel carbon footprint values show minor differences between the cities. Amsterdam, Belfast and Doha apply the default values (=European average). In Amsterdam, the low private car ownership combined with a limited annual driving distance result in the lowest relative and total emissions for mobility between the six case studies. Qatar University campus emissions exceed the other communities by far. The combination of high car use and high car ownership for the students and staff makes mobility related emissions account for a third of the total (33%).

Waste. Similar carbon footprint indicators for domestic waste processing are applied across all the case studies. The sectoral impact is therefore based on the three remaining factors: the amount of domestic waste produced annually, the applied recycling fraction and the prevailing waste processing method used. For inter-city comparability, the aforementioned factors are combined into one carbon footprint indicator, expressed per kg of domestic waste (see Table 3.3). This indicator reveals that Sydney has the best performing waste management, whereas Doha shows the highest carbon impact per kg of waste produced. This is mainly due to landfilling being the prevailing method of waste management.

Food. Food related emissions are discussed in the discussion part of this chapter.

Table 3.3 Sectoral carbon footprints per capita [kg/cap*yr] of the baseline assessment. The determinative factors of resource demand and carbon footprint indicators are listed in *italic*.

FEW Sector	**AMS** K'burg	**BEL** Inner-East	**DET** OAF	**TOK** T'plaza	**DOH** Campus	**SYD** Syd-West
Food (LCA assessment)	993	1270	1152	1366	1285	1083
Total food consumption [kg/cap/yr]	321	311	287	451	504	304
Energy, electricity	849	473	5608	864	2749	3093
electricity demand [kWh_e/cap/yr]	*1614*	*1395*	*6301*	*1954*	*4612*	*3818*
carbon footprint [kg_{CO2}/kWh_e]	*0.526*	*0.339*	*0.890*	*0.442*	*0.596*	*0.810*
Energy, thermal	1034	1060	5003	3719	0	874
gas demand [m^3/cap/yr]	*549*	*524*	*1062*	*1387*	*0*	*455*
carbon footprint [kg_{CO2}/m^3]	*1.89*	*2.02*	*1.91*	*2.23*	*0*	*1.92*
Energy, car mobility	147	360	750	312	2747	274
annual distance driven [km/cap/yr]	*5800*	*6400*	*14.200*	*7200*	*22.000*	*8700*
car ownership [# cars/household]	*0.313*	*0.667*	*0.753*	*0.704*	*n.a.*[2]	*0.536*
Water, production & distribution	15	7	40	22	1021	23
Water, wastewater treatment	46	23	77	32	255	42
Water, rainwater treatment	n.a.	25	187	35	n.a.	n.a.
Water use [m^3/cap/yr]	*40*	*53*	*80*	*80*	*91*	*101*
Rainwater pre-treated before disposal?	*No*	*Yes*	*Yes*	*Yes*	*No*	*No*
Waste processing	246	227	420	239	312	232
Domestic waste produced [kg/cap/yr]	*492*	*416*	*492*	*312*	*514*	*550*
Carbon footp. waste procc. [kg_{CO2}/kg_{waste}]	*0.65*	*0.65*	*0.73*	*0.45*	*1.02*	*0.39*
Total emissions	3329	3445	13213	6589	5961	5619

[1] Own assessment: $impact\ waste\ [kg_{CO2}/kg_{waste}] = ((PCP_{dw} * r_{rec}) * \sum(r(n)_{waste} * ef(n))/PCP_{dw}$

[2] Assumptions apply to estimate car ownership, see appendix 3D.

[spacer]

3.4 Discussion

The first section discusses the food sector emissions calculated in this work. Section 3.4.2 explains the link between food consumption assessment and urban food production design within the FEWprint platform.

3.4.1. Food emissions

The total carbon impact of food consumption is found in the range of 993 kg/cap*yr (Amsterdam) to 1366 kg/cap*yr (Tokyo) and the relative consumption starts from 9% (Detroit) up to 37% of the total (Belfast). Where the data was available, country-specific consumption data was combined with country-specific carbon footprint indicators. Based solely on the comparative assessment of this study, an unambiguous correlation cannot be measured between the food intake composition and the resulting food sector emissions as it uses a combination of variable data entries.

Substantial sectoral and total carbon emission differences are observed between the case studies. However, food consumption related emissions show the least differences between the cases. The coefficient of variation, i.e. relative standard deviation (c_v), between the cases' food sector emissions is the lowest of all sectors: 11%. The other sectors show a relative standard deviation of $c_{v(waste)}$= 28%; $c_{v(electricity)}$= 99%; $c_{v(thermal)}$ = 170%; $c_{v(mobility)}$ = 270% and most deviated $c_{v(water)}$ = 573%. These differences are also visually recognisable in Figure 3.4a (left). This insinuates that the relative role of food consumption emissions within a community [%] is, in this assessment, mainly determined by the carbon performance of the other five sectors.

The BAU scenario assessment provides an estimative figure on the contribution of food consumption to a FEWprint. In cities where the relative carbon impact of food consumption is lower, such as Detroit (9%), more emphasis could initially be put on improving thermal energy management (38%) rather than directing the focus to local food production. In Amsterdam and Belfast, where food constitutes respectively 30% and 37% of the emissions, (low-hanging fruit) strategies in the food sector, either in the form of diet changes or in the form of local production, could potentially lead to significant reductions in the total impact of these communities. However, this assessment does merely address the numerical space for improvement. Further contextual analysis, local goals and local ambitions should incite continued investigations into urban food production.

3.4.2. Design of urban food production

An implemented urban food production (UFP) system is considered as an integrated part of the neighbourhood, not only spatially but also in terms of its environmental footprint. The tenor is that carbon impact of UFP, provided it serves the local community, cannot be holistically estimated without accounting for its fundamental output: food. As such, the UFP's resource input scope and carbon assessment scope is matched with the neighbourhood's resource input and carbon assessment scope. Consequently, the aggregated CO_2eq footprints produced in this work, referred to as the FEWprints, can serve as the initial conditions from which to begin and test integrated UFP measures towards a decarbonised built environment.

Urban farming can materialise in different forms (low tech - high tech) at different scales and by means of varying food production techniques (e.g. soil-based, hydroponic, aquaponics, DFT, NFT, aeroponic, stacked farming). In addition, UFP will perform differently in various climates, similar to conventional farming. Finally, UFP is claimed to offer benefits on various environmental aspects compared to our conventional food systems (Rothwell et al., 2016). Urban agriculture can position itself as the nexus within urban resource flows to foster circular or synergistic solutions (Goldstein, Hauschild, Fernández, & Birkved, 2016a). The diversity and inherent complexity of (urban) food production makes it difficult for non-experts to provide holistic evaluations, especially during the exploratory phase of design when performance assessment needs to keep up with rapid trial-and-error based decision-making.

When viewed through a carbon impact lens, the aim of UFP is to reduce the community's emissions by substituting imported food with local alternatives, potentially avoiding part of the emissions associated with conventional food production, like land use/land use change and food transport (Poore & Nemecek, 2018). Ideally, local production should be managed through the optimal use of renewable resources and/or resource circulation in order to achieve mutual benefits between the farm and the community and subsequently maintain a sustainable system with minimal remaining emissions. In addition, the resource demand imposed on a community by the new UFP system should be proportionate to the existing community resource demand. In other words: the goal should justify the means. These means, in this work the food system design, co-depend on the availability of suitable farming spaces, as this could be determinative for the chosen food production forms and products. The UFP component of the platform provides the framework to streamline this nexus-challenge between space, method, product, resources and impact and translates UFP implementations into performance indicators relevant to urban designers and planners.

The platform has been developed for the evaluation of urban food production strategies, for which three key purposes are formulated, displayed in Figure 3.5. First, it provides a user-friendly framework for the calculation of the carbon footprint profiles of communities, which is demonstrated in this paper. Second, the tool can be employed to assess the implications of community-wide dietary changes on the total carbon footprint, which is discussed in (P. N. ten Caat, Tenpierik, & Dobbelsteen, 2022). Third, it offers the exploratory design component that can deliver an indication of the agricultural output of a self-composed UFP system and calculates the required FEW resources, plus corresponding carbon impacts, for preliminary evaluation of an urban food strategy. All three components are interconnected with each other and are therefore not completed in a linear fashion, but rather facilitate an iterative process of design and assessment. This also includes design modifications of non-food related infrastructure, like local energy production, building stock improvements, mobility systems, water recovery and processing and waste reuse and diversion.

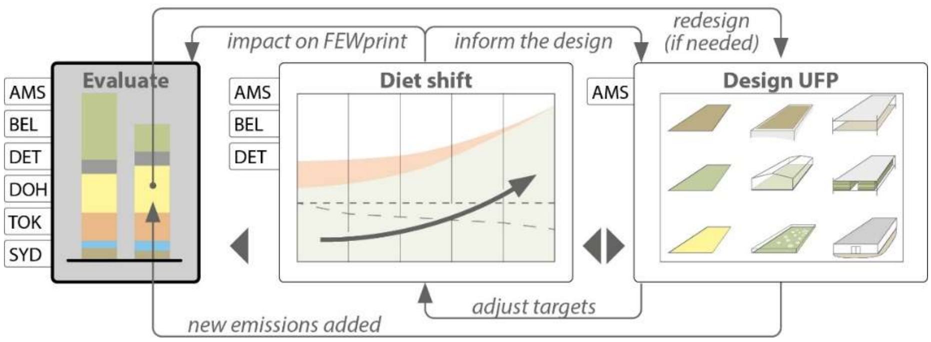


Figure 3.5. *The FEWprint consist of 3 components, corresponding with the 3 key purposes of the platform: carbon emissions assessment, diet shift assessment and UFP design.*

3.4.3. Practical implications and contribution

Carbon footprints are a useful index to quantify a community's contribution to climate change and to monitor the progress towards the carbon emission goals. The FEWprint offers a user-friendly digital interface to produce the carbon profile of a community and, afterward, to ex-ante estimate the impact on this profile after alternative resource management solutions and/or local food production implementations. The platform is developed to provide a strategy and framework for non-agriculturist (e.g. urban planners and designers) and to support the UFP design process through the lens of the FEW nexus. It does so by reducing UFP complexity to a handful of elementary building blocks.

The platform serves an informative role in the conceptual stage of the design process by rapidly delivering preliminary feedback on resources implications of design choices. With the FEWprint, urban design strategies that contain elements of food production -whether they are radical concepts or more subtle proposals that fill in a pre-existing long-term vision-can be better substantiated with holistically assessed estimations on carbon impact reductions and the overall potential can therefore be better evaluated. The design and evaluation of UFP strategies is discussed and demonstrated in future disseminations.

To encourage accessibility, the platform has been developed with Microsoft Office Excel software (Professional Plus 2016 version) and is open for download, free of registration or costs, from the research project website or by contacting the corresponding author. Step-by-step information is provided within the various tabs of the platform to inform about its functioning and the required data. The platform does not require specific technical knowledge to operate and carbon footprint assessments could be performed with the provided default data in case context-specific data is unavailable.

3.4.4. Sensitivity analysis

The assessed food inventory of this study has been limited to semi-unprocessed food items and excludes drinks. In addition, food impact is assessed with food category indicators instead of product-level values to make the data acquisition phase less time consuming for a platform user. Categorical indicators combine all the known product-level footprint indicators within that food category into one average figure. This is a simple and quick method to overcome missing data for certain food items when a detailed figure on these specific items is not important. However, as food items tend to not be consumed in equal proportion to each other, applying an average indicator could result in footprints that deviate from reality.

The two limitations resulted in a deficient representation of the food sector emissions. Previous research showed for the entire USA, the food related emissions of self-reported diets to be 4.70 kg CO_2eq per capita per day, or 1715 kg/year (including food losses), 563 kg more than calculated in this work (Heller et al., 2018). A study in The Netherlands calculated the greenhouse gas emissions derived from the Dutch National Food Consumption Survey 2012–2016 and found a daily impact of 4.96 kg CO2eq per day for the total population (age 1–79, n = 4313), or 1810 kg CO2eq per year (Vellinga et al., 2019). This is 817 kg more than the emissions calculated in this study.

For the Kattenburg (Amsterdam) community, the effect of the two limitations has been calculated by performing three alternative assessments: a limited scope assessment with product-level indicators for the carbon footprint of food items (column II in Figure 3.6), a full-scope assessment with category indicators (column III) and a full scope assessment with product-level indicators (FSPI) in column IV. The latter alternative assessment produces the most representative reflection of reality as it is most comprehensive and uses detailed data. Out of the six case studies analysed in this study, only Kattenburg is further assessed in such detail as extensive food consumption data was readily available from the same source as for the limited scope assessment.

As expected, the analysis quantified an emission deficit due to the limited food inventory used in this study. First, a full scope assessment more than doubles the food sector emissions compared to this study. This is mainly because the meat intake is doubled with the inclusion of processed meat products and due to the added impact of soda, coffee, tea and alcoholic drinks. Second, the analysis points out that the food sector emissions significantly drop when product-specific footprints are used. It should be noted that in column III, the large emission portion of drinks is mainly caused by the erroneous accounting of tap water drinking (high in consumption, nearly zero impact in reality) with the categorical indicator of 0.64 kg CO2/kg.

The FSPI (Full Scope, Product-level indicators) assessment (column IV, Figure 3.6) shows similar results to the study by Vellinga et al. (Vellinga et al., 2019), which was based on the same food consumption survey data and LCA impact data. If the food sector outcomes of this work are substituted with the comprehensive and detailed FSPI assessment, the total carbon footprint of Kattenburg (Amsterdam) will increase to 4248 kg/cap*yr (=22%) and the food sector emissions will increase from 30% to 45% in the total. A detailed overview of the analysis results is provided in detail in Appendix 3F.

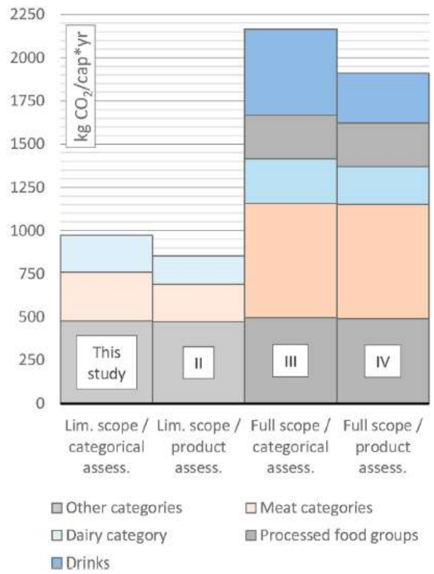


***Figure 3.6**: Results of the sensitivity analysis. This work = 973 kg/cap*yr; LSPI = 854kg/cap*yr; FSCI = 2165 kg/cap*yr; FSPI = 1911 kg/cap*yr. The FSPI column follows the same method as used by Vellinga (2019) and shows a similar outcome.*

3.4.5. Study limitations

Care and consideration are taken in this study to synchronise the inventory of assessed food items between the six case studies in order to increase the inter-comparability. However, there are differences between national data registrations on the aspects of food categorisation, taxonomy, grouping of food items, data availability and consumption data gathering methods. This inevitably leads to discrepancies between the total daily food intake among countries (787–1380 g/cap*day). The question arises whether the cause of this observed consumption difference can be assigned to data collection and interpretation or to actual differences in food consumption in reality. Without systematic gathering of survey-based data on food intake in each of the six urban areas, this remains a recurring uncertainty in carbon accounting of food with secondary data.

Per capita food consumption data, commonly released at the national level (Figure 3.2), may not always be representative of local diets. This applies especially to larger countries like USA and UK as many factors including geographic, social, economic, climatic, and cultural factors define community diets. Contextualising the national diet to the neighbourhood level diet can be done to a limited extent with the halal (removes pork) and carnivorous fractions (explained in Appendix 3E), but further contextualisation might be necessary by a considerable customisation of the national diet into a local diet when doing a more thorough assessment.

Finally, the carbon footprint values for food groups/items are not available at national level in Tokyo, Doha and Sydney. Therefore, the sectoral impact is based on global mean data provided by the UN Food and Agricultural Organisation. This study could produce a more accurate carbon accounting of these contexts if these values were available at the time of writing this paper.

3.5 Conclusion and future directions

This work introduces the FEWprint, acronym for Food, Energy and Water carbon footprint assessment platform and provides a user-friendly framework for the assessment of urban carbon emission equivalents. Under the umbrella-theme of urban food production, this research contributes to the downscaling and substantialising of the FEW nexus discourse by consideration of the resource nexus at the local scale. The evaluation component of the FEWprint is discussed in this work and produces the consumption-based carbon equivalent footprint of urban communities derived from food consumption, thermal and electrical energy use, car fuel demand, potable water management and domestic waste processing. This application is demonstrated in this paper for six urban communities in six global cities: Amsterdam, Belfast, Detroit, Doha, Tokyo and Sydney. Per capita emission equivalents fall in the range of 3329 kg/yr for a community in Amsterdam up to 13,237 kg/year in Detroit. The results show that in terms of total emissions, the sectoral impact of food consumption falls in the range of 993 kg/cap*yr (Amsterdam) to 1366 kg/cap*year (Tokyo). In terms of relative impact, the food sector emissions constitute between 9% (Detroit) and 37% (Belfast) of the total carbon impact of a community. The FEWprint carbon profiles give a preliminary indication of the carbon mitigation potential of a dietary transition or local food production and serves as the initial condition to start from and test holistically assessed urban farming strategies towards community carbon neutrality, which will be further elaborated in follow-up disseminations.

This work introduced the FEWprint's evaluation component for the integrated carbon assessment of urban communities. Part two, Diet Shift, explores the impact on a community's carbon footprint when transitioning away from animal-sourced food towards plant-based alternatives (P. N. ten Caat et al., 2022). The third part, UFP Design, describes the design component of the platform and its applicability to explore food production solutions for urban communities with the aim of mitigating carbon emissions through a FEW nexus lens.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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4

Towards a More Sustainable Urban Food System

Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform

In the previous chapter, a carbon footprint assessment strategy was discussed and demonstrated. The method was applied to six urban communities to show how the FEWprint platform can be employed to calculate a carbon emissions profile for urban communities. The baseline carbon profile contains a food consumption assessment conducted at a semi-disaggregated level. This degree of food inventory detail allows to test the carbon emissions impact of dietary changes.

The next chapter elaborates the second component of the FEWprint platform: *diet shift.* This component has been developed to assess the mitigation effect of dietary changes on the food sector emissions. Even though any form of dietary adjustments can be tested, the general idea is to simulate the impact of a protein transition. This means that dietary animal-sourced protein is substituted with plant-based protein, which generally present a lower carbon intensity then their animal-based counter-parts. The FEWprint can be applied to calculate the carbon emissions reduction and to see how substitute plant-based food can be used to counter the possible protein deficit that emerges during transition.

The shift component is used to test the impact of a community-wide protein transition for the case studies of Amsterdam, Belfast and Detroit. The chapter shows that a diet shift from animal-based protein to plant-based protein results in a mitigated carbon impact in all considered communities. However, both the relative [%] and absolute [kg/year] impact varies considerably per city and depends on various country-specific parameters, like initial meat consumption before transition or local carbon footprint indicators.

The introduction chapter discussed the environmental impact of food consumption and in particular animal-sourced food. The method and materials section discusses the following aspects: why protein is a suitable nutritional quality indicator (chapter 4.1.1), how protein intake is affected during a transition (chapter 4.2.2), the framework used in the platform to simulate a protein transition (chapter 4.2.3), the diet scenarios tested in the demonstrator of this paper (chapter 4.2.4) and the equations framework (chapter 4.2.5). The Results section compares the carbon emission impacts of the three cases. The Discussion section dives deeper into the mutual substitutability of animal and plant-based protein and how to account for this during a diet transition (chapter 4.4.3) and other relevant limitations in the FEWprint approach.

4

Towards a More Sustainable Urban Food System

Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform

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Aside from layout changes and minor textual differences, the content of paper has not been amended for uptake in this dissertation.

4. Towards a More Sustainable Urban Food System—Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform

Abstract.

The production, processing, and transportation of food, in particular animal-based products, imposes great environmental burden on the planet. The carbon emissions associated with the current food supply system often constitutes a considerable part of the total emissions of urban communities in industrialised cities. Urban food production (UFP) is a method that can potentially diminish the food related emissions. In parallel, a shift towards a predominantly plant-based diet that meets the nutritional protein intake is an effective method to curtail carbon emissions from food. Considering the high land use associated with the production of animal-based products, such a shift will prompt a community food demand that is more inclined to be satisfied with local production. Therefore, during the design process of a future low-carbon city, the combined application of both methods – diet change and urban food production- is worth exploring. This work introduces, describes, and demonstrates the diet shift component of the FEWprint platform, an UFP assessment platform for designers that is constructed around the broader three-pronged strategy of evaluation, shift, and design. For three neighbourhoods, in Amsterdam, Belfast, and Detroit, the local food consumption and country-specific environmental footprint data are applied to simulate a theoretical community-wide, incremental, diet shift from a conventional to a vegan diet, whilst maintaining protein intake equilibrium. The results show that in total terms, the largest carbon mitigation potential awaits in Detroit (916 kg CO2eq/cap/year), followed by Belfast (866 kg) and Amsterdam (509 kg). In relative terms, the carbon reduction potential is largest in Belfast (25%), followed by Amsterdam (15%) and Detroit (7%). The FEWprint can be used to generate preliminary figures on the carbon implications of dietary adaptations and can be employed to give a first indication of the potential of UFP in urban communities.

Keywords

diet assessment, carbon accounting, sustainable cities, FEW nexus, diet transition, sustainable urban planning, protein intake, CO2 emissions, plant-based diet

4.1 Introduction

Throughout the various agricultural revolutions, crop yields kept pace with the increasing food demand of populations (De Schutter, 2017; Khush, 2001). Maintaining sufficient food yields for a growing demand imposes a great environmental burden on the planet, for example, freshwater depletion, eutrophication, acidification, pollution, biodiversity reduction, and the emissions of greenhouse gasses. Research estimates that in 2015, the agriculture sector was responsible for about a third (range 24–42%) of the global greenhouse gas (GHG) emissions. Impact estimations are different between research institutes due to different analysis methods, taxonomy, and/or scopes. In addition, the estimation can vary between years, partly due to developments in the other sectors (e.g., transportation or energy) (Crippa et al., 2021). During the course of the 20th and early 21st century, subsidence agriculture is shifting towards highly optimised and resource-intensive bio-industry, thus driving up the emissions of greenhouse gasses (De Schutter, 2017; Pimentel, 1996). In addition, populations increasingly rely on international food trade, a trend that is expected to continue in especially developing nations (Geyik et al., 2021). This increases the distance between the food producers and consumers and is in the carbon accounting discourse often described as *food miles* (AEA Technology Environment, 2005). At overseas farms, but mainly in tropical areas (Gibbs et al., 2010), cropland is expanded at the cost of forest land (Winkler et al., 2021). This is commonly referred to as land-use/land-use change and is a common method to boost food yields, leading to the large-scale atmospheric deposition of carbon dioxide emissions and the loss of soil organic carbon stocks. As the global demand for animal-sourced protein is rising (FAO, 2006), a large portion of the global GHG emissions can be assigned to the livestock sector.

The meat, dairy, and fishery industries are responsible for more than half of the food sector's global environmental impact (Poore & Nemecek, 2018). In addition to playing a considerable role in global land-use change (FAO, 2006), the livestock sector also contributes to the global greenhouse gas problem by emissions through enteric fermentation and manure management. Enteric fermentation mainly applies to ruminant livestock, i.e., the beef, dairy, and mutton sector, and is the result of microbes breaking down feed and releasing the strong GHG methane (CH_4) in the process (Crutzen et al., 1986). Anaerobic breakdown of organic matter during manure storage mainly leads to methane emissions, and manure application to farmland leads to the release of various greenhouse gasses (mainly N_2O, nitrous oxide).

Greenhouse gas emissions, also referred to as carbon dioxide equivalent (CO_2eq) emissions throughout this work, caused by the consumption of food, can constitute a significant part of the total emissions of an urban dweller. In the previous chapter, that introduced a carbon assessment approach for neighbourhoods, the carbon emission profiles for various urban communities around the world were produced (N. ten Caat et al., 2022). These carbon profiles have been coined *FEWprints*, or Food Energy & Water carbon emission footprints, named after the platform specifically developed for this carbon assessment. The profile incorporates emissions associated with the management of throughput resources commonly used at the household level, which are thermal energy demand, electricity demand, fuel demand for personal mobility, water provision, water treatment, rainwater management, the processing of domestic waste, and food consumption – shown in figure 4.1 on the next page. This work only focuses on food-related emissions.

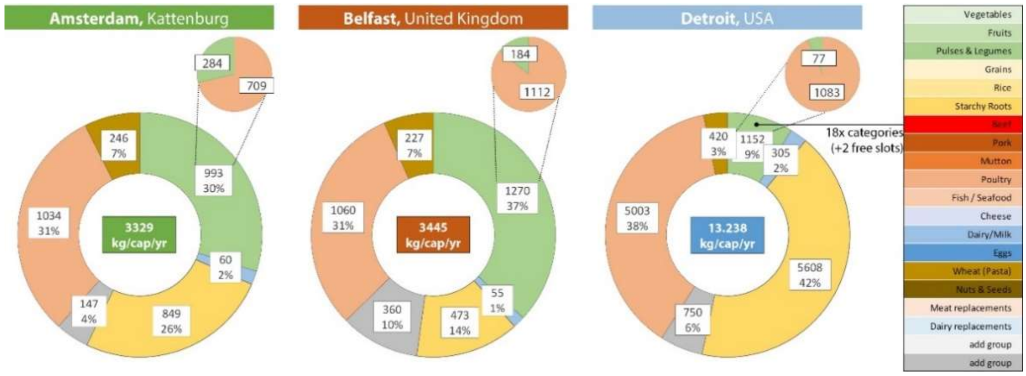

Figure 4.1. *Based on the results in Caat et al. (2022). The FEWprint of the Kattenburg community (Amsterdam, AMS), the Inner-East community (Belfast, BEL) and the Oakland Avenue Farming Community (Detroit, DET). Values are expressed in kg CO_2eq/capita/year. The secondary graph shows the animal (pink) and plant based (green) emissions. Legend: food = green, water = blue, electricity = yellow, mobility = grey, thermal energy = red, waste = brown.*

FEWprint assessment of an urban community in the neighbourhood of Kattenburg (Amsterdam), Inner-East (Belfast), and Oakland Avenue (Detroit) has revealed that food-related emissions are responsible for respectively 30%, 37%, and 9%, or 993, 1270, and 1152 kg/capita/year. The assessments are based on contextual resource demand and country-specific (or at a more granular level when available) carbon footprint indicators. The food sector emissions are estimated based on national food consumption survey data combined with country specific emission factors. Only non-processed food items/groups—subdivided into 18 food categories—were added to the food assessment scope. The relative impact of food [% of total emissions] is often dictated by the impact of the other resource sectors recorded in the carbon profile, hence leading to the considerable range (9–37%).

In essence, food sector emissions can be brought down by making improvements to the supply chain or by altering the demand on the consumer's side. One alternative strategy to the conventional food supply chain is urban food production (UFP): the production, processing, and marketing of food products in urban centres or in the urban periphery. This can potentially offer various ecological benefits (Lin, Philpott, & Jha, 2015), environmental benefits when managed sustainably (Goldstein et al., 2016a; Rothwell et al., 2016), and deal with various other challenges in the urban setting (Goldstein et al., 2016b). A collective dietary change at the consumer level can bring about environmental benefits on a scale that is difficult to achieve by the producers of the food (Poore & Nemecek, 2018).

The greenhouse gas emissions related to food consumption have been studied extensively in the past decades, and so has been the impact of a diet change to mitigate food sector emissions (Aleksandrowicz et al., 2016; Foley et al., 2011; Scarborough et al., 2014; Springmann et al., 2016). In general, it can be stated that the scientific community is in consensus on the lower environmental impact of adopting a diet that predominantly consists of plant-based food categories (Mbow et al., 2019), and the World Resource Institute has included this as one of the key steps to achieved sustainable food security in the future (WRI, 2018). Also, when considered and calculated at the community or neighbourhood level, changing food consumption patterns is expected to bring about carbon emissions benefits. However, due to the variation in sectoral emissions between communities (figure 4.1), it is likely that a dietary shift from animal-based to plant-based protein would impact the total FEWprint to a different extent in each community, which is tested in this work.

Urban food production is increasing in popularity among the general public, architects, urban designers, and policymakers in urban centres (Rothwell et al., 2016), quite often driven by the claim that *local* is inherently better for the environment (Enthoven & Van den Broeck, 2021). However, the carbon emissions-reducing impact of UFP strategies is difficult to holistically quantify as food production is a complex and multi-faceted system and a comparison between a local and an imported product is not easily drawn. Local food production, especially in a dense inner-city location, often operates at a smaller capacity. This leads to a decreased energy efficiency per unit of food output and an increased footprint, a concept coined the *ecology of scale* (Schlich & Fleissner, 2005). Considering the inverse relationship between farm-scale and impact per unit of food, UFP should not be approached as merely the relocation of farming to an urban context, which effectively only shortens food miles and reduces food waste, but rather as the integration of a food system within the urban resource infrastructure. This could disclose an array of opportunities for symbiotic resource management between the two systems, a potential that is discussed more often in literature (N. ten Caat, Graamans, Tenpierik, & Dobbelsteen, 2020; Goldstein et al., 2016b; McDougall et al., 2019; Shah et al., 2021).

Within the ambition of urban design practice that is in pursuit of self-sufficiency, resiliency and the decarbonisation of a neighbourhood, food demand and UFP design are at interplay with each other, particularly during the conceptual stage of the design process. Community-wide food consumption patterns determine the food demand. A combination of UFP and conventional food imports are responsible to meet this demand. In view of the high land use associated with animal-based protein (Nijdam et al., 2012; Poore & Nemecek, 2018), diets that are inclined towards plant-based food offer more potential in space-limited urban centres or peripheries. As such, a dietary intake shift could play a determinative role in the ratio between locally produced protein and imported protein. With our research, we intend to provide a strategy and framework for non-agriculturist (e.g., urban planners and designers) and support the UFP design process with instant preliminary figures on food yield, resource demand, and environmental impact after design moves. To achieve this, the FEWprint operates as an integrated UFP assessment platform and has been constructed around the three-pronged strategy of (1) *evaluation*, (2) *diet shift,* and (3) *design*.

This work introduces and describes the *diet shift* component of the FEWprint platform. The component is demonstrated by employing it to determine the theoretical impact on the carbon equivalent emissions of the three aforementioned case study communities when animal-based protein is gradually replaced by plant-based protein. Protein intake is used as the functional unit, and chapter 4.2 further elaborates on securing a protein intake equilibrium during diet transition. The first objective of this study is to see the extent to which the community's food sector emissions are diminished throughout a series of drastic diet scenarios. The second objective is to see how the daily food intake pattern changes as a consequence of maintaining a protein intake balance throughout these diet scenarios. The preceding FEWprint *evaluation* component has been discussed in Caat et al. (N. ten Caat et al., 2022) and the successive UFP *design* component will be discussed in future disseminations.

4.2 Materials and Methods

4.1.1. Dietary Quality Indicator: Protein

Protein is a macro-nutrient that is composed of long chains of various types of amino acids. Dietary protein supplies the human body with the full range of essential or indispensable amino acids, i.e., the types of the body cannot synthesize on its own. By breaking down the dietary protein during digestion, the body is able to self-compose various other amino acids important to sustain bodily functions, also referred to as the non-essential amino acids (Boye, Wijesinha-Bettoni, & Burlingame, 2012). Briefly: amino acids are vital components for growth, metabolic interactions, and maintenance of the body. Parts of the amino acids are further broken down to produce energy for the body. The recommended daily protein intake is different among individuals and depends on age, gender, physical condition, or sports activity. For the general population, the world health organisation recommends a minimum safe level of daily protein intake for adults (male + female) of 0.83 g/kg of body weight (WHO, 2007). Long-term deficient intake of protein can affect vital organs and the immune system, making protein content and protein quality of food products and/or diets an important criterion of adequate nutrition (Boye et al., 2012). This study applies the daily protein intake [$gram_{prot}$/day] as the currency of nutritional quality of the alternative diet, a method that has been used more frequently in the past (Berners-lee, Hoolohan, Cammack, & Hewitt, 2012; Saxe, Larsen, & Mogensen, 2013).

Both animal-based and plant-based food contain protein. It are however animal products that are considered as the typical source of protein in current diets (Milton, 1999). Animal-based protein contains, in higher quantities, the full range of essential amino acid combinations required by the body, which can be an essential component to close nutrition gaps in especially developing countries (Neumann, Harris, & Rogers, 2002). Plant products contain a lower amount of proteins and plant protein contains fewer amino acids or they are present in non-optimal proportions, making them harder to break down through digestion (Day, 2013). Even though total protein consumption or protein content of food items is popularly used as an umbrella unit, nutritional quality of a diet should be assessed at the level of the individual amino acid intake (Bohrer, 2017; FAO, 2013; Phillips, 2017). This is underlined by Bohrer by stating that "plant derived proteins usually have large amounts of some to most essential amino acids, but have little or no amounts of some essential amino acids" (Day, 2013) [p. 105], meaning shortages of specific amino acids can be bypassed through variety in plant-protein. Various studies have shown that a healthy amount of indispensable amino acid intake can be achieved by consuming only plant-based protein, i.e. a vegetarian/vegan diet (American Dietetic Association, 2009; Bohrer, 2017; Day, 2013; Young & Pellett, 1994)

4.2.2. Maintaining a Healthy Protein Intake

An inconsiderate transition towards a (partly) plant-based diet could lead to an abatement of total protein intake, even when the amount of food consumed in terms of weight is kept equal by consuming substituting plant-based products. The size of such emerging protein-gap depends on various factors, namely the current reliance on meat and dairy for protein intake, the present consumption of the other food groups, the extent of the assessed diet shift, and the applied protein content indicators for the various food groups. But as argued in the previous sectin, a considerate consumption of plant-based amino acids can avoid such a risk of protein deficiency.

On a single source basis, plant products offer reduced protein intake with a lower bioavailability compared to their meat analogues (Day, 2013). However, a combination of various plant proteins, extracted from a range of crop types, can be fully adequate to provide the necessary diversity of indispensable amino acids (Young & Pellett, 1994). The EAT-Lancet committee recommends diversity within a largely plant-based diet, with a modest amount of animal sources (Willett et al., 2019). When only plant-based food products are consumed, variation remains an essential aspect and will secure an adequate diet (Gaillac & Marbach, 2021; Melina, Craig, & Levin, 2016). Therefore, for the simulation in this study, a varied selection of plant-based groups that are generally high in protein are added to the diet in order to close the emerged protein gap after transition. These groups are legumes and pulses, grains (cereals), nuts and seeds, and meat replacers (soy-based). Dairy (includes milk and yoghurt) is substituted with soybean-based dairy replacers.

The FEWprint platform can be used to compose a new and less impactful diet, whilst maintaining protein intake equilibrium with the current diet. In order to produce a meaningful evaluation of nutritional quality with regard to the protein intake of a new diet, it should preferably be evaluated at the amino acid level, where each amino acid combination is quantified separately. However, as each food product contains a different composition and quantity of essential amino acids, it would complicate the mechanics and data requirements of the platform considerably. Since the platform has been developed on the values of inter-component integration and scope comprehensiveness, whilst securing simplicity and functionality (N. ten Caat et al., 2022), it, therefore, simplifies the assessment by only considering the total protein intake [$gram_{prot}$/cap/day].

A holistic assessment and comparison of conventional diets with alternative low-impact plant-based diets along the axis of sustainability and nutritional quality is a complex task as it requires indicators for both aspects and the possibility to link them (Perignon, Vieux, Soler, Masset, & Darmon, 2016). The protein content of food [$gram_{prot}$/100 $gram_{food}$] is such a factor when (re)establishing the protein intake equilibrium between two diets. Both detailed product-level, as well as aggregated, group-level, lists of protein content of numerous retail food can be retrieved from online public databases, however, protein content data shows a lot of variation (Gaillac & Marbach, 2021). This can also be observed in Table A5, where the protein content of food groups, retrieved from national databases for the Netherlands, the United Kingdom, and the USA, is tabulated in grams of protein per 100 g (retail weight). This study however, applies the global average FAO values for the assessment (FAO, 2001), which are based on a combination of various items within a group, and only products that are considered a customary staple food for daily consumption are included, see Appendix 5B for more information.

4.2.3. Diet Shift: Framework of Diets and Diet Shift Component

The platform applies five commonly followed diet types to frame a community-wide transition towards a plant-based diet: *pesce-pollotarianism (PPT)*, *pescetarianism (PT)*, *vegetarianism (VT)*, *ovo-vegetarianism (OV),* and finally *veganism (VG)*. Since formal definitions of these terms may differ depending on the addressed source or context, this study applies elementary definitions that are based on the ADA descriptions (American Dietetic Association, 2009). In the pesce-pollotarian diet, red meat is removed from the menu, which is beef, pork, and lamb/mutton. In a pescetarian diet, red meat and poultry are not eaten whilst the consumption of fish and seafood is still allowed. In a vegetarian diet, all red meat, poultry, and fish and seafood groups are removed. People who follow an ovo-vegetarian diet additionally remove dairy and cheese from the menu, but the eggs are still allowed. This is a very uncommon diet in reality but is added to the selection as it can be a relevant in-between step when designing an urban food production strategy. Finally, all animal-based food groups are removed in the vegan diet.

Figure 4.2 displays a screenshot of the *diet shift* component of the MS Excel based platform that consists of steps 3a to 3d. The dietary transitions are inserted in step 3a. The percentages, noted by r_{1-5}, represent the fraction of the total community that follows a specific diet. The dietary levels follow a hierarchy according to increasing removed food groups, and each broader restriction contains the lenient one (e.g., a vegan must by definition also be a vegetarian, but a vegetarian is not necessarily a vegan). This means that the inserted value of a diet tier can therefore never be higher than the preceding tier. In step 3b, substitution food is selected and quantified to maintain consumption balance based on weight. Step 3c is used to manually reinstate protein intake equilibrium with plant-based products after diet shift. Step 3d can be used to manually adjust the diet according to the users' preferences.

4.2.4. Diet Scenarios

For all three assessed communities, four alternative incremental diet scenarios and their impact on the community's total carbon footprint are calculated and compared with the baseline. The scenarios are in order of removed animal products, illustrating a gradual transition towards a vegan diet. Substitution factors are presented in table 4.1. In each scenario, the applicable animal food group(s) are completely removed from the diet. The equation framework and parameters used to assess the transition are further discussed in chapter 4.2.5.

The five scenarios:

1. *Business as Usual (BAU)* represents the current situation without any dietary changes. Food consumption is based on national survey data.

2. *Pesce-Pollotarian diet—animal substitution* (PPTA, $r_1 = 1.00$). For all people in the assessed community, the beef, pork and mutton food groups (red meat) are completely removed from the diet and replaced with animal-based substitutions: poultry ($r(poultry)_{sub1} = 0.5$) and fish, ($r(fish)_{sub\,1} = 0.5$).
3. *Pesce-Pollotarian diet—plant substitution* (PPTP, $r_1 = 1.00$). For all people in the assessed community, beef, pork, and mutton food groups (red meat) are completely removed from the diet and replaced by plant-based alternatives. Substituting food groups and values are listed in Table 4.1.
4. *Vegetarian diet* ($r_{1-3} = 1.00$). For all people in the assessed community, the food groups beef, pork, mutton, poultry, and fish are completely removed and replaced with plant-based alternatives according to the values listed in Table 4.1.
5. *Vegan diet* ($r_{1-5} = 1.00$). For all people in the assessed community, all animal-sourced food groups are removed and replaced by plant-based food according to the substitution values listed in Table 4.1.

Table 4.1. Substitution fractions ($r(n)_{sub}$) used for the diet scenarios in this study. The symbol '><' means fully removed from diet in that scenario. The fraction indicates how much of the removed food groups are replaced by the corresponding group.

food group (n):			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	
Weight and protein compensation[1]	Scen.	Eq.:	**Vegetables**	**Fruits**	**Leg. & Pulses**	**Grains**	**Rice**	**Starchy Roots**	**Beef (&veal)**	**Pork**	**Sheep/Goat**	**Poultry**	**Fish & Sea food**	**Cheese**	**Dairy (other)**	**Eggs**	**Pasta (durum)**	**Nuts & seeds**	**Meat replacers**	**Dairy replacers**	**Total**
business as usual (BAU)	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
pesce-pollotarianism - animal substitutes (PPTA))	(2)	[1]	-	-	-	-	-	-	><	><	><	½	½	-	-	-	-	-	-	-	1
pesce-pollotarianism - plant substitutes (PPTP)	(3)	[1]	-	-	¼	¼	-	-	><	><	><	-	-	-	-	-	-	¼	¼	-	1
pescetarianism (PT)	n.a.	[2]	-	-	¼	¼	-	-	><	><	><	><	-	-	-	-	-	¼	¼	-	1
vegetarianism (VT)	(4)	[3]	-	-	¼	¼	-	-	><	><	><	><	><	-	-	-	-	¼	¼	-	1
ovo-vegetarianism (OV)	n.a.	[4]	-	-	-	-	-	-	><	><	><	><	><	><	><	-	-	-	-	1/1	1
veganism (VG)	(5)	[5,6]	-	-	¼	¼	-	-	><	><	><	><	><	><	><		-	¼	¼	-	1

[1] Please note: in this study, the substitution factors used to maintain equal food intake and the surplus consumption to maintain protein intake equilibrium are in the same proportion within a scenario and are therefore presented in the same overview.

Table 4.2. Dietary intake of the 18 food groups, *PCC(n)* [gram/cap/day] + applied contextualization parameters r_{hal}, r_{car} and r_{add}[%], explained in Appendix 3E. N.d. = no data available or not mentioned as an individual food group but logged under other group. Consumption values only contain non-processed food items. FAO data is used for further assessment and values represent the average protein content of an extensive list of products. Protein content values apply to retail weight.

Food category		Food intake [gram/cap/day]			Carbon footprint [kg_{CO2}/kg_{food}]			Protein content [g/100 g_{food}]
•	Food groups (n)	AMS[3]	BEL[4]	DET[5]	AMS[6]	BEL[7]	DET[8]	FAO[10]
	r_{hal}[%]	15%	0%	3%	-	-	-	-
	r_{car}[%]	25%	20%	22%	-	-	-	-
	r_{add}[%]	15%	15%	15%	-	-	-	-
1	Vegetables	131.0	92.0	99.7	1.82 (31)	1.77 (3)	0.48 (57)	1.90 (29)
2	Fruits	113.8	114.0	77.5	1.53 (18)	0.90 (1)	0.57 (32)	0.70 (37)
3	Legumes & pulses	4.5	3.0	11.6	2.53 (3)	3.40 (2)	0.80 (18)	24.2 (12)
4	Grains & Cereals	138.3	106.0	150.8	1.32 (12)	1.00 (2)	0.46 (14)	14.0 (12)
5	Rice	n.d.	15.0	n.d.	1.71 (2)	3.90 (1)	1.73 (4)	6.70 (7)
6	Starchy roots	72.2	93.0	57.7	0.92 (1)	0.40 (1)	0.25 (3)	2.10 (16)
7	Beef (& veal)	12.6	21.0	51.8	30.82 (6)	68.8 (1)	32.85 (1)	16.4 (?)
8	Pork	13.0	31.0	39.4	13.73(4)	7.90 (1)	5.56 (1)	13.1 (?)
9	Sheep & Goat (+lamb)	0.6	5.0	0.7	n.d.[12]	64.2 (1)	34.75 (1)	13.5 (?)
10	Poultry & Turkey	16.6	36.0	75.1	12.21(2)	5.40 (1)	3.20 (3)	15.2 (?)
11	Fish & Seafood	12.9	22.0	8.2	8.61 (19)	5.40 (1)	7.70 (6)	13.5 (?)
12	Cheese	32.6	18.0	34.2	11.28 (5)	4.50 (1)	9.97 (1)	17.0 (?)
13	Dairy (Milk & Yog.)	254.3	262.0	138.6	2.31 (11)	1.90 (2)	1.33 (2)	8.30 (?)
14	Eggs	12.7	15.0	27.3	4.32 (1)	4.90 (1)	3.75 (1)	10.7 (?)
15	Pasta (durum wheat)	47.1	14.0	n.d.	1.52 (1)	1.00 (1)	n.d.	11.8 (?)
16	Nuts & Seeds	6.3	5.0	13.9	4.16 (8)	2.00 (1)	1.93 (12)	13.0 (13)
17	Meat replacements[1]	1.5	n.d.	n.d.	n.d.[11]	n.d.[11]	n.d.[11]	13.0 [1]
18	Dairy replacements[2]	8.4	n.d.	n.d.	0.76 (1)	n.d.[12]	0.53 (2)	3.0 [2]
	total [gram/cap/day]	**878**	**852**	**787**				

[1] Retail product assumed for meat replacer: Tofu, uncooked (33% water), 13 g protein /100 g product

[2] Retail product assumed for dairy replacer: Soy Drink, natural, 3.0 g / 100 ml of product

food consumption data:

[3](RIVM, 2017), [4] (DEFRA, 2020a) & [5](USDA ERS, 2017). An extensive breakdown of the 18 food categories into individual food items or subgroups can be found in Caat et al. (N. ten Caat et al., 2022).

carbon footprint data:

[6] (RIVM, 2020b): Based on Life Cycle Inventory studies. Data reflect cradle-to-consumption greenhouse gas emissions factors. Dataset is in Dutch.

[7] (Scarborough et al., 2014): Based on Life Cycle Inventory studies. Data reflects cradle-to-retail distribution centre. Source document GWP: (Audsley et al., 2009)). Note source: values are weighted for production in the UK, imports from the EU, and imports from outside the EU.

[8] (Heller et al., 2018). See Appendix 5C for more information and dataset processing.

protein content data:

[9](FAO, 2001). See Appendix 5C for more information and dataset processing.

[11] Not specified in source: assumed value applies: 2.0 kg CO_2eq/kg_{food}.

[12] Not specified in source. Global value applies (provided by (Poore & Nemecek, 2018): Mutton = 24.00 kg CO_2/kg, Dairy repl. = 0.90 kg CO_2eq/L.)

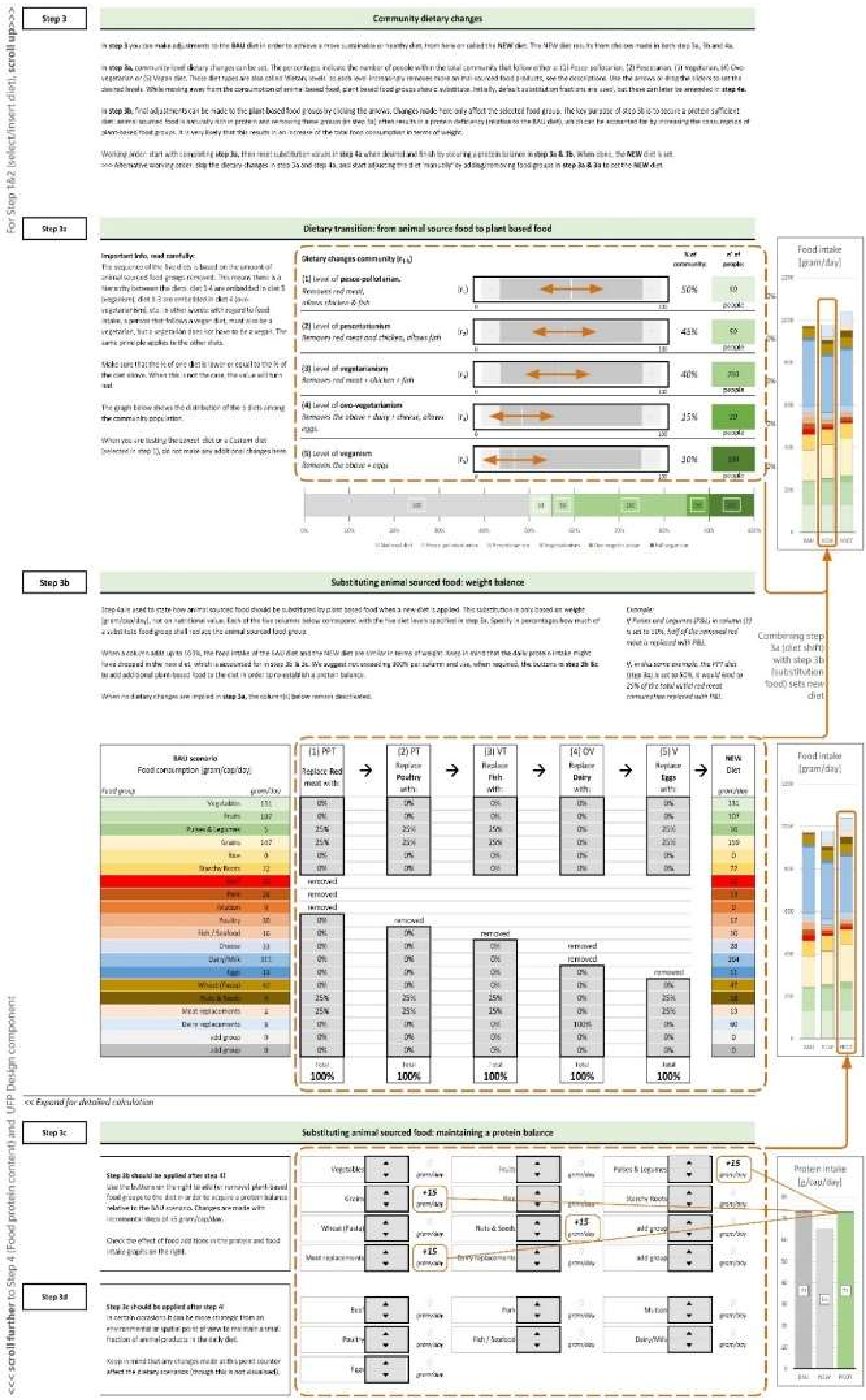

Figure 4.2. Screenshot of the FEWprint tool interface. Step 3a: The sliders used to set the values ($r_{1–5}$) for the various diets. The graph shows the NEW diet (=weight balanced) and PROT diet (=protein balanced) Step 3b: Substitution values should be inserted for each of the five-diets tier, or default values can be used. Step 3c & 3d: Increase or recompose the food intake of plant based or animal-based food groups to account for the protein deficiency. Displayed values are exemplary.

4.2.5. Equations Framework

A new and community-wide diet scenario is simulated by inserting the fraction of the community that will follow an intended alternative diet. Equations (1)–(6) are used to determine how removed animal-based food categories are substituted throughout the five dietary levels with plant-based food groups in order to maintain an equal food intake in terms of weight. The various values applied in this study are similar to the default values used in the FEWprint (listed in Table 4.1) and aim towards a lower-emission alternative diet with increased consumption of varied plant-based food groups that are naturally high in protein content.

$$PCC(7{,}8{,}9)_{new} = PCC(7{,}8{,}9)_{ctx} \times (1 - r_1) \quad [1]$$

$$PCC(10)_{new} = (PCC(10)_{ctx} + (PCC(7{,}8{,}9)_{ctx} \times r_1 \times r(10)_{sub\,1})) \times r_2 \quad [2]$$

$$PCC(11)_{new} = (PCC(11)_{ctx} + \sum(PCC(7{,}8{,}9{,}10)_{ctx} \times r_{1,2} \times r(11)_{sub\,1,2})) \times r_3 \quad [3]$$

$$PCC(12{,}13)_{new} = (PCC(12{,}13)_{ctx} + \sum(PCC(7-11)_{ctx} \times r_{1-3} \times r(12{,}13)_{sub\,1-3}) \times r_4 \quad [4]$$

$$PCC(14)_{new} = (PCC(14)_{ctx} + \sum(PCC(7-13)_{ctx} \times r_{1-4} \times r(14)_{sub\,1-4})) \times r_5 \quad [5]$$

$$PCC(n)_{new} = PCC(n)_{ctx} + \sum(PCC(7-14)_{ctx} \times r_{1-5} \times r(n)_{sub\,1-5}) \quad [6]$$

To start, equations 1-6 and the default values are embedded in a matrix of the *diet shift* component of the FEWprint platform to streamline the simulation. All calculations start with the (contextualised, ctx) present food intake of a food group, denoted by the Per Capita Consumption, $PCC(n)_{ctx}$ [g/cap/day], where *n* refers to the food group represented by its listing number 1–18 in table 4.2. The new per capita food consumption is noted by $PCC(n)_{new}$ [g/cap/day]. A dietary shift towards a PPT, PT, VT, OV, and VG diet are respectively simulated with the factors r_1, r_2, r_3, r_4, and r_5, where the number refers to the diet tier. The *r* value sits between 0% (no people in the community will follow that specific diet) to 100% (everybody). Since the lower-tier diets are contained in the higher ones, the constraint $r_{n-1} \geq r_n$ applies. The substitution percentages are represented by $r(n)_{sub\,1}$ to $r(n)_{sub\,5}$, where the *sub* number corresponds with the diet tier. For example, $r(10)_{sub\,1} = \frac{1}{2}$ implies that half of the removed red meat after the BAU to PPT shift is replaced with poultry (group 10). Within one diet tier, the total of all $r(n)_{sub\,x}$ values should add up to 1.0 to secure an equal food weight intake. The aforementioned factors are displayed in figure 4.3 below for clarity. The combined effect of applied r_{1-5} and $r(n)_{sub\,1-5}$ values in one tier trickle down to all the lower diet tiers, as is visualised in figure 4.4 (next page)

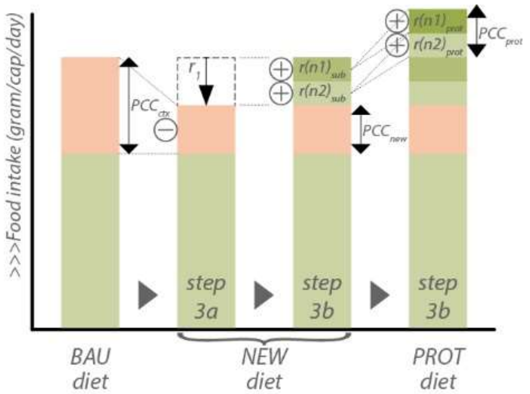

Figure 4.3. *Various factors used in diet shift simulation.*

As was mentioned in chapter 4.2.3, the animal-based food that is removed by a diet shift, is substituted with four different plant groups: (1) Legumes and Pulses, (2) Grains, (3) Nuts and Seeds, and (4) Meat replacers. These products are used both to maintain equilibrium in terms of weight (step 3b) as well as securing a protein intake equilibrium (step 3c). In order to maintain a protein equilibrium, the above products are repeatedly added in steps of 5 g in the same sequence as listed above, until a similar protein intake as the baseline situation is achieved, which is called the PROT diet. In addition to the ability of starting with a fully customisable diet, all the diet transition levels (r_x), substitution ratios ($r(n)_{sub\ x}$), and plant alternatives used as protein replacers can be specified according to the user's priority in the platform.

Figure 4.4 depicts the diet hierarchy applied in the FEWprint platform and shows how changes on one level trickle down to affect the dietary composition on successive levels. Community-wide dietary changes throughout tier 1 to 5 are based on the contextualised diet, i.e., the national diet adjusted to the local context by accounting for halal diets and the meat lover population. Finally, the consumption of plant-based food groups can be adjusted to re-establish protein equilibrium in step 3c. In addition, any other dietary changes the user wishes to simulate, for example, an increase in fruit consumption, can be inserted in steps 3c and 3d.

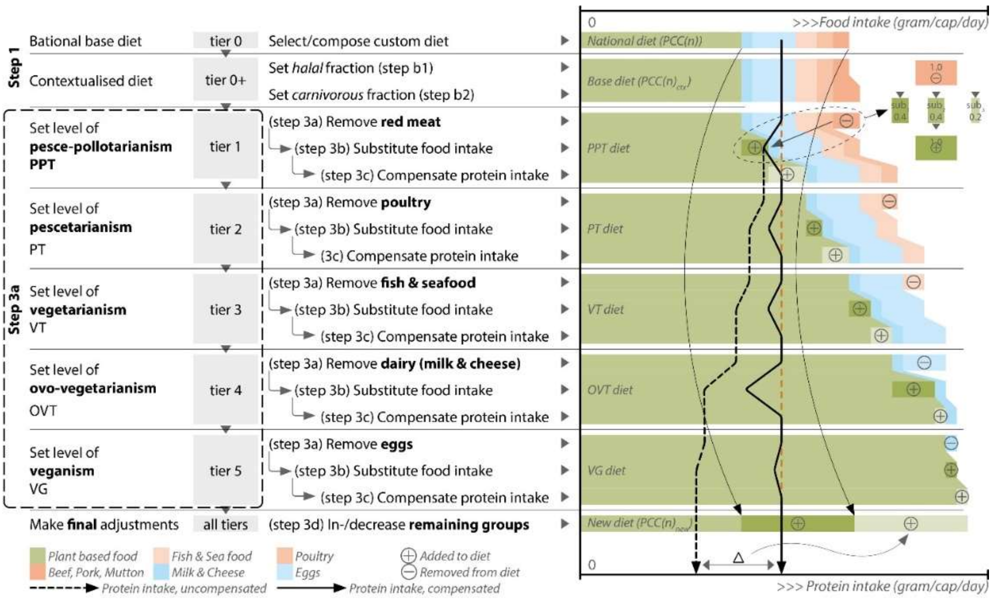

Figure 4.4. *FEWprint diet and calculation hierarchy. Step 3a to 3c correspond with the FEWprint steps shown in Figure 2 and are used to establish the new diet. The dashed lines indicate the protein intake without supplementary food for protein balance, the straight line represents the balanced intake.*

4.2.6. Urban Case Studies: Amsterdam, Belfast & Detroit

Three urban communities have been selected for a continued analysis on the role of food and a diet transition with regards to their FEWprint carbon profile. The first case is the residential neighbourhood of Kattenburg in Amsterdam, which holds a population of about 1700 people. The second case is Inner-East in Belfast, where about 32,000 people live. The third case is the smaller Oakland Avenue Farm community in Detroit, where currently 427 people are living. The three cases, their consumption of FEW resources, and the relevant carbon emission indicators are more thoroughly discussed in Caat et al. (N. ten Caat et al., 2022) and in Appendix 3D. Table 4.2 lists the dietary intake [gram/cap/day], country-specific carbon footprint data [kg CO_2e/kg food] and protein contents [g/100g_{food}] applied in this study.

4.3 Results

Five diet scenarios were assessed with the FEWprint platform for an urban community in Amsterdam, Belfast, and Detroit. The first objective is to assess the theoretical carbon emission mitigation potential of a diet shift towards a plant-based diet. The second objective is to see how the average food intake changes during the diet shift when a protein intake equilibrium is maintained.

4.3.1. Carbon Implications

The *business as usual* (BAU) and the four theoretical diet scenarios have been assessed based on their total [kg/cap/y] and relative impact [%] on the overall carbon equivalent footprint of the community, shown in Figure 4.5a-d. The substitution factors, incremental diet shifts, and assumed amount of protein contained within a food item/category are similar for each of the cases during the simulations, whereas site-specific data is used for food consumption and carbon footprints of food groups. In addition, the scope of assessed food consumption is aligned between cities as much as possible so that for each community, the same food types are accounted for in this carbon assessment (N. ten Caat et al., 2022).

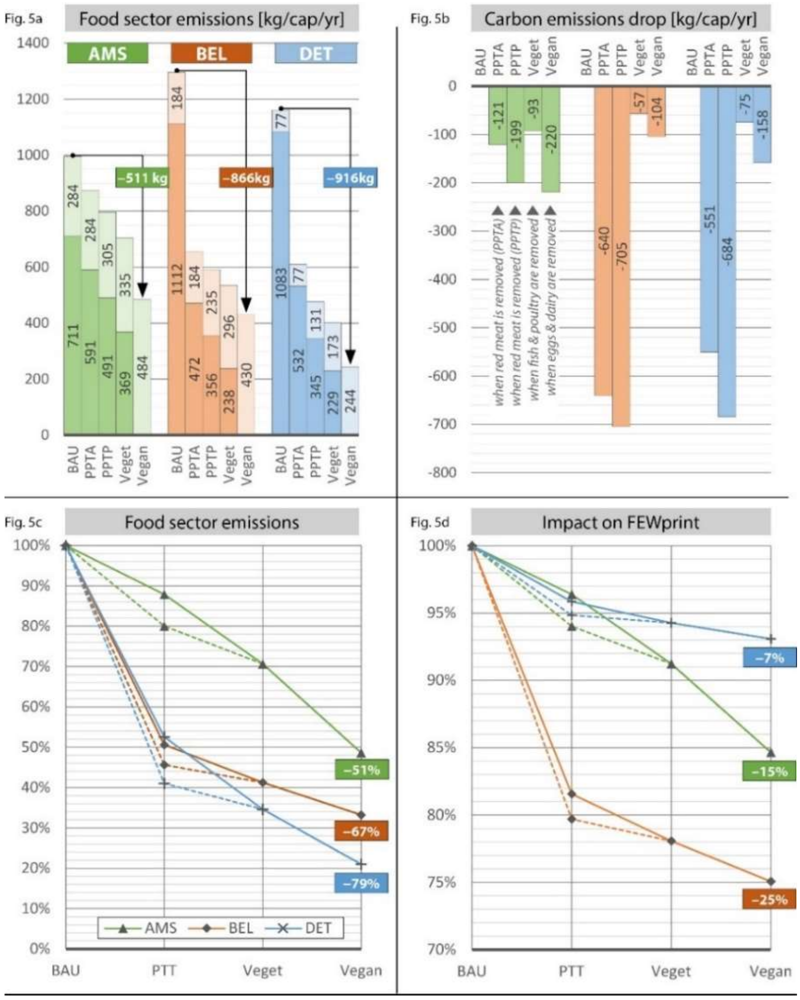

Figure 4.5. Carbon emissions of the food sector (dark color = animal products, light color = plant products. ***Figure 4.5a****: [top left] Food sector emissions (AMS, BEL & DET) for the 5 diets [kg/cap/year].* ***Figure 4.5b****: [top right] Carbon reduction per removed food categories* ***Figure 4.5c****: [bottom left] Relative impact of a dietary change on the food sector emissions [%]. The PPTA and PPTP diet has been split in two nodes, where the PTTP (plant alternatives) diet is represented by the dashed line.* ***Fig 4.5d****: [bottom right] Relative carbon emission reduction of a diet shift on the total FEWprint of a community.*

Figure 4.5a shows the absolute impact of diet change on food-related emissions. Removing animal-sourced food categories and replacing them with plant-based alternatives predictably leads to a drop in the food-related emissions for all three communities. However, the carbon emissions mitigation potential of such diet transition varies considerably per country. The largest carbon mitigation potential, i.e., the difference between the present situation and the vegan scenario, awaits in Detroit (−916 kg CO_2eq), closely followed by Belfast (−866 kg CO_2eq) and then Amsterdam (−511 kg CO_2eq). The red meat categories dominate a significant part of the emissions in the Belfast and Detroit cases, which is evidently visible in the graph. In Amsterdam, the largest drop in emissions can be seen when cheese and dairy are removed from the diet.

Figure 4.5c,d shows the relative impact throughout the four alternative diets for respectively the food sector and the total FEWprint of the community. In Amsterdam, Belfast, and Detroit, the food sector initially constitutes respectively 30% (993 kg CO_2eq) 37% (1270 kg CO_2eq), and 9% (1152 kg CO_2eq) of the total emissions. Even though the largest reduction is in absolute numbers theoretically achievable in Detroit (−916 kg/cap/y, Figure 4.5a), when a vegan diet is maintained, in relative terms, the impact sits just below 7%. In comparison, a vegan diet in Belfast would reduce the total carbon emissions of a community by about 25%—the highest reduction potential of the assessed case studies.

Figure 4.5c,d show two curves for each case study. For all three cities, the upper node in the PPT column represents the scenario where the red meat category is substituted with animal-sourced alternatives (PPTA). The bottom node represents the scenario in which red meat is substituted with plant-based food (PTTP). Substituting red meat with plant alternatives instead of meat alternatives leads to lower emissions in all three cases, with the Detroit case showing the largest difference (132 kg CO_2e/y).

4.3.2. Food Intake Shift

When transitioning through the diet alternatives, removed animal-based food products are equally substituted in weight equivalents according to the substitution factors listed in Table 4.2. In addition, as a result of securing a protein intake equilibrium relative to the current situation, surplus plant-based food that is naturally high in protein content should be added, which is shown in figure 4.6 below.

When comparing the present diet with the vegan diet in each case study, most surplus food is required in Amsterdam (+80 g/cap/day), followed by Detroit (+75 g) and Belfast (+65 g). All communities show a steep drop in protein intake when dairy and eggs are removed from the diet, resulting in a considerable increase in surplus consumption to compensate. This can be attributed to the combined effect of relatively high consumption of dairy (AMS: 254, BEL: 262 and DET: 139 g/day) and high protein content of dairy (8.30 g/100g_{food}), that is fully substituted with a soy-based alternative with a lower protein content (3.0 g/100g_{food}), hence requiring more consumption from the other categories to level the intake.

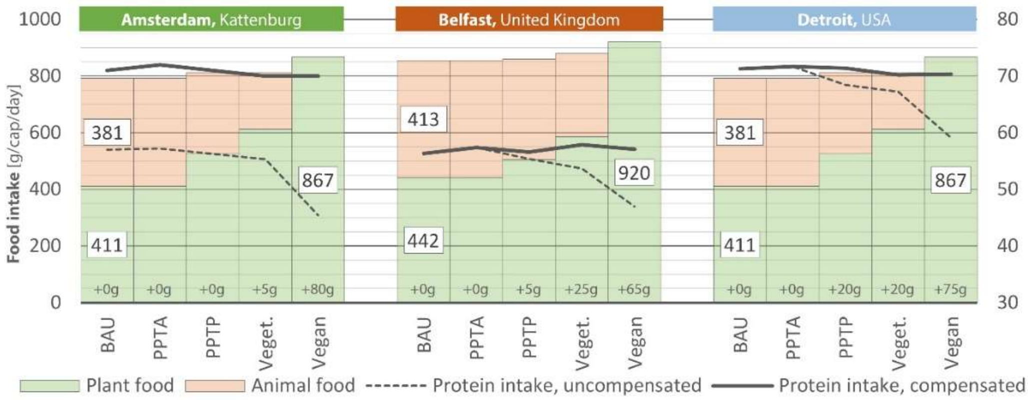

Figure 4.6. *Change of food intake throughout the five diets, subdivided in animal and plant-based products [left vertical axis, gram/cap/day]. The dashed line shows daily protein intake [right vertical axis, g/cap/day] when protein deficiency would not be compensated with surplus food. The values right above the horizontal axis show the surplus food intake relative to the BAU situation. Due to roundups/decimals, the compensated protein intake line is not fully straight.*

4.3.3. Interpretation

A dietary transition from a conventional diet to a full-vegan diet has a different impact on a community's FEWprint in each of the three cities. With regards to the food sector emissions only, the differences in outcome between cities can be ascribed to the effect of combining two key variables: the community-specific food intake (PCC_{ctx}) and the country-specific (LCA based) global warming potential of food groups ($ef(n)$). With regard to the total FEWprint, inter-city differences are also caused by the -often more dominating- role of the other resource sectors.

When simulating a pesce-pollotarian diet (removes red meat), a considerable drop in emissions is observed for Belfast and Detroit, whereas in Amsterdam, the drop is less significant during this diet shift. This can be explained by the considerable differences in initial red meat intake of the communities (AMS: 26.2 g, BEL: 57.0 g & DET: 91.9 g) and the higher carbon emission factors applied to red meat in Belfast, see Table 4.2. A similar observation can be made when a fully vegan diet is simulated and eggs and dairy are removed, resulting in the largest emission drop in Amsterdam. Consuming additional plant-based food to secure protein intake equilibrium has a counteractive effect on the carbon emissions drop caused by the initial diet shift. These surplus emissions are however in a lower order of magnitude than the avoided emissions associated with the diet shift.

4.4 Discussion

4.4.1. Robustness of Outcomes

In order to obtain accurate output figures, resource consumption data should be collected/measured at the lowest possible data aggregation scale. Data collected at higher scales will increasingly lose its relatedness with the considered community. Protein content should be based on the actual food commodities that are consumed by the community. Finally, environmental footprint indicators should be based on, (a) Life Cycle Inventory assessments and (b) the actual resources/products/services used or consumed in the considered urban context. However, situational consumption data may not always be readily available, and producing this relevant context-based data is resource-intensive. As the platform is intended to support non-experts during urban design concept explorations –for which highly accurate output is not essential– certain simplifications are permitted to grasp the situation. Naturally, this leads to compromises surrounding the robustness of the output.

This study makes use of Life Cycle Inventory based GHG emissions factors for food that have been retrieved from peer-reviewed literature (Belfast and Detroit) or independent consultants (Amsterdam). It is likely that outcomes will be different when different carbon footprint databases are addressed, when different values are assumed for the protein content of food categories or when a more comprehensive food scope is used. In previous research, it was revealed that between developed cities, consumption data is often collected/measured at very different scales (N. ten Caat et al., 2022). We recommend platform users to search, study and insert contextual data when available, before resorting to data collected at, for example, the national level.

4.4.2. FEWprint Application Potential

The parametric FEWprint *diet shift* component demonstrated in this study is part of a three-pronged urban food production assessment strategy. The component can be used to generate an estimation of the role of food consumption to the total FEWprint of a community and how the food sector emissions compare to the other sectors. This insight gives a preliminary idea on which resource sector to emphasise when exploring an urban redesign strategy or any other city decarbonisation effort. The rigorous and rather optimistic diet transition scenarios applied here remain particularly hypothetical. However, the impact assessment of such community-wide behavioural changes could instil inspiration and incentivise a movement to further explore opportunities for urban farming design, which could be of great value in the process of future urban design.

From a techno-spatial perspective, a diet shift could increase the potential of urban food production in terms of self-sufficiency. This is especially relevant when a UFP strategy is designed as part of a long-term strategy that takes into account projected or speculative developments surrounding (local) food culture. The agricultural output of an urban food system could be expressed in protein availability per community member and the extent of meeting the lower threshold level for an average person (0.83 g/kg body weight) can be articulated as a self-sufficiency fraction. Considering the high space demand for animal husbandry resulting from grazing and feedstock production, maximising self-sufficiency in space-constrained (peri-) urban contexts could be more feasible if the community demand for plant-based protein is increased at the exchange of animal protein. This is however a context-dependent challenge as each urban environment offers a unique canvas for a food production design. Hybrid plant-animal protein solutions are likely more feasible in terms of protein provision and more space-efficient when resource loops are closed, for example by applying high-density livestock with higher food conversion ratios (poultry, fish, eggs) or using neo-food products like insect protein.

The FEWprint platform embeds evaluation, diet shift, and UFP design into an iterative process. The *diet shift* component is linked with the *design* component of the platform and it can be granted a *determinative* or a *responsive* role. In a *determinative* role, it can translate the community's food demand into concrete targets for agricultural output, according to which a system should be composed and designed. In a *responsive* role, a new diet can be configured around the agricultural capacity of a UFP strategy and translated into a daily food intake, i.e., a per capita daily availability of local production.

4.4.3. Limitations

Several limitations arose during the research and development of the platform. Most limitations revolve around data availability and food composition data.

4.4.3.1. Protein Content

The macronutrient content between similar food products can vary significantly because of climate, geography, agricultural practises, crops genetics, or processing influences during the food production and preparation stages (Burlingame, Charrondiere, & Mouille, 2009). In addition, food consumption patterns lead to country-specific foods, recipe compositions, and food brands. For a representative output, each diet simulation and UFP strategy should be conducted with local data that has been collected and processed according to international standards for comparability (INFOODS, 2021). However, research for this study revealed discrepancies between countries when comparing protein content for individual food items and aggregated values used for food groups (Table A5 and figure A2).

In line with the user-friendliness aim of the platform, this study uses datasets that are publicly available. The Dutch online dataset consists of 2152 food items and nutritional values that are derived from chemical analysis in accredited laboratories. Before values are recorded, a quality check is conducted surrounding the description of the food item, sampling procedure, and method of analysis (RIVM, 2019). The Belfast dataset is provided by the British Nutrition Foundation and consists of pre-aggregated protein indicators for food groups (British Nutrition Foundation, 2012). No further information is provided on the origin of the data nor the sub-products contained within the values. The Detroit values are provided by the US Food and Nutrition Information Centre (USDA, 2018). Despite providing an elaborate list of well-described food items, values are expressed in household units (e.g., cups, slice, serving) making it difficult to determine reliable protein content values. Only meat items are consistently expressed in ounces (~28.4 g) and are therefore submitted to Table 4A1. The FAO provides an extensive dataset of *as purchased* protein values and claims to be suitable for international use, however, no further information is provided about the data's origins (FAO, 2001).

The protein content of food categories determines the composition of the new diet. Variation of protein factors between cases would influence the way a new diet is formed during the transition and subsequently affect the emissions associated with that resulting diet. In order not to include a third variable in the equation and decrease the comparability between case studies, this study applies the universal FAO food balance sheets to all three cases, despite the sometimes considerable differences with the national values for certain food categories. A graphical and tabulated overview of the protein data is provided in Appendix 5B.

4.4.3.2. Food Scope and Aggregating Indicators

The FEWprint uses 18 food categories to frame UFP design and assessment. To secure inter-component integration, the platform's food scope is limited to unprocessed and minimally processed food products, while drinks, with the exception of milk products, have been excluded (N. ten Caat et al., 2022). Therefore, the range of food products provided by the datasets has to be transformed and aggregated (or disaggregated) into a single representative indicator per category. This process of data clustering applies to all three key factors (food intake, carbon impact, and protein content) as none of the source's scopes aligns seamlessly with this study's food scope. In addition, the three factors are provided by different institutions that do not align on their scopes and/or nomenclature among each other, thus compromising the comparability between the case studies. Combined with the aforementioned uncertainties around the institution's data collection methods, the accuracy of the output in this study comes with a degree of uncertainty, affecting the comparability.

4.4.3.3. Animal vs. Plant Products: Mutually Substitutable?

In chapter 4.2.1 it was mentioned that for a meaningful and accurate assessment, the protein quality of a plant-based diet should be considered at the amino acid level (AA). The quality of food-borne protein depends on the digestibility of the protein and the composition and bioavailability of essential amino acids in the food (WHO, 2007). To account for protein quality at the product or diet level, the *Digestable Indispensible Amino Acid Score* (DIAAS) factor was developed, a successor to the PDCAAS indicator (FAO, 2013). This index considers amino acids as individual nutrients and applies a more accurate measuring method. The nutritional quality score of protein, a food product, or a dish is dictated by considering the least digestible amino acid within that item. An extensive catalogue of DIAAS values for various human food products is still unavailable, but first publications show that the DIAAS factors of animal-based products (groups) are superior to their plant-based siblings (Ertl, Knaus, & Zollitsch, 2016; Phillips, 2017). This insinuates that animal and plant products are not mutually substitutable merely on the basis of protein quantity and suggests that, after compensating for the total protein content at the product level, also the quality difference at the protein level should be accounted for.

Plant proteins are often limited by the lack of one or two key amino acids, leading to a reduced DIAAS index (Bohrer, 2017). Cataloguing the digestible indispensable amino acid contents of food groups and/or individual products can inform the combination and ratio of plant-based food mixtures, where one product compensates for the AA deficits of the other on the plate. Herreman demonstrates this for a rice-peas mixed dish, where rice, as a sole-source would have a DIAAS of 47 due to the poorly available amino acid *Lysine,* and peas have a DIAAS of 70 (limiting AA = *methionine* and *cysteine*). A rice-peas mix, however, in which rice constitutes 41% of the protein content, would lead to a DIAAS score of 84 (Herreman, Nommensen, Pennings, & Laus, 2020). Achieving a >100 DIAAS score for daily food intake, and subsequently, the community diet, could be achieved by a strategic combination of plant-based protein and minimal amounts of animal protein to close the gap, ideally with lower impact products like chicken and eggs.

Without the strategic combination method as described before, integrating the DIAAS quality correction factor to secure protein intake equilibrium could lead to an unreasonable surplus intake of plant-based food to compensate for the least digestible amino acid. This subsequently puts an unnecessary high demand on the food system, especially in developed countries with an already varied diet. The authors acknowledge the reduced bioavailability of essential amino acids and the added value of working with DIAAS. However, we decided not to adjust for this gap in this research as it would overcomplicate this assessment with regard to its purpose, it would complicate the platform, and it would further increase the uncertainty of outcomes due to the current unavailability of suitable data.

To summarise, this study only adjusts for the lower protein content of crops at the product/group level to keep the platform comprehensible. We assume an adequate and heterogeneous intake of amino acids is achieved by adhering to the general recommendation to focus on variety within the new diet and replace animal protein with four plant-based categories (legumes, grains, nuts and seeds, soy products) in an equal proportion during the various simulations.

4.4.3.4. Radical Diet Scenarios

A near-future and community-wide abandonment of animal products for the purpose of decarbonisation is a rigorous and unrealistic scenario and therefore remains theoretical. National survey data reveals that the prevalence of the vegetarian-vegan population, in its purest sense, is still very low: for example respectively ±5% and ±0.4% in the Netherlands (CBS, 2021) and 5% and 3% in the USA (Reinhart, 2018). Food consumption is deeply rooted in cultural behaviour or identity, people have been omnivorous for many generations and arbitrary impositions of dietary change on a community are unlikely to yield the intended desirable shift as food consumption remains a personal choice (de Boer & Aiking, 2021). This study discusses the carbon reduction potential of changing a diet and does not consider the complex reality of bringing about such socio-cultural interventions, which goes beyond the technocratic nature of this research alone.

The arbitrary diet scenarios used in this study are culturally independent, non-geographical, and can be projected to any diet that is consumed in a locality. The assessed alternative scenarios are therefore also not based on context-based opportunities or agricultural potential but rather function as qualitative labels that are attachable to any conventional diet. The change to a more plant-based diet, as is simulated in this study, is usually a personal choice driven by intrinsic and external motivations; therefore, the community’s engagement is very important. Consumer behaviour towards food consumption depends on a broad range of factors, and some simulated changes might not be considered reasonable or realistic within a community, possibly neglecting cultural acceptability (Perignon et al., 2016). Sustainable diet alternatives that are composed according to cultural aspects and local food management opportunities are likely more realistic and therefore more interesting to assess. The platform offers the framework for evaluating such diets, as long as the dietary recommendations can be translated into the 18 food groups used in the platform. In addition, two free slots are provided to insert food categories that are relevant to the considered context but that do not fit the 18 default categories.

4.4.4. Outlook

4.4.4.1. Data

In this study, we perform a comparative analysis between three urban communities. Comparative analysis requires harmonisation between sources on data gathering by measuring standardisations, scale level of data aggregation, scope alignment, coherence regarding units, and similarity in taxonomy. Life Cycle Inventory Analysis provides the framework to overcome the aforementioned challenges and is increasingly used to quantify the environmental impact of products and services. However, more work is required to integrate the LCI method in public datasets and –equally important– commutate the underlying calculation methods to the user. At last, we want to emphasise the importance of using independent and scientifically validated sources when assessing food.

4.4.4.2. Further Research

The parametric platform was developed based on the principles of the FEW nexus and informs the user during the conceptual and exploratory phase of UFP design. The diet shift component is demonstrated in this work and provides rapid feedback on the implications of a diet shift on the sectoral and total emissions of a community and calculates the food intake changes based on user-defined settings. The three components are interlinked with each other and are not completed in a linear fashion but rather facilitate an iterative process of design and evaluation that leads to a numerically supported UFP strategy (Figure 4.7). The *design* component of the platform will be discussed in future dissemination.

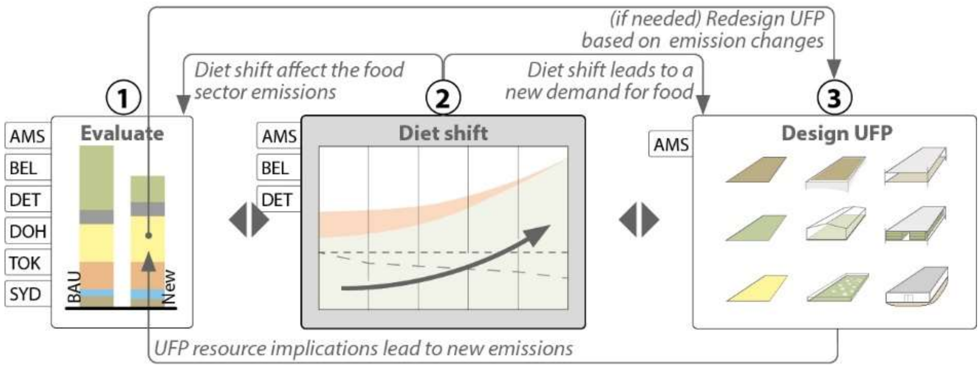

Figure 4.7. *The FEWprint platform is composed of 3 components that correspond with the 3 key purposes of the FEWprint platform. The labels indicate the considered case study cities.*

4.5 Conclusions

In industrialised nations, the consumption of food often constitutes a significant part of a community's total carbon emissions footprint. Animal-sourced food products are usually responsible for the largest share of the food sector emissions. Urban food production (UFP) is a strategy that could mitigate the carbon emissions from the producers' side; however, adequate design and assessment platforms for urban designers are lacking. A community-wide shift towards a plant-based diet is an effective way to reduce emissions from the consumers' side. When (re)designing neighbourhoods with the intention of food self-sufficiency and low-carbon impact, the combined application of both strategies is worth exploring. This article introduces and demonstrates the *diet shift* component of the FEWprint platform to simulate and assess, at the community level, the carbon emissions and food intake implications of a rigorous transition to a fully vegan diet, whilst maintaining protein intake equilibrium. As part of a larger UFP approach strategy, the FEWprint can be deployed to rapidly generate preliminary estimations on the carbon mitigation potential of dietary alterations. Three urban communities in the cities of Amsterdam, Belfast, and Detroit were studied, where consumption of a selection of 18 staple food groups currently emits respectively 993, 1270, and 1152 kg/capita/year, or 30%, 37%, and 9% of the total emissions. A dietary shift to a vegan diet would mitigate the emissions with 25% in Belfast (−866 kg CO_2eq), 15% in Amsterdam (−511 kg CO_2eq), and 7% in Detroit (−916 kg CO_2eq). The protein intake deficit that emerges during transition can be adjusted for with an estimated surplus consumption of +80 (AMS), +65 (BEL), and +90 g (DET) of various high-protein plant-based food categories. Future disseminations will demonstrate the design component of the platform and how UFP can further mitigate the food sector emissions.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1. Document 1: FEWprint platform_20-01-22_v9.0 - template; Document 2: FEWprint platform_20-01-22_v9.0_Example BAU assessment; Document 3: FEWprint platform_20-01-22_v9.0_Example BAU assessment + Diet shift; Document 4: FEWprint platform_20-01-22_v9.0_Example BAU assessment + Diet shift + UFP Design.

Author Contributions:

Conceptualization, P.N.t.C, A.v.d.D.; methodology, P.N.t.C., M.T., A.v.d.D..; software, P.N.t.C..; investigation, P.N.t.C.; data curation, P.N.t.C,M.T.; writing—original draft preparation, P.N.t.C..; writing—review and editing, P.N.t.C, M.T., A.v.d.D..; visualization, P.N.t.C..; supervision, M.T., A.v.d.D..; project administration, P.N.t.C..; funding acquisition, A.v.d.D.. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Study did not require ethical approval

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PART III

Design & Implementation

5

Towards fossil free cities

A Supermarket, Greenhouse & Dwelling Integrated Energy System as an Alternative to District Heating: Amsterdam Case study

It is inadequate to evaluate the impact of urban farming without taking into consideration the agricultural output of the farming system and how this material flow affects the carbon balance of a community. Similarly, there can be no holistically considered urban food system design without an integrated carbon assessment method. Chapters 2 and 3 presented a carbon assessment method that is mutually suitable to capture the urban resource demand as well as the metabolism of food producing systems. Within the manuscript, chapter 5 functions as a pathfinder towards an UFP design strategy that is suitable to be added to the FEWprint platform.

In this second scaffolding chapter, the decarbonisation potential of urban food production is once more explored by means of a hypothetical and explorative research. A small-scale greenhouse structure with artificial lighting is added on top of a residential building in the inner-city of Amsterdam to occupy the double-function of a solar collector and a food producer. A balanced synergy between this greenhouse, the adjacent dwellings and a supermarket is simulated, and the carbon performance of this system is estimated based on accurate hour-based climate variables and various greenhouse operation settings. This chapter demonstrates the added value of (high tech) local food production when such systems are considered as an assimilated element within the urban metabolism and not as a parasitic entity. The decarbonisation potential is achieved by drawing a comparison with a non-synergistic solution that is currently preferred by policy makers: district heating.

This chapter provides a detailed explanation of all the system-components (5.2.1), the calculation of the energy balances of the components (5.2.3) and the translation into energy profiles (5.2.4), the interconnectivity between the components and the system configuration to achieve system balance is discussed in 5.2.6. The environmental impact of all the scenarios (BAU, energy synergy and district heating) are calculated in the results section. Section 5.3.4 demonstrates that various ways of greenhouse operation lead to different electrical energy demand and thermal energy and crop yields, which has consequences on the performance of the total system. A scenario analysis for the design proposition made in the conclusion chapter.

5

Towards fossil free cities

A Supermarket, Greenhouse & Dwelling Integrated Energy System as an Alternative to District Heating: Amsterdam Case study

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Aside from layout changes and minor textual differences, the content of paper has not been amended for uptake in this dissertation.

5. Towards Fossil Free Cities—A Supermarket, Greenhouse & Dwelling Integrated Energy System as an Alternative to District Heating: Amsterdam Case Study

Abstract

The municipality of Amsterdam has set stringent carbon emission reduction targets: 55% by 2030 and 95% by 2050 for the entire metropolitan area. One of the key strategies to achieve these goals entails a disconnection of all households from the natural gas supply by 2040 and connecting them to the existing city-wide heat grid. This paper aims to demonstrate the value of considering local energy potentials at the city block level by exploring the potential of a rooftop greenhouse solar collector as a renewable alternative to centralized district heating. An existing supermarket and an ATES component complete this local energy synergy. The thermal energy balance of the three urban functions were determined and integrated into hourly energy profiles to locate and quantify the simultaneous and mismatched discrepancies between energy excess and demand. The excess thermal energy extracted from one 850 m^2 greenhouse can sustain up to 47 dwellings, provided it is kept under specific interior climate set points. Carbon accounting was applied to evaluate the system performance of the business-as-usual situation, the district heating option and the local system. The avoided emissions due to the substitution of natural gas by solar thermal energy do not outweigh the additional emissions consequential to the fossil-based electricity consumption of the greenhouse's crop growing lights, but when the daily photoperiod is reduced from 16 hour to 12 hour, the system performs equally to the business-as-usual situation. Deactivating growth lighting completely does make this local energy solution carbon competitive with district heating. This study points out that rooftop greenhouses applied as solar collectors can be a suitable alternative energy solution to conventional district heating, but the absence of growing lights will lead to diminished agricultural yields.

Keywords

urban farming, FEW nexus, carbon accounting, CO2 emissions, synergetic design, energy transition, solar energy, sustainable city, Amsterdam

5.1 Introduction

Anthropogenic climate change and gradual depletion of fossil fuels necessitate a transition to sustainable energy systems in cities (IPCC, 2018a). Climate change imposes threats to the health and wellbeing of urban dwellers in the form of heavier or longer lasting weather extremes like pluvial flooding, long periods of draughts and heat stress due to an intensifying urban heat island effect (Albers et al., 2015). The challenge urban designers and policy makers are confronted with now and in the coming decades is no longer to stop or reverse this change, but to prevent an excessive temperature increase and adapt to the climate changes that have been set in motion already since the industrial revolution (UNFCCC, 2015b). Cities in the Netherlands are responsible for 13% (24.4 Mton out of 189.3 Mton) of the total national CO_2e emissions due to the demand for thermal energy resources, primarily natural gas (IPCC, 2019). Here awaits a significant potential for improvement.

The Dutch government has committed to the global UNFCCC (United Nations Framework Convention on Climate Change) Paris 2015 climate agreement and has set the challenging nation-wide target of a 49% reduction of greenhouse gas emissions by 2030 and 95% by 2050, relative to 1990 levels (UNFCCC, 2015b). On a more local level, the municipality of Amsterdam has set more stringent CO_2 reduction targets for itself: 55% by 2030 (−3200 kton) and again 95% by 2050 for the entire Amsterdam metropolitan area. One of the strategies to achieve these goals entails a disconnection of all households and commercial buildings from the natural gas supply grid by 2040, which should lead to an annual carbon emission reduction of 370 kton CO_2 (Gemeente Amsterdam, 2019b). Amsterdam policy makers propose to achieve this disconnection by (1) transitioning to all-electric systems (e.g., heat pumps), (2) scaling up biogas production as a direct substitution of natural gas and (3) expanding the existing city heat grid, both by adding more thermal sources from industry or biomass incineration on the supply side as well as connecting more neighbourhoods on the receiver side (Gemeente Amsterdam, 2016).

The achievement levels of a sustainable city can be incremented based on their level of organizational, technical and design complexity, and the pathways to move forward throughout these levels are complex to outline (Siebe Broersma & Fremouw, 2015). Amsterdam—and other cities—aim to move towards a nearly fossil free built environment by 2050, which implies a detachment from current fossil-based energy resources and a near-complete transition to renewable energy. Fossil freedom goes beyond the level of energy neutrality, which persuades annual net zero-energy by means of energy demand reduction and renewable production. This is on its turn is more ambitious than carbon neutrality, that allows for CO_2 compensation or carbon capture & storage methods to offset the city's emissions (Dobbelsteen et al., 2018). In order to become climate neutral, energy neutral or fossil free, cities are compelled to undergo an energy transition towards renewable energy sources (Solomon & Krishna, 2011).

A dense and heterogeneous inner-urban environment produces a high demand for energy while at the same time this context cannot provide the necessary space to generate this energy on site by means of conventional methods—for example, by means of solar photovoltaic (PV) or wind energy. Designing a city that produces sufficient renewable thermal and/or electrical energy within its own physical footprint in order to achieve full fossil freedom is a challenging task for urban engineers and designers (Dobbelsteen et al., 2014). A comprehensive pathway towards making the neighbourhood of Gruž (Dubrovnik) energetically self-sufficient was described and calculated by Dobbelsteen et al., yet it includes rather drastic urban interventions and theoretical changes that it serves a more inspirational purpose for policy makers than an actionable plan (Dobbelsteen et al., 2018) One energy master planning method that frames this urban challenge is the New Stepped Strategy (NSS) (Dobbelsteen, 2008), the successor to and an upgrade of the Trias Energetica, introduced by Lysen in 1996 (Lysen, 1996), which on its turn builds upon the three staged approach by Duijvestein (Duijvestein, 1989). The NSS proposes three steps for sustainable urban (re)design with fossil freedom as the intended ambition level: (1) reduce the demand, (2) reuse waste energy and (3) increase renewable production. Based on the NSS, Tillie et al. (Tillie, Dobbelsteen, Doepel, Jager, et al., 2009) developed the Rotterdam Energy Approach & Planning method (REAP), in which a cross-scalar approach is proposed that considers opportunities for energy exchange, storage and cascading across various scales of urban design. The aim is that simultaneous discrepancies between supply and demand can be united by synergistic systems, direct heat exchange and cascading and intermediate storage of energy (Dobbelsteen et al., 2014). In addition to initial end-user demand reduction, thermal energy exchange between components increases the exergy efficiency of already invested resources and mitigates the demand for renewable energy further (Stremke, Dobbelsteen, & Koh, 2011). Integrated urban (re)design in which various urban functions are energetically interlinked, increases the likelihood of achieving energy neutrality or even fossil freedom without having to import thermal energy across the site boundaries, as is the case with city heat grids that expand across cities.

The aim of this explorative study is to move cities away from fossil-based energy sources and decentralization energy management by means of local synergistic systems as one way to support the energy transition. This study investigates the potential of a rooftop greenhouse for heat provision and its capacity to enable a transition to renewable solar thermal energy at the building level, intending to avoid the import of external thermal energy or energy carriers. The archetypical glass greenhouse can double as solar collector since large quantities of thermal energy have to be removed from it to maintain a suitable indoor climate for crop production. This method is already applied in practice at a larger scale in peri-urban areas, but not yet on a building level in the urban setting.

By means of a case study demonstration and a scenario comparison, this study intends to inspire policy makers and urban designers into structurally considering local thermal energy production, exchange and storage during the design of the future city. The total carbon equivalent emissions (CO_2e) forms the key performance indicator and is assessed for three energy scenarios for an inner-urban case in Amsterdam. The scenarios are: (1) business as usual (BAU), (2) a synergetic thermal energy system and (3) the city district heating method. Scenario 1 assesses the CO_2e footprint of the present dwellings and an adjacent supermarket, which are currently powered by non-renewable electricity and heated with natural gas. In scenario 2, a synergetic energy system is designed, into which the existing supermarket, the new greenhouse and the adjacent residential buildings are plugged. The gas supply is substituted by solar thermal energy extracted from a greenhouse building. At the same time, the new greenhouse adds an additional electricity demand (e.g., for artificial crop lighting) to the system that should be carbon accounted for. In scenario 3, the gas demand of the dwellings is fully substituted with thermal energy provided by the central city heat grid.

Holistic carbon accounting of the three scenarios reveals to what extent the local greenhouse collector solution can be carbon competitive with the city heat grid. In the calculations of scenario 2, a high level of accuracy regarding facade properties, climate influences and other relevant parameters is maintained. However, the calculations will not course into installation/utilities and systems level as this study provides insights in the order of magnitude of the method and the associated environmental impact.

Capturing an energy cascading strategy into a generic policy or method comes with its challenges. For increasing urban spatial scales, the possibility and effectiveness of an energy cascading and storage strategy depends principally on local urban properties, as thermal energy is not efficiently transported over long distances (Gommans, 2012). Synergetic designs are custom for each unique environment and cannot directly be projected onto other urban environments without contextualization and reassessment. This study demonstrates an integrated design approach on a relatively small city block to come up with a tailored energy synergy and calculates its impact regarding carbon emissions. The underlying idea is that this approach can be repeated for many city blocks in Amsterdam, each time resulting in a different system scale and configuration with varying effects. The intended and persuaded ideology is that numerous smaller interventions combined can lead to a robust system and have a significant positive impact.

5.2 Materials & Methods

The integrated greenhouse-supermarket-dwelling energy system of scenario 2 is designed and configured through a sequence of steps. Section 5.2.1 describes the urban scope and Section 5.2.2 details the performance indicator. In Section 5.2.3, the greenhouse and the supermarket energy balances are introduced and briefly discussed. The various energy flux equations, parameters, climate data, structural properties and other factors are further described in Appendix 5. Equations and data are added to a Microsoft Excel calculation model that is set up for the purpose of this study. In Section 5.2.4, hourly energy balances are combined into visually representative energy profiles, which can then be used to locate and quantify energy deficits and excesses. In Section 5.2.5, the design and integration of the local system is elaborated and storage + transport losses are embedded in the model. The addition of a greenhouse introduces additional demands to the electricity net, which are also described in this section. Finally in Section 5.2.6, the system as a whole is balanced by adjusting the system scale and greenhouse climate parameters.

5.2.1. Scope: Urban Components

In this study, local implies the scale of the city block, demarcated by circumjacent streets. The examined case is a block in the center of Amsterdam: the Helmersbuurt-Oost neighborhood, Figure 5.1. For this research, system boundaries are similar to the physical street boundaries. This residential city block is part of an early 20th century city expansion plan and consists predominantly of 4–6 story buildings with mixed commercial-residential functions at the street level. Table 5.1 gives an overview of the identified buildings in this block that are potentially suitable to act as a component in the new energy system.

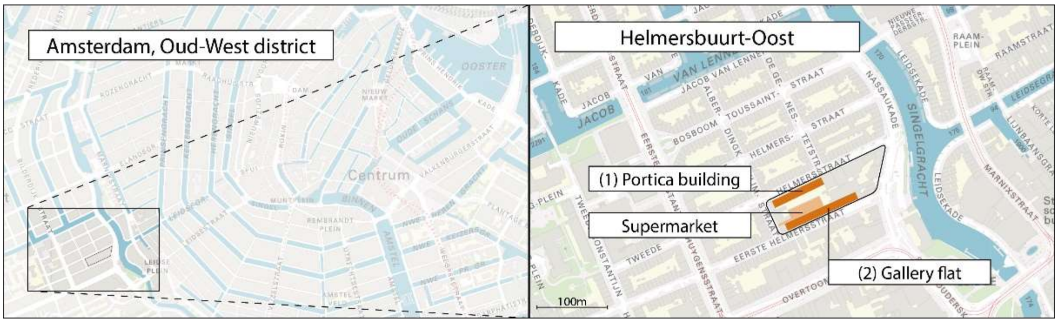

Figure 5.1. *Location of the case study in Amsterdam.*

Table 5.1. Identified components within the system boundaries that are considered suitable for the new energy system. Each component is discussed separately in section 5.2.1.

Dwellings (Section 2.1.3.)	Supermarket (Section 2.1.2.)	Rooftop Greenhouse (Section 2.1.1.)
(1) Tenement building (1926), 5 floors 47 hous-holds [1] Current average energy label: E or D (range G–D) [3] (energy label varies per cluster) (2) Gallery building (1965), 6 floors 68 households [1] Current average energy label: C (range D–B) [3]	Lidl Helmersbuurt (constructed in 2007) Located at the ground floor of the city block Internal dimensions: 15.4 m × 46.0 m × 2.9 m $(l \times w \times h)$ Sales floor area: 715 m^2	Conventional closed greenhouse(s). Located at the rooftop of the residential buildings. Max. dimensions [2] (length x width) Greenhouse 1: Rooftop tenement building: 10.8 × 78.8 = 851 m^2 Greenhouse 2: Rooftop gallery building: 8.0 × 107.0 = 856 m^2

[1] Number of households from Gemeente Amsterdam (Gemeente Amsterdam, 2019a);

[2] Rooftop dimensions are measured with Google Earth satellite imagery;

[3] Current energy labels are retrieved from interactive map by RIVM—Nationale Energie Atlas (RIVM, n.d.).

5.2.1.1. Greenhouse

In scenario 2, a rooftop greenhouse is added to this city block and plugged into the local energy system. Since this study is exploratory in the field of urban energy management, certain factors that would be constraining in practice are not considered or assumed possible. This means building regulations or municipal zoning plans are ignored, investment or maintenance costs are not considered and the existing substructure is assumed suitable to support the urban farms. In this particular city block, the rooftop greenhouse could only be placed directly on top of the residential buildings since the ground-level supermarket building, located in the courtyard, would be shaded most of the time by said buildings. This lack of direct sunlight is confirmed by the solar atlas tool by the Amsterdam municipality (Gemeente Amsterdam, 2019c).

In respect to the energy system, the key purpose of the added rooftop greenhouse is to act as a solar collector in summer and collect sufficient thermal energy to, primarily heat itself during the winter months and secondarily, to provide a high-temperature energy source for the heat pump of the dwellings. The dimensions of the greenhouse footprint are constrained by the outer dimensions of the residential substructures, as such the maximum possible greenhouse floor area can be 78.8 m × 10.8 m (851 m^2 in total) on top of the tenement building (building 1, Figure 5.1) or 107 m × 7.8 m (835 m^2) on top of the gallery building (building 2, Figure 5.1). An overview of the shape and main structural dimensions and facade properties of the greenhouse can be found in Appendix 5A. The greenhouse is imagined as an archetypical glass structure on a concrete floor and the rooftop is designed under an inclination to allow for water runoff. The greenhouse is modelled as a single rectangular crop production volume, hence any crop processing and packaging stations, storage rooms or other supportive spaces are not taken into account.

5.2.1.2. Supermarket Building

The supermarket (exploited by Lidl Nederland, Huizen, the Netherlands) is located at the ground level of this city block, partly enveloped by the surrounding dwellings. Only the sales floor, by far the largest space inside the supermarket building, is taken into account for the calculation of the energy profile. The interior dimensions of this space measure 15.4 m × 46.0 m × 2.9 m (*w* x *l* x *h*). The electricity consumption of this supermarket was 256 MWh in 2015 and 258 MWh in 2016; for the calculations in this study we apply the average of the two (personal communication, 2017).

5.2.1.3. Dwelling

Two buildings are located within the demarcated system boundaries that are considered suitable to be included in the local energy network. The first building is a 1926 tenement complex (1), composed of a concatenation of 6 clusters made up of 8 dwellings. One ground level dwelling is missing to make space for a passage to the inner courtyard, leaving 47 households in total. The second building is a gallery building completed in 1965, with a total number of 68 apartments (2). Both buildings provide a large, rectangular shaped and flat rooftop surface (assumed) suitable for a rooftop glass structure and both buildings have been designed with a certain degree of constructive and architectural repetition, making any structural refurbishments more likely.

5.2.2. Performance Indicator

All three scenarios are assessed on their carbon equivalent emissions (CO_2e) consequential to the demand for final electrical and thermal energy resources, see Table 5.2. In scenario 2, the heating and cooling systems of the dwelling, supermarket and greenhouse are synthesized and electrified, which puts additional demands on the national electricity grid. The underlying aim in the design of scenario 2 is to satisfy energy demands with onsite renewable energy production. This study focuses on solar thermal energy as an alternative to gas or district heating, consequently meaning that electricity must still be imported from across the system borders, for which standard Dutch grid mix electricity is used.

Table 5.2. Inventory of greenhouse gas emissions of relevance to this study.

Energy	Product/Activity	Carbon Footprint	Unit	Note (Source)
Electric	Dutch national grid mix electricity	0.526	kg CO_2e/kWh	Country specific value (chain emissions and network losses included) [21]
Thermal	Natural gas (dry)	1.788 56.6	kg CO_2e/m^3 kg/GJ$_{th}$	Country specific value, 2018 value used (annually updated) [22]
Thermal	District heating, CCGT [1] source	36.0	kg CO_2e/GJ	(CE Delft, 2016) See Section 5.3.3 (power plant)
Thermal	District heating, AVI [2] source	26.5	kg CO_2e/GJ	(CE Delft, 2016) See Section 5.3.3 (waste incineration)

[1] CCGT = Combined Cycle Gas Turbine (power plant);

[2] AVI = Afval Verbrandings Installatie (translation: waste incineration plant).

This paper evaluates the environmental impact of the built environment by assessing the footprint of CO_2e, corresponding to the three main greenhouse gasses released into the atmosphere, multiplied by their 100-year global warming potential (GWP), i.e., carbon dioxide (CO_2, GWP = 1), methane (CH_4, GWP = 28) and nitrous oxide (N_2O, GWP = 265). The GWP indicates the potential greenhouse effect of an emitted gas relative to an equivalent mass of carbon dioxide, measured over a period of 100 years after its release into the atmosphere (World Resources Institute, 2014).

5.2.3. Energy Balances

Steady-state thermal energy balance equations are solved for the greenhouse and the supermarket for every hour during a period of one year, resulting in 8760 energy fluxes (Heating/Cooling, H/C) that are aggregated into an energy profile for further evaluation and design (section 5.4). Accordingly, the measured energy demand of the dwelling is converted into an hourly demand to align with the other components; see section 5.3.2. This hourly approach allows us to generate a detailed representation of the components' energy profiles, as for every hour the external climatological factors can be applied. In addition, heat loads that are periodical can be accurately (de)activated according to their time schedules, and diurnal patterns of heating or cooling demand can be precisely calculated instead of relying on assumptions or correction factors. Hourly measurements of the ambient air temperature (T_e), solar heat load (I_{sun}), wind velocity (v_{wind}) and relative humidity (RH) are based on NEN5060 climate reference data (NEN, 2018). An extensive Microsoft Excel worksheet is employed to calculate energy balances, to generate energy profiles for the three buildings and to adapt various parameters in order to establish a thermal energy equilibrium within the system as a whole.

5.2.3.1. Energy Balances: Supermarket

Many supermarket buildings in the Netherlands have a continuous heat surplus due to the cooling loads coming from both product display coolers, as well as sales-floor cooling. Recently built supermarkets come with an integrated system, where the back side excess heat from the cooled displays is directly removed from the sales floor and exhausted into the atmosphere, occasionally reusing (a part of) it for heating purposes. The supermarket in this study does not have this modern system and works with individually operating cooling units, where excess heat is exhausted into the space. Nowadays, supermarkets are expected to install glass doors to cover the cooled product displays in order to contain the cold. A direct consequence of this is the necessity to mechanically cool the sales floor to prevent unwanted condensation on the cold surface of the glass doors. Energy balance equation 1 is used to calculate the cooling demand of the supermarket. The equation only describes the thermal balance of the sales floor and does not take into account the rejected energy generated by the product cooling units. For the calculations in section 5.2.5 this study is assuming that the exhaust air coming from the climate control system pivots around 35 °C throughout the whole year.

$$Q_{int}(t) + Q_{inf}(t) + Q_{vent}(t) + Q_{trans}(t) + Q_{cool}(t) = 0 \quad [1]$$

The various components of the supermarket energy balance equation and the applied parameters are further specified and explained in Nomenclature section and Appendix 5A.

5.2.3.2. Energy Demand: Dwellings

The thermal energy demand from the tenement building (building 1 in figure 5.1) and the gallery flat (building 2 in figure 5.1) are not manually calculated with energy balance equations. Instead, they are retrieved from publicly available datasets provided by the regional energy network manager Liander (Liander, 2019). Liander gathers and publishes the annual gas and electricity demand of all addresses connected to its network (in an anonymized form). Annual gas consumptions are converted into an hourly representation so they can be compared with the energy profiles of the supermarket and the greenhouse. For this we use the caloric value of Dutch natural gas of 35.17 MJ/m^3 (Zijlema, 2018). In addition to the total energy demand, Liander also published a predictive dataset of hourly fractions of the annual gas and electricity use, based on secondary data from +10.000 customers and normalized for the average temperature profile of the past 20 years, Figure 5.2 (Liander, 2014). Gas used for cooking purposes is not addressed separately in this study as it represents a negligible amount (3.9%) relative to the total gas consumption (Majcen et al., 2013).

Figure 5.2 *For exemplary purposes: 24 h gas demand curve for an average household in NL, based on Liander data. The % represents the demand for that hour relative to the daily total. Two peaks are evident for each of the four curves: a morning peak when people wake up, turn on the heat-ing and have a shower and an afternoon peak, when people tend to cook dinner (on gas stoves) and switch on the heating (again).*

In both scenario 2 (local energy system) and 3 (district heating system), all the apartments are assumed to have undergone an impactful energy renovation, increasing the energy performance up to energy label B. Based on the research conducted by Majcen (Majcen et al., 2013) on the actual gas consumptions vs. theoretical gas consumptions of dwellings relative to their ascribed energy labels, the reductions in gas demand due to the renovation can be estimated. The gas demand of the gallery building should be diminished with 7% (from energy label C > B) and the demand of the tenement building drops with 26% (D > B or E > B, average is 26%), see Table 5.3. It is expected that the theoretical renovation provides sufficient additional thermal insulation that a comfortable indoor temperature can be maintained by medium-temperature heating delivery systems operating at 45 °C.

Table 5.3. Current demand for energy by the residential buildings (hh = household) and estimated gas demand reduction after renovation.

Building: (See Figure 5.1)	No. of hh	Average; Total Elec. Demand	Average; Total Gas Demand	Present average Energy Label	Present Energy Label Range.	Post-Renovation. Energy Label	Expected reduction in gas Demand
(1) Gallery flat Eerste-Helmersstraat	68	1697 kWh/hh/year; 115.396 kWh/year	717 m3/year; 48.800 m3/year	C	D–B	B	−7% (C > B)
(2) Tenement Tweede-Helmersstraat	47	1805 kWh/hh/year; 84.835 kWh/year	1114 m3/year; 52.400 m3/year	E or D	G–D	B	−24% (D > B) −28% (E > B)

It is relevant to understand how the energy demand for space heating (SH) and energy demand for domestic hot water (DHW) relate to each other due to their different temperature requirements. For the DHW, a set point temperature of 55 °C is used as a calculation value. In practice, the heat pump will boost the temperature of the water periodically up to a minimum of 65 °C to prevent legionella from developing in the system, but this peak is neglected for the energy calculations in this study. Schepers et al. estimate that in a well-insulated 1900–1945's dwelling, the gas demand for DHW would be 40% of the total gas use on an annual basis (2015). In practice there would be zero to limited gas demand for space heating during the summer months. However, this ratio is still projected to every hour of the year, due to the unavailability of correct consumption data at the hourly level.

5.2.3.3. Energy Balance: Greenhouse

The rooftop greenhouse is the new plugin component added to the existing built environment and acts as a solar collector, capturing thermal energy from the sun by means of floor cooling. The interior temperature (T_{in}) of this greenhouse is governed by the exterior climate, the energy transfer across the building skin and the resulting interior energy fluxes. T_{in} at time (t) can be calculated with Equation (2) and builds upon the temperature calculated at (t − 1) by assuming the heat flows are stationary during the time-step from t − 1 to t (Δt) and includes the effect of thermal inertia. In this calculation time steps (t) of one hour are used.

$$T_{in}(t) = T_{in}(t-1) + \frac{Q_{H/C}(t) \times 3600}{\sum M} \quad [2]$$

$Q_{H/C}$ represents the energy deficit (H, positive flux) or excess (C, negative flux) relative to the intended minimum of maximum greenhouse indoor temperature $T_{min}(t)$ and $T_{max}(t)$ and is further specified in Equation (5a,b). The total thermal capacity ($\sum M$, (kg)) is the sum of the thermal effective components in the space and is calculated with Equation (3):

$$\sum M = (V_{air} \times \rho_{air} \times c_{air}) + (A_{floor} \times 0.08 \times \rho_{con} \times c_{con}) \quad [3]$$

For simplification purposes, only the greenhouse air (V_{air}) and the thermally active layer of the concrete greenhouse floor with mass m_n (kg) and specific heat capacity c_n (J/kg.K) are included in the calculation. The top 80 mm concrete corresponds approximately to the thickness of the concrete layer active in the diurnal thermal exchange cycle.

The energy balance of the archetypical greenhouse with solar energy as its main source for photosynthetically active radiation contains several passive and active fluxes, as defined in Equation (4), adapted from Sabeh (2007) The greenhouse is assumed to be a closed system, hence ventilation-related energy fluxes are excluded.

$$Q_{sun}(t) + Q_{inf} + Q_{int}(t) + Q_{em}(t) + Q_{trans}(t) + Q_{par}(t) + Q_{H/C}(t) = 0 \quad [4]$$

The dominant fluxes across the façade are the result of solar radiation and ambient temperature and are respectively noted as Q_{sun}(W) and Q_{trans} (W) for conductive, convective and radiative transmission. These fluxes influence the greenhouse climate and consequently the dominant interior exchange: the latent (Q_{lat}) and sensible (Q_{sen}) heat exchanged by crop transpiration, Q_{par} (W). Q_{inf} (W) represents the heat transfer by infiltration and is related to the outdoor wind speed. Greenhouse thermal emissivity to the external hemisphere is noted by Q_{em} (W). The total interior heat gain is described by Q_{int} (W) and consist of q_{eq}, q_{light} and q_{per}, respectively thermal heat gain by active equipment, installed artificial lights and present workers/visitors. $Q_{H/C}$ is determined by the set points for minimum greenhouse indoor air temperature during photoperiod (T_{min-P}), minimum indoor air temperature during dark period (T_{min-D}) and maximum indoor temperature T_{max} (°C). When the (combined) heat influxes produce high indoor greenhouse temperatures, the redundant thermal energy is removed by means of floor cooling, Q_C (W). When the thermal fluxes to the external environment exceed the combined influxes and the minimum indoor set point temperature is passed, thermal energy is added to the greenhouse by means of floor heating, Q_H (W). Equation (5a,b) isolate Q_H or Q_C and builts upon the indoor temperature calculated at (t − 1). The positive thermal flux $+Q_H$, i.e., heating, activates if $T_{in}(t) < T_{min-D}$ or $T_{in}(t) < T_{min-P}$ at (t − 1) and $-Q_C$, i.e., cooling, is active when $T_{in} > T_{max}$ at (t − 1). Equation (5a,b):

$$+Q_H\ (t) = \left(q_{sun}(t) + \sum q_{int}(t) + q_{sen}(t) + q_{lat}(t) + q_{em}(t)\right) \times A_{floor} - (U_n \times A_n + q_{inf}(t)) \times (T_{in,}(t) - T_e(t)) \quad [5a]$$

$$-Q_C\ (t) = \left(q_{sun}(t) + \sum q_{int}(t) + q_{sen}(t) + q_{lat}(t) + q_{em}(t)\right) \times A_{floor} - (U_n \times A_n + q_{inf}(t)) \times (T_{in,}(t) - T_e(t)) \quad [5b]$$

The various interior and exterior fluxes of the energy balance, used equations, applied parameters, structural properties and other factors are described in Appendix 5B. The last section of Appendix 5B discusses the effect of the food crops on the energy balance of the greenhouse.

5.2.4. Energy Profiles

The outcomes of the energy balance equations (Equations 1 and 5a,b) and the dwelling thermal energy demand are aggregated into a matrix of 24 h by 365 days. This is displayed in figure 5.3a, 5.3b and 5.3c, in this study coined energy profiles, and are used to locate and quantify the simultaneous and mismatched discrepancies between thermal energy excesses and demands. In the visualizations below, orange indicates an excess of thermal energy, i.e., a cooling demand in order to maintain the intended temperature set-point $Tmax$. Blue represents a heating demand, i.e., a deficit of thermal energy relative to the intended minimum indoor temperature. The intensity of the colour depicts the height of the heating/cooling demand. The 3D figures represent monthly totals (kWh) and emphasize the seasonal, daily demand patterns and weather influences and show how the energy profiles relate to each other in terms of magnitude.

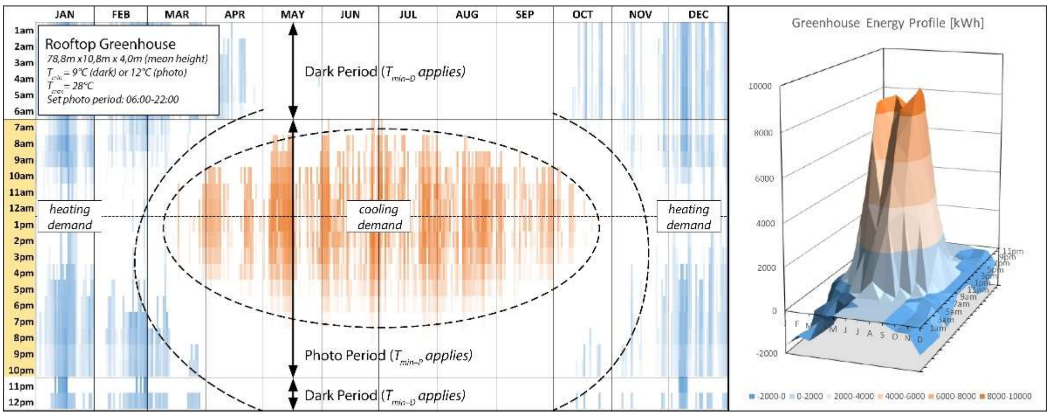

__Figure 5.3a__. Greenhouse: the energy profile of the greenhouse shows a white transition zone when the greenhouse indoor temperature is within the desired range. Temperature set points and photoperiod used for the initial situation are mentioned in the figure.

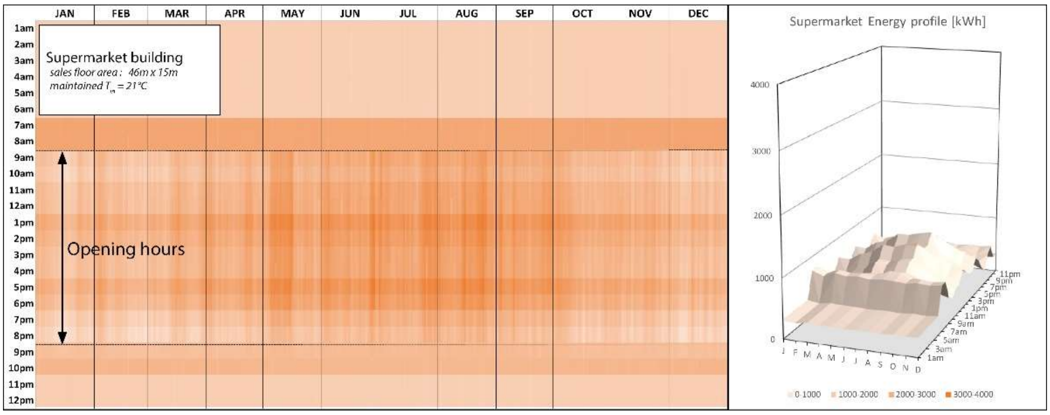

Figure 5.3b. *Supermarket energy balance: The supermarket has a year-round cooling demand, ranging from 2 kW in winter up to 40 kW during peaks in summer. The building does not have a heating demand at any moment of the year.*

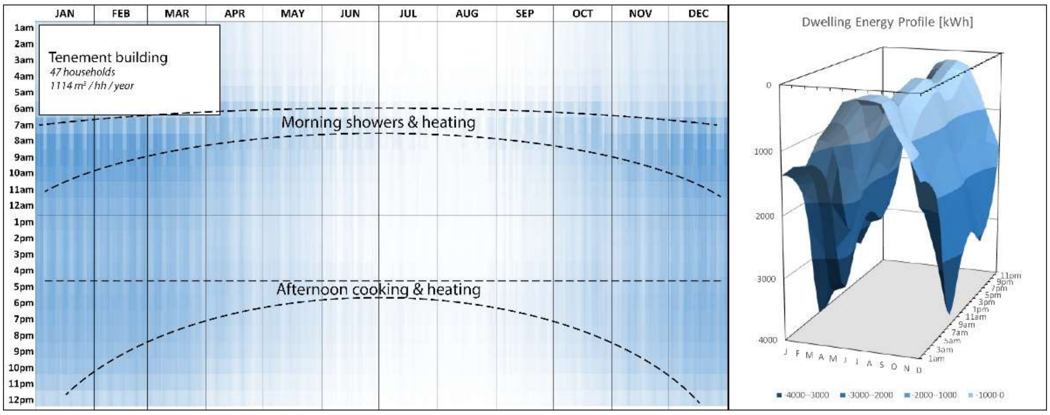

Figure 5.3c. *Dwellings: the hourly demand for thermal energy is ranging from 4 kW for some warm hours during nights in August, up to peak heating demand of 147 kW during January mornings. The dwellings are not actively cooled, as is common practice for this architectural typology in the Netherlands.*

5.2.5. System Integration

To overcome the seasonal mismatches between supply and demand, an aquifer thermal energy storage (ATES) is proposed (Section 5.5.1). The new energy system is introduced and discussed in Section 5.5.2 and is reversible, providing both a summer setting (Section 5.5.3) and winter setting (Section 5.5.4) to serve the core purpose of both heating and cooling. The design of the integrated energy system is not supported by calculations at the level of the individual system or utility (i.e., flow rate) but remains abstract as more detail would not contribute to the intended aim of this study.

5.2.5.1. Aquifer Thermal Energy Storage

Excess thermal energy that is extracted from the greenhouse volume by means of floor cooling (medium = water) needs to be stored over the season. Considering that the local energy system operates on low temperatures, serves a city block and surface space is limited in this inner-urban context, an underground doublet aquifer thermal energy storage (ATES) is considered the most suitable method to tackle the seasonal mismatch between heat excess and heat deficits. Underground energy storage is characterized by both high storage efficiencies and capacities. Open-loop ATES systems store sensible heat in water-rich earth layers (the aquifers), using the groundwater as the transport and storage medium, subtracting and injecting warm and cold water between the respective wells (Fleuchaus et al., 2018). Low-temperature (T < 25 °C) ATES systems are prevailing (99%) over high-temperature systems and about 85% of all systems is located in the Netherlands, where the soil offers favorable hydrogeological conditions and where the climate has substantial seasonal variations in ambient temperature to make an ATES effective (Bloemendal & Hartog, 2018).

One way to express the thermal performance of an ATES is by looking at the thermal recovery efficiency (η_{rec}), the fraction between the energy injected and retrieved. The energy recovered from a well is generally lower than the energy injected due to dissipation losses to the surroundings and advection due to local groundwater flows. Calculating the exact recovery is complicated, as many site-specific hydrological parameters are involved. It also depends on system-specific factors such as the injection temperature, the deviating pumping volumes between seasons because of demand patterns and the distance between the warm and cold well. Sommer et al. mention a numerically modelled recovery value of 75% in a stagnant aquifer (2013) no groundwater flow) and report a 65% storage recovery from the warm well and a 82% cold recovery based on field measurements (Sommer et al., 2015). Another report by Steekelenburg et al. (2011) mentions a higher efficiency between 85–90% over a period of 180 days. Considering the uncertainties and small scale of these particular systems, this study applies a conservative ATES efficiency (η_{re}) of 0.75 for both the warm well and the cold well.

To avoid systematic heating or cooling of the subsurface over time, which would disturb the ground water quality and eventually lead to ineffective and unsustainable system performances, Dutch provincial regulators require a thermally balanced system (Sommer et al., 2014). Most provinces in the Netherlands include a clausal in their groundwater act permit prescribing an energetically balanced system. Due to unpredictable climatological circumstances, certain deviations in the ATES balance are allowed. One province (Noord-Brabant) allows a 15% deviation from this balance for a 5-year period and a 10% deviation over a period of 10 years (SenterNovem, 2007), but also balance requirements within 5 years are reported (RVO, 2016). A field study on the balances of Dutch ATES systems revealed that the average energy balance for utility projects is +5% (n = 56) i.e., less heat is extracted than cold, and for residential ATES systems −34% (n = 5), meaning less cold gets extracted than heat (DWA & IF Technology, 2012). Energetically balanced urban functions (combining both heat- and cold-demanding functions in a certain urban area) therefore are paramount. To correct for storage unbalances, regenerative mechanical ATES cooling or heating could be employed, but this option is not considered for this study. For COP calculations (later discussed in section 5.2.5.3.), the average water temperature in the warm well is assumed to drop with 3 °C between seasons and the cold well water temperature remains unaffected.

5.2.5.2. System Configuration

The local energy system inter-connects four components: the dwellings, the rooftop greenhouse, the supermarket and the ATES. The system is reversible, providing a summer and winter setting to serve the core purpose of both heating and cooling. The greenhouse is the only component that shows both a heating and a cooling demand and is therefore decisive in determining the cooling and heating period for the entire system. Figure 5.4 shows the indoor temperature of the greenhouse without any mechanical heating or cooling and without energy exchange with the supermarket. The diagram is based on greenhouse configuration temperatures: $T_{max} = 28\ °\text{C}, T_{min-} = 9\ °\text{C}$ and $T_{min-P} = 12\ °\text{C}$. The configuration of the whole energy system, i.e., the period when thermal energy is stored and when it is extracted, is based on the indoor greenhouse temperature, which correlates with thermal energy excess or deficit. The months April and October evidently show a mixed demand for heating (morning + evening) and cooling (afternoon). Considering that greenhouse cooling can be achieved passively by opening up windows at the expense of losing thermal energy to the ambient environment, these two months are set to heating mode. This means that the cooling period is set to May–October (6 months); the other half of the year the system is set to heating mode. For simplification, a full month round-off applies and no in-between system reverses are included.

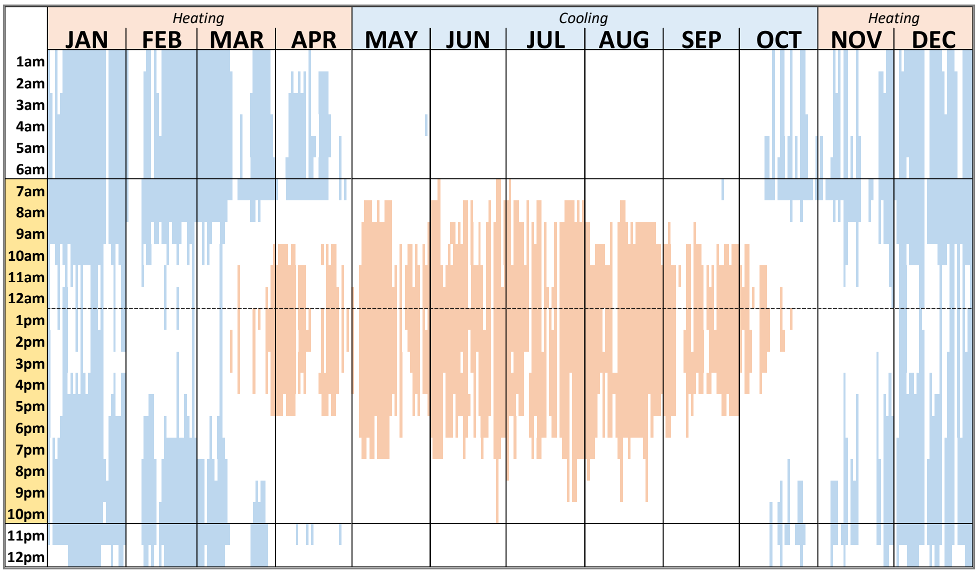

Figure 5.4. Indoor Greenhouse temperature (°C). Initial set point temperatures: T_{max} = 28 °C, T_{min-D} = 9 °C, T_{min-P} = 12 °C. Blue indicates that T_{min} has been reached or surpassed, red indicates that T_{max} has been reached or surpassed and white indicates that the GH indoor temperature is within desirable range. The yellow hatched hours indicate the photoperiod (PP) timeslot.

Figure 5.5 gives an abstract representation of the energy flows within the new local en-ergy system and the medium temperatures where relevant. In the following sections first discusses the winter configuration (point 1–5, left), followed by the summer configuration (point 6–8, right).

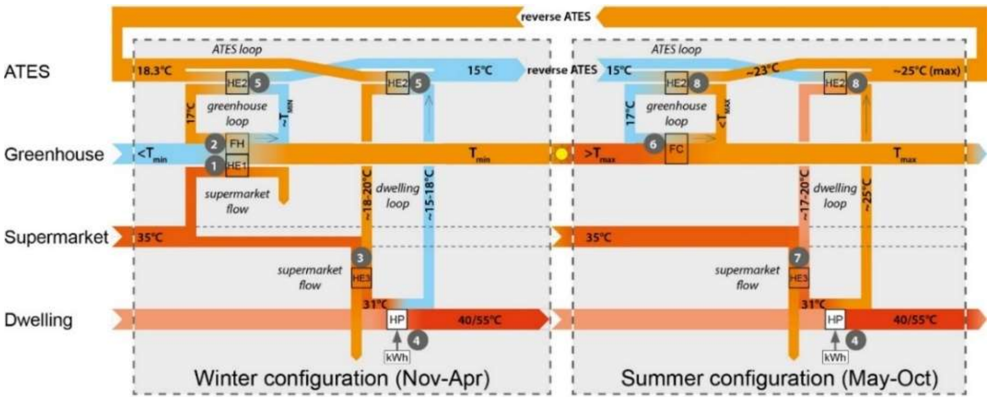

***Figure 5.5**. Abstract representation of the thermal energy flows in scenario 2a–d: the local system. Relevant medium/component temperatures are mentioned where ~ indicates an estimated temperature. FH = floor heating, FC = floor cooling, HE = heat exchanger. The ATES reverses at the beginning of May, when the cooling season starts and at the end of October, when the heating season starts. The temperature of the warm well of the ATES is assumed to drop with 3 °C be-tween seasons (see section 5.2.5.3).*

5.2.5.3. System Configuration: Winter

The local energy system operates for two core purposes: heating in winter and cooling in summer, as shown in a flow chart in figures 5.5 and schematically drawn in figure 5.6. During winter, the supermarket exchanges thermal energy through a heat exchanger (medium = air) with the greenhouse when $T_{\_in} \leq T_{\_min}$, point 1 in Figure 5.5. When the greenhouse $T_{\_in}$ is within the accepted range, the energy system uses the excess thermal energy from the supermarket to increase the temperature of the warm water ($T_{\_low}$) coming from the ATES warm well. The water is boosted from +/−18.3 °C (estimated ATES water temperature) to 31 °C, with the aim of increasing the COP of the heat pump, thereby reducing the electrical energy investment (point 3

& 4). The efficiency of the air-to-water heat exchanger is assumed to be 90%. If the supermarket cannot provide sufficient energy to maintain a suitable greenhouse indoor temperature, warm water from the ATES is pumped through the floor of the greenhouse (point 2), which simultaneously drops the temperature in the loop and charges the cold source of the ATES. Here, an exchange efficiency (water-water) of 90% is applied (point 5). The heat pump output flow is used to charge the ATES cold source; again, an exchange efficiency of 90% applies (point 5).

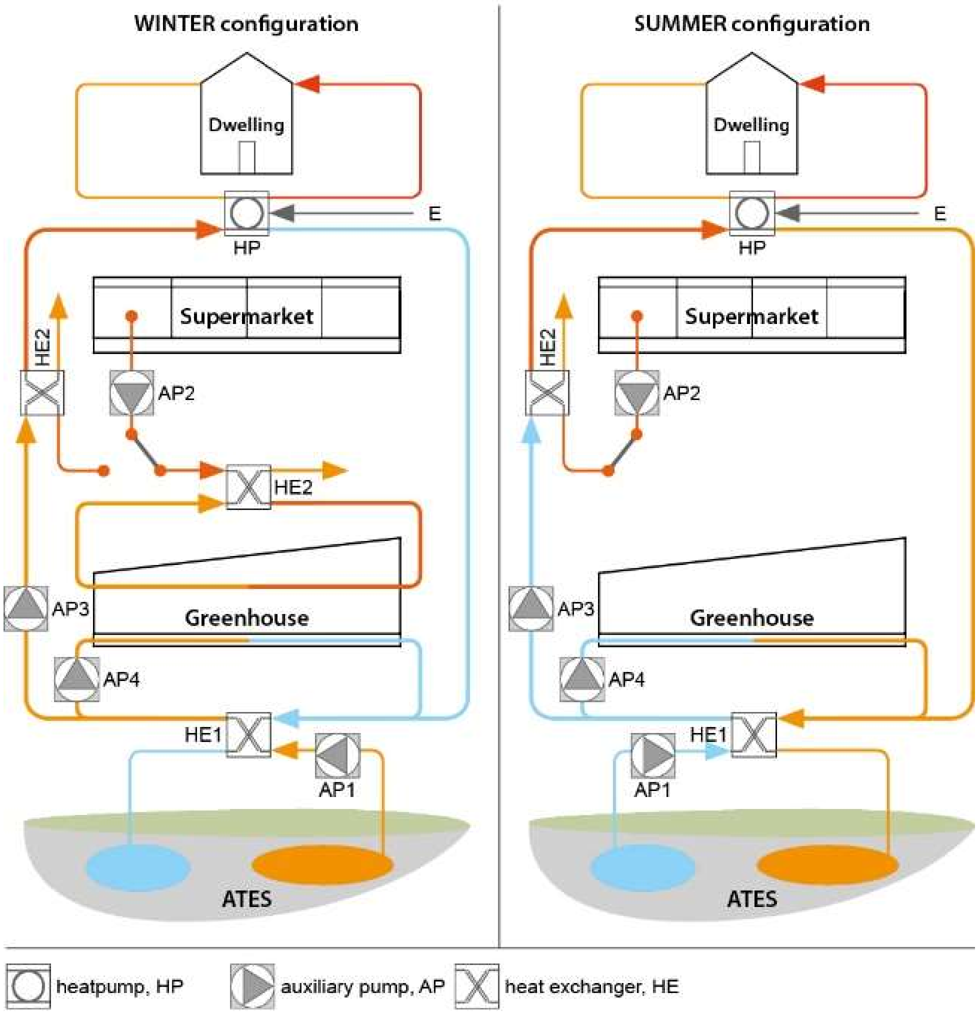

Figure 5.6. *Position of the Auxiliary pumps (AP), Heat exchangers (HE) and Heat Pumps (HP) within the local energy system for both system configurations.*

Equation (6) calculates the minimum amount of thermal energy that should be stored in the ATES annually ($\sum_{n=1}^{4380}(Q_{ATES\_H}\,(t) \times \Delta t_n)$) and is based on the energy demand by the greenhouse ($Q_{GH\_H\_ATES}$) and the energy required by the dwelling ($Q_{DW\_H\_ATES}$), taking into account the efficiency (η_2 = 0.9) of the heat exchange (HE2, Figure 6.6) between the ATES loop and the GH & DW loop and the ATES recovery efficiency ($\eta_{re} = 0.75$).

$$\sum_{n=1}^{4380}(Q_{ATES\_H}\,(t) \times \Delta t_n) = \sum_{n=1}^{4380}((Q_{GH\_H\_ATES}\,(t) + Q_{DW\_H\_ATES}(t)) \times \frac{1}{(\eta_2 \times \eta_{re} \times \eta_2)} \times \Delta t_n) \qquad [6]$$

The stored thermal energy reserved for the greenhouse, $Q_{GH\_H\_ATES}$ (W) can be calculated with Equation (7). If the greenhouse's interior temperature $T_{in}(t-1) \leq T_{min}(t-1)$, surplus energy ($Q_{Lidl}$) from the supermarket in the form of warm air ($T_{air} = 35$ °C) is shared with the greenhouse, taking into account the efficiency of the heat exchanger (HE2, η = 0.9). When this energy flux is insufficient to maintain a suitable indoor greenhouse temperature, additional energy is retrieved from the ATES.

$$Q_{GH\_H\_ATES}(t) = Q_{GH_H}(t) + (Q_{Lidl}(t) \times \eta_2), \quad \text{if } T_{in}(t-1) \leq T_{min}(t-1) \quad [7]$$

Equation (8) is used to calculate the stored thermal energy reserved for the dwelling, $Q_{DW\_H\_ATES}$ (W). Since the thermal energy provision of the dwelling involves a heat pump, electrical energy E is converted into thermal energy and becomes part of the total energy required, Q_{DW_H}. When $T_{in}(t-1) \geq T_{min}(t-1)$, the energy rejected from the supermarket ($Q_{Lidl}(t)$) is used to pre-heat the heat pump approach water (T_{low}) from +/−18.3 °C (estimated ATES extraction temperature, see Table 5.4) to approximately 31 °C, based on a heat exchange efficiency of 0.9 (HE3). The Coefficient of Performance of the heat pump (COP_{HP}) is estimated from the Carnot efficiency, with an assumed practice efficiency (η_{car}) and varies throughout the year due to the two possible approach temperatures (18 °C if straight from the ATES or 31 °C if upgraded) and two different upper temperatures: $T_{hig} = 45$ °C for SH and $T_{hig} = 55$ °C for DHW.

$$Q_{DW\_H\_ATES}(t) = Q_{DW\_H}(t) + (Q_{Lidl}(t) \times \eta_3) + E(t), \text{ if } T_{GH}(t-1) \geq T_{min}(t-1) \quad [8]$$

where $E(t)$ is the electrical energy demand from the heat pump at moment (t):

$$E(t) = \frac{Q_{DW\_H}(t)}{COP(t)} \quad [9]$$

where the COP is calculated with Equation (10):

$$\text{COP(t)} = \frac{T_{high}(t)}{T_{hig}\ (t) - T_{low}(t)} \times \eta_{car} \quad [10]$$

T_{low} (°C) is the approach temperature of the water passing through the heat pump. When the energy rejected by the supermarket is not used to heat the greenhouse, it will be used to increase the COP of the heat pump. η_3 represents the efficiency of the heat exchange between the supermarket warm air and the heat pump approach water (HE3) and is set to 0.9. The temperature of the supermarket exhaust air is noted by T_{air} (°C) and is assumed to be around 35 °C. An overview and explanation of the various values for T_{high} and T_{low} can be found in Table 5.4. η_{car} represents the ratio of the real COP in practice to the Carnot COP; it is set to 0.5 (Meggers, Ritter, Goffin, Baetschmann, & Leibundgut, 2012).

Table 5.4. Different values applied for T_{low} and T_{hig} in the calculation of the heat pump COP (Equation (10)). DHW & SH constitute respectively 40% and 60% of the total energy demand (section 5.3.2).

Factor	Value	When	Note/Formula
winter configuration			
$\boldsymbol{T_{low}}$	18.3 °C	If greenhouse $T_{in}(t) \leq T_{min}(t)$	ATES temperature drop is assumed 3 °C. ATES extraction temperature (T_{low}) depends on GH cooling set point temperature: $T_{low} = (T_{max} \times \eta_2 - 3\ °C) \times \eta_2$, so (26 °C × 0.9−3 °C) × 0.9 = 18.3 °C (for scenario 2b–d)
$\boldsymbol{T_{low}}$	31.4 °C	If greenhouse $T_{in}(t) \geq T_{min}(t)$	Supermarket excess energy temperature = set to 35 °C $T_{low} = T_{air} \times \eta_3$, so 35 °C × 0.9 = 31.4 °C
$\boldsymbol{T_{high}}$	45 °C	Set-point temperature for space heating	Based on medium-temperature dwelling heating system
$\boldsymbol{T_{high}}$	55 °C	Set-point temperature for DHW	The weekly temp. boost (T = 65 °C) is not accounted for.
summer configuration			
$\boldsymbol{T_{low}}$	31 °C	Full duration summer period	$\boldsymbol{T_{low} = T_{air} \times \eta_3}$, i.e., 35 °C × 0.9 = 31.4 °C
$\boldsymbol{T_{high}}$	45 °C/55 °C	As winter configuration	As winter configuration.

5.2.5.4. System Configuration: Summer

In summer, the system functions similarly to the winter configuration. Cold water ($T = +/-15$ °C) that was previously stored in winter, is now discharged with the sole purpose of cooling the greenhouse by means of floor cooling (point 6). During the process, the cooling water warms up to approximately T_{max}, after which it can recharge the thermal well of the ATES (point 8). In summer, the full capacity of the supermarket excess energy is used to preheat the tap water and the water in the heat pump loop, again narrowing the temperature jump and increasing the COP (point 7). The outflow of the heat pump (point 4) is used to charge the ATES heat source (point 8) and this temperature is assumed to be around 25 °C. The total cooling energy ($\sum_{n=1}^{4380}(Q_{\text{ATES\_C}}\,(t) \times \Delta t_n)$) that should be stored by the ATES is calculated by Equation (11). As mentioned, only the greenhouse is supplied with cooling energy from the cold well. $Q_{GH\_C\_ATES}$ (kWh) is the cooling demand greenhouse at (t).

$$\sum_{n=1}^{4380}(Q_{\text{ATES\_C}}\,(t) \times \Delta t_n) = \sum_{n=1}^{4380}(Q_{GH\_C\_ATES}(\text{t}) \times \frac{1}{\eta_2 \times \eta_{re} \times \eta_2} \times \Delta t_n) \qquad [11]$$

In summer, the excess energy from the supermarket is used in its full capacity to narrow the temperature increase within the heat pumps of the dwellings, similar to the winter setting. The warm air is passed by the return loop of the heat pump, preheating the water up to a temperature of around 31 °C. The COP_{HP} and the required electrical energy are calculated with respectively Equations (9) and (10).

5.5.5. System Configuration: Additional Electricity Demand

The local energy system consists of four sub-flows that are put into motion by electrical pumps: (1) the ATES loop, (2) the greenhouse loop, (3) the dwelling loop and (4) the supermarket air flow (Figure 5.6). The added emissions due to the electricity consumption of these pumps is included in the carbon evaluation of the system. The ATES doublet loop pumps water between the warm and the cold well (or vice-versa) whilst extracting the cooling or heating energy with a water-to-water heat exchanger (HE1). The warm air from the supermarket cooling system is either pumped towards the greenhouse or the heat pump of the dwellings, where thermal energy is exchanged with the dwelling flow. The dwelling flow circulates between the heat pump of the dwellings and the heat exchanger of the ATES flow, where the flow is preheated by heat exchange (HE3). Finally, there is the greenhouse flow, connecting the greenhouse floor heating/cooling system with the ATES flow. As this study does not get into systems level detail, the power of the electrical pumps remains an estimation.

The greenhouse lighting system switches on when the photoactive radiation (PAR) from the sun drops below 30.6 W/m2 (corresponding with 140 µmol/m^2/s PPFD, see Appendix 5B) and when time (t) is within the scheduled photo period. To account for operational activities within the greenhouse that do not relate to cooling, heating or crop lighting, a value of 5 kWh/m2/year is assumed (Graamans et al., 2017). An overview of the aforementioned electrical demands related to the auxiliary pumps (AP) or the greenhouse can be found in table 5.5.

Table 5.5. Electrification of the system. Overview of auxiliary pumps, greenhouse crop lighting and operational activities.

Component, Medium (See Figures 5.5 and 5.6)	Part/Description	Symbols (See Figure 5.6)	In Operation, Description	Power (W), (W/m2)	Operational Hours	Annual Demand (kWh_e)
(1) ATES doublet loop, warm/cold water	Water pump, warm > cold and vice-versa (P_{ATES} (W))	AP1	24/7 (2 possible settings)	1000 W [2]	8760	8760
(2) Supermarket flow, warm air	AC system > GH or DW, (HE2 connected)	AP2	24/7 (2 possible flow directions)	250 W [2]	8760	2200
(3) Dwelling loop, warm water	ATES > Heat pump DW (HE1 + HE2 connected)	AP3	24/7	750 W [2]	8760	6570

(4) Greenhouse loop, warm/cold water	Floor cooling + heating system (HE1 connected)	AP4	If $\boldsymbol{T_{in}} \leq \boldsymbol{T_{min}}$ or $\boldsymbol{T_{in}} \geq \boldsymbol{T_{max}}$	1000 W [2]	varies [3]	varies [3]
Lighting system	PPFD = 140		If PAR ISUN < 30.6 W/m2	54 W/m^2	varies [1,4]	varies [4]
Operational activities	Electricity required for various other uses		24/7	5 kWh/m^2/yr	8760	4255

[1] Determined with the calculation model developed for this study;

[2] Assumed power of pumps. The assumed power of the ATES pump is included in the sensitivity analysis (Section 5.4.1);

[3] Depends on the temperature set points, further specified in Section 5.2.5.3;

[4] Depends on the chosen photoperiod, in this study 06:00–22:00 (scenario 2a), 06:00–20:00 (scen. 2b), 08:00–16:00 (scen. 2c) or growing lights deactivated (scen. 2d), see Section 5.3.4.

5.2.6. System Configuration: Balance

For a durable performance of the ATES, the stored/retrieved thermal energy should be in balance with the stored/retrieved cooling energy. The fraction in equation 12 is used to determine the balance of the ATES for one summer-winter cycle. An outcome above 1.00 indicates that the heating demand is exceeding the capacity of the warm well. This could, for example, imply that insufficient thermal energy is extracted from the greenhouse during summer or that the heating demand is too high. An outcome below 1.00 reveals that more thermal energy is stored in summer than is used during winter. In the Netherlands, an ATES balance may be achieved over multiple seasons as predicted estimated demands and actual energy demands do not always overlap. This study aims for an annually balanced ATES, still, minor deviations from 1.00 are considered acceptable. The system can be brought into balance with hard and soft reconfigurations. Hard reconfiguration are physical modifications of the system, for example (dis)connecting a certain number of households to lower the heating demand or increasing the size of the greenhouses. The greenhouse functions as the main control component of the system. Soft configurations imply changes in the greenhouse indoor environment that directly affect its energy balance and therefore the system-performance. For example, lowering the cooling set point to increase the extracted solar energy. In this study, system balancing is a process of trial and error with earlier mentioned calculation model.

$$\frac{\sum_{n=1}^{4380}(Q_{ATES\_H}(t)\times\Delta t_n)}{\sum_{n=1}^{4380}(Q_{ATES\_C}(t)\times\Delta t_n)} = 1.00 \qquad [12]$$

Figure 5.7 (left) points out the unbalance if both the tenement building (47 hh) as well as the gallery building (68 hh) were to be supplied by one single rooftop greenhouse. Applied indoor climate and other relevant configuration specifications are listed per scenario in section 5.3.4. The combined demand for heating by the dwellings plus the greenhouse exceeds the thermal energy that can be extracted from the greenhouse over the summer. Even when the T_{max} is dropped to 25 °C, insufficient energy can be extracted from the greenhouse to heat the dwellings. Figure 5.7 (middle) corresponds with scenario 2a and shows that a balance can be achieved when only the tenement building is connected and if T_{max} is set to 26.0 °C. The right graph in Figure 5.7 shows the ATES balance if the greenhouse solar collector would be placed on top of the gallery building and T_{max} is set to 27 °C. The carbon evaluation in the results chapter continues with the tenement building + greenhouse + supermarket combination but could be repeated similarly for the configuration with the gallery flat.

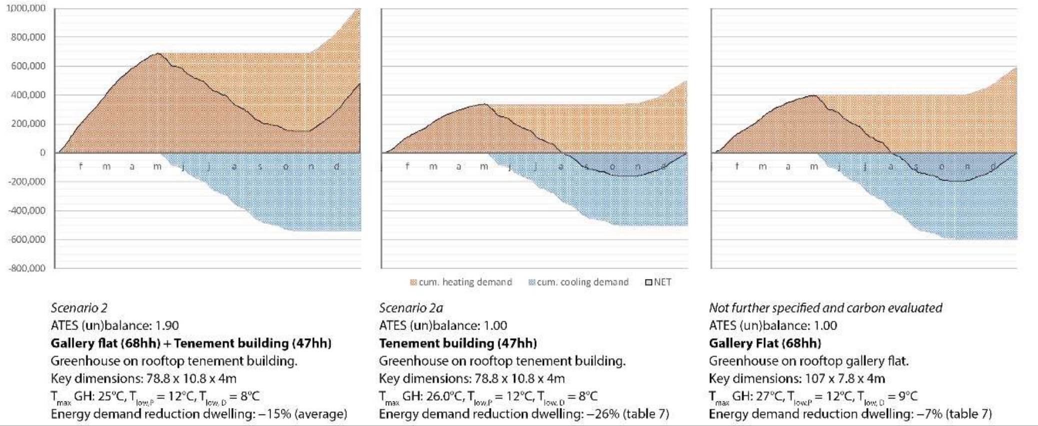

Figure 5.7. *(Dis)charging of the ATES. Both the tenement building as the gallery building can be heated by means of a rooftop solar collector, provided that the system is configured under specific climate settings. Scenario 2 & 2a correspond with the scenarios described in section 5.3.4.*

5.3 Results

Carbon accounting of all used energy resources is used to determine the CO_2e footprint of the three scenarios of this case study.

5.3.1. Scenario 1: Carbon Footprint Business as Usual (BAU)

The apartments in the tenement building (n = 47) use on average 1114 m^3 of natural gas per year for space heating, cooking and domestic hot water. For the carbon calculations in the BAU scenario it is assumed that none of the apartments is making use of electric cooking or heating systems. The average annual electricity consumption of the apartments is 1805 kWh/year. The supermarket is all-electric and consumes 257 MWh of electricity per annum. The electricity demand by the residential building and the supermarket combined with the use of natural gas leads to a total carbon emission of 274 tons annually, see Figure 5.8.

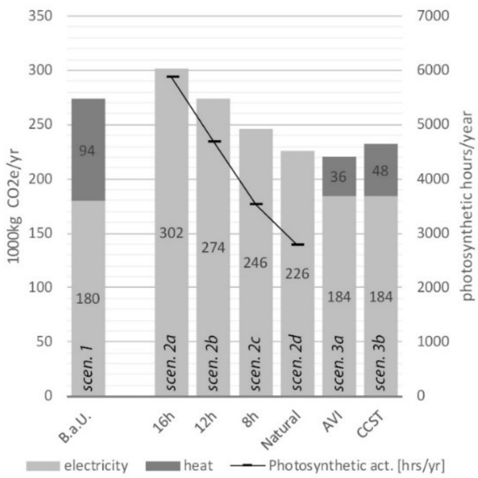

Figure 5.8. *Scenario analysis: BAU, local energy system (scen. 2a–d), district heating method (3a,b). AVI = waste incineration based district heating system, CCST = power plant waste heat based district heating system.*

5.3.2. Scenario 2: Environmental Footprint Greenhouse Solar Collector

In a balanced local energy system, the gas use of the tenement building is fully substituted with renewable solar thermal energy, which is extracted from a greenhouse that fits on the rooftop of the same building (851 m^2). This leads to a carbon cutback of 94 ton/year. The greenhouse and the system introduce an additional electricity demand to the national grid. The change to heat pumps and electric cooking adds 51 MWh_E/year and 8 MWh_E/year annually. Auxiliary energy required for the internal system pumps add an estimated 20 MWh_E. The electricity demand from the dwellings and the supermarket, 84 & 257 MWh_E, remain unaffected by the new energy system. The greenhouse-related electricity demand is composed of 4 MWh_E for operational activities and 149 MWh_E for crop growing lights when the optimal crop growing conditions regarding the greenhouse's indoor temperature and PPFD are maintained (scenario 2a). The carbon emission corresponding with all aforementioned energy demands cumulates to 302 ton/year, which is a 28-ton increase compared to the initial BAU scenario, see table 5.6. The carbon performance of scenario 2 is primarily controlled by the set photoperiod (PP). Would this be shortened to 12 h, 8 h or be fully deactivated, the annual cumulative carbon footprint of the full system drops to respectively 268 (−6 ton relative to BAU), 246 (−28 ton) or 226 ton (−53 ton).

Table 5.6. Carbon accounting: inventory of consumed resources and corresponding carbon footprints. Scenario 2a and 2d correspond with scenario 2a and 2d described in section 5.4 and are in ATES balance (discon. = disconnected)

Building		**Resource Demand**				**CO2 Equivalent Emission (Ton/Year)**			
Component	**Sub-Component/System**	**Final Resource**	**Unit**	**Use. (Unit/Year)**	**Energy (GJ)**	**Scen 1: BAU**	**Scen 2a: 16 h PP**	**Scen 2d: Natural PP**	**Scen. 3a,b: AVI/STEG**
Supermarket	-	elec.	kWh	256,973	925	135	135	135	135
Dwelling	(1) Tenement building, 47 hh	elec.	kWh	84,835	305	45	45	45	45
		gas	m3	52,358	1363	94	0	0	0
	(2) Gallery building, 68 hh	elec.	kWh	discon.	0	0	0	0	0
		gas	m3	discon.	0	0	0	0	0
	Heat pumps	elec.	kWh	50,712	182	0	28	30	-
	Dis. Heat, AVI	-	GJ	-	1363 [1]	0	-	-	25
	Dis. Heat, STEG	-	GJ	-	1363 [1]	-	-	-	33
	Electric cooking	elec.	kWh	8225 [2]	30	-	4	4	4
Greenhouse	Lighting system	elec.	kWh	varies	varies	-	78	0	-
	Operational activities	elec.	kWh	4255	15	-	2	2	-
ATES/System	Auxiliary pump systems (Table 5)	elec.	kWh	20,157	73	-	11	11	-
total (ton/year)						274	302	227	220/232
difference relative to BAU (ton)						0	+28	−53	−53/−42
difference relative to BAU (%)						100	+10	−19	−19/−15

[1] Total annual gas demand tenement building reduced with 26%: 52,358 m3 × 35.17MJ × (1 − 26%) = 1363 GJ/year;

[2] Study assumes the traditional gas stove is replaced with induction cooking, leading to an assumed additional electricity demand of 175 kWhe/hh, or 8225 kWhe/year in total.

5.3.3. Scenario 3: Environmental Footprint Amsterdam District Heating

In scenario 3, the residential building is connected to the existing Amsterdam heat grid. Currently, there are two individually operating heat grids in the city, which are heated by two different sources. The North-West network is fuelled by the Amsterdam waste incineration plant (Amsterdam Energie Bedrijf, or AVI) and a biodiesel factory and is exploited by Westpoort Warmte. The South-East network is energized by a Combined Cycles Gas Turbine (CCGT, Dutch: STEG) power station and is exploited by NUON-Vattenval (Akerboom et al., 2016). At the moment, these two networks primarily serve the inner urban ring, but future plans include a coupling between the two systems and a grid expansion towards both the region, as well as the inner-city. Current plans intend to make the district heating system fully renewable by 2040. This goal in itself seems feasible, but due to uncertainties surrounding the development of required technologies, exact potential, timeline and costs, the specific mix of various renewable sources cannot be predicted and remains speculative (CE Delft, 2019b). This study therefore performs the carbon assessment based on the present methods.

The case study location is in close proximity of branches from both heat grids (Vattenvall Warmte, 2020). To the extent of the authors' knowledge there are no urban plans available to accurately determine which parts of the city will be connected to which network in the future. Therefore, this study considers both networks as a possible option and includes both for carbon evaluation. The district heating systems deliver high temperature water of around 70–90 °C at the end-user, which is considered sufficient for both SH and DHW. Hence, this study assumes no additional heat pumps are necessary and a heat exchanger will suffice.

In 2016, CE Delft published updated carbon footprint values for centralized heat generation technologies, which also include the two aforementioned methods. The footprints are based on conservative calculations, consist of direct and indirect carbon emissions released during the generation of heat, take into account generally accepted average transportation losses (15%) and include a coefficient to account for the reduction in electricity generation due to the removal of steam for heat generation. For a detailed description of the calculation methods applied and aspects included, see the report by CE Delft (2016). Should the tenement building be connected to the heat grid connected to the waste incineration plant, the cumulative CO_2e footprint would become 220 ton/year (Table 5.6 and Figure 5.8), based on a carbon footprint of 26.5 kg CO_2e/GJ (listed in table 5.2). If a connection is made with a branch of the CCGT heat grid, the annual emission of the buildings becomes 232 ton, based on 36.0 kg CO_2e/GJ. Similar to scenario 2, this scenario also assumes that the dwellings are energetically renovated.

5.3.4. Configuration: Optimal Growing Climate or Optimal Energy Performance

In the calculation model, the minimal indoor temperature of the greenhouse is coupled with the photo activity of the crops, which is in this study only determined by simultaneous suitable key conditions for indoor temperature and PPFD, respectively $T_{in} \geq 12$ °C and PPFD = 140 µmol/m^2/s. A desired PPFD can be reached naturally by letting in solar radiation or can be managed by supplementary artificial crop lighting for the duration of the specified photoperiod (PP). This study does not model agricultural productivity separately, but by counting the hours in which both key parameters show the desirable growing conditions, preliminary statements on the greenhouse productivity can be made. If the PP is shortened with the purpose of reducing the carbon footprint of the lighting system, concessions on the greenhouse productive hours have to be made. A photoperiod of 16 h (06:00–22:00) is considered optimal and corresponds with 5893 photosynthetic active hours per year. Narrowing this PP window to 12 h (06:00–18:00, scen. 2b), 8 h (08:00–16:00, scen. 2c) or completely deactivating supplementary growing lights (scen. 2d) diminishes the photosynthetic active hours to respectively 4456 (−4%), 3534 (−40%) and 2775 h (−53%). The growing lights produce a significant internal thermal gain and modelling points out that the heating demand of the greenhouse increases when the PP is shortened. To compensate for this, the heating set point temperature in scenario 2c and 2d has to be increased in order to maintain system equilibrium. An overview of the key system parameters used to achieve system-equilibrium for various tested scenarios can be found in table 5.7 below.

Table 5.7. Various system configurations. Overview of relevant parameters and their values. Scenarios 2a–d are all in balance, but differ in photoperiod duration. Key greenhouse dimensions: 10.8 m × 78.8 m × 4 m (mean height), orientation: 66° relative to North (building 1 in Figure 5.1).

Setting/Result	**Unit**	**Scen 2.** Max. N households (Figure 5.7, Left)	**Scen 2a** Crop Priority 16 h PP [1]	**Scen 2b** Energy Priority 12 h PP	**Scen 2c** Energy Priority 8 h PP	**Scen 2d** Energy Priority Natural PP
T_{MAX}	°C	25.0	26.0	26.0	26.0	26.0
$T_{MIN,P}$	°C	12.0	12.0	12.0	12.0	12.0
$T_{MIN,D}$	°C	8.0	8.0	8.0	8.5	9.0
N of hh, tenement building	-	47	47	47	47	47
N of hh, gallery building	-	68	disconnected	disconnected	disconnected	disconnected
Assumed reduced demand DW	%	15 (average)	26	26	26	26
HP Set point temp. for SH	°C	45	45	45	45	45
Start-End PP [1]	time	06:00–22:00	06:00–22:00	06:00–18:00	08:00–16:00	natural light
Supplementary lighting, ON	h/year	3271	3271	1827	857	0
Screens down period	time	20:00–08:00	20:00–08:00	20:00–08:00	20:00–08:00	20:00–08:00
Cooling demand GH	MWh/year	325.2	302.5	300.5	298.8	298.6
Heating demand GH	MWh/year	64.9	65.3	56.6	56.6	61.1
Photosynthetic activity crops [2]	h/year	5893 (= max)	5893	4456	3534	2775
Difference from max	%	100%	100%	−24%	−40%	−53%
ATES balance fraction	-	1.90	1.00	0.99	1.00	1.02
CO_2 emission BAU.	ton/year	421	274	274	274	274
CO_2 emission (Δ BAU)	ton/year	391 (−30)	302 (+28)	268 (−6)	246 (−28)	226 (−48)

[1] PP = Photo Period. The timeslot when artificial lighting is used to activate photosynthesis in the crops;

[2] In this study crop growth is coupled with indoor temperature ($T_{min,P}$) and PAR and only a combination of two suitable values results in photosynthesis. Suitable growing conditions ($T_{in} \geq T_{min,P}$ & $PAR \geq 30$ W/m^2) can either come passively from natural sunlight or can be achieved mechanically by artificial lighting or greenhouse heating.

5.4 Discussion

5.4.1. Sensitivity Analysis (SA) Assumed Parameters

For reasons of simplification or due to lack of applicable data from literature, certain parameters represent assumed values. Four of these are tested in a sensitivity analysis: η_2, η_{rec}, η_{car} and the power of the ATES pump, P_{ATES}. The efficiency parameters (η) are tested with incremental steps of ±5% (figure 5.9 right). P_{ATES} is tested with incremental steps of ±10% (figure 5.9 left). The parameters η_{Car} and P_{ATES} are assessed based on their impact on the total carbon emission of the system (ton/year). The parameters η_2 and η_{rec} primarily influence the energy losses within the system and are therefore assessed on the total thermal energy that should be extracted from the greenhouse in order to carry the system over the following winter. In other words: a decrease in efficiency leads to an increase in heat extracted in order to compensate.

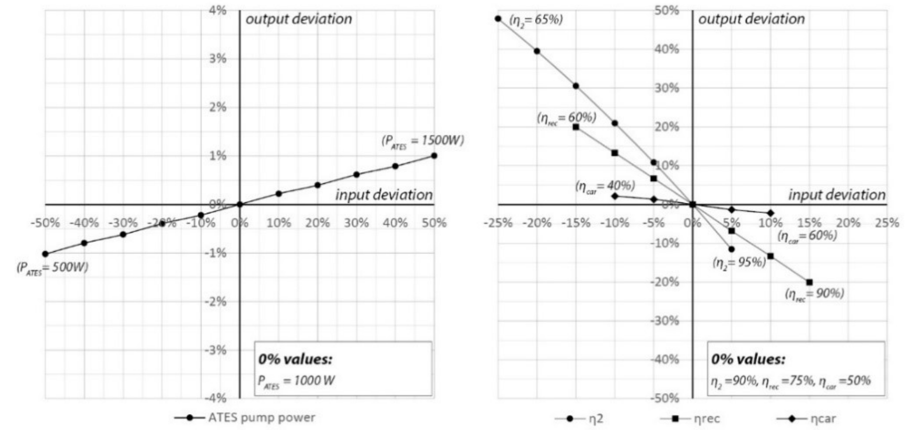

Figure 5.9. *Sensitivity analysis of four parameters. Left: P_{ATES}. Right: η_2, η_{rec} and η_{car}.*

Efficiency η_2 accounts for the energy losses during the energy exchange between the greenhouse floor cooling/heating circuit and the ATES and is set to 90%, an acceptable value for modern heat exchangers. The SA indicates a strong correlation between the overall storage efficiency of the system and the η_2 value used. Hard system reconfigurations might be required to reestablish a balanced system should η_2 become too low, for example disconnecting some households.

An ATES recovery efficiency (η_{rec}) cannot be captured in a generic representative value as it is depending on too many physical, geological and system characteristics. Performances found in practice represent a range of efficiencies, for that, η_{rec} is set to a conservative 75%. An η_{rec} increase from 75% to 90% would reduce the minimum required extracted thermal energy with 20% or expressed in terms of system scale: 20% more dwellings could be added to the system.

In practice, Carnot efficiencies of heat pumps range between 40% to 60%, hence the η_{car} in this study is positioned in the middle: 50%. Applying a 40% or 60% Carnot efficiency results in a ±~2% deviation in the output, i.e., a slight in or decrease of carbon emissions.

Estimations are used to describe the power input for the auxiliary pumps. The SA is limited to the ATES pump only as it is the most powerful pump that is considered and it is in operation year-round, making its analysis representative for the other auxiliary pumps that are less powerful and/or show fewer hours in operation. Deviating 50% from the assumed P_{ATES} leads to a marginal ~1% carbon emission increase.

5.4.2. Research Relevance

5.4.2.1. Societal Relevance

Urban rooftop solar collectors can provide parallel benefits to the generation of renewable thermal energy. The method is suitable for an architectonical and urban typology typically associated with (social) housing for middle or lower income classes: e.g., large gallery buildings, tenement buildings and older terraced housing rows. In the Netherlands, these buildings have been built in sixties and seventies in large numbers at the perimeters of towns and often form entire neighbourhoods, providing a quick solution to a pressing housing need. Studies show a correlation between income levels and people's food intake, showing unhealthy diets for the economically disadvantaged (RIVM, 2017). Visibly producing and retailing food crops in the locality could offer affordable and healthy alternatives to this social group, benefitting their physical wellbeing over a longer period of time. Coupling the horticultural activities with social programs for people with a distance to the labour market, introducing shared responsibility or working with co-ownership models could potentially lead to improved social cohesion within these neighbourhoods (Timmeren & Hackauf, 2014).

5.4.2.2. Scientific Relevance

The applied methods in this study allow for an accurate representation of the proportions within the carbon inventory of the local energy system and how carbon competes with district heating. This study offers a first insight on the capacity and impact of a rooftop greenhouse solar collector for a specific case study and can serve as a steppingstone towards urban upscaling, systematization and a more detailed assessment. Even though this study is limited to the appraisal of energy, it points towards a neighbourhood-level integrative design and holistic evaluation of all relevant resources, adding to the research gap surrounding the food, energy and water nexus (FEW nexus) that is currently prevailing at the regional, national or global level, as discussed in for example Zhang et al. (2019), Rees (2013), Leck et al. (2015), Terrapon-Pfaff et al. (2018) and Hang et al. (2017). It will be at the local scale where policies and strategies turn into physical interventions and where policy makers can combine public, private and civic interventions in order to counter climate change with a larger fist (Gondhalekar & Ramsauer, 2017).

5.4.3. Outlook

5.4.3.1. Upscaling the System and Future Use

Exclusively based on an energy and/or carbon assessment, a rooftop-based greenhouse solar collector as described in this study might already be feasible for one single dwelling, which would logically not be sensible from a technical, agricultural or an economic perspective. Further research should attempt to connect energetic feasibility with economic and agricultural feasibility and technical possibility. Greenhouse upscaling or clustering increases the effectiveness and productivity of the system as will the investment or operational costs be reduced.

5.4.3.2. FEW Nexus Assessment: Avoided Food Miles

The CO_2e assessment in this study is restricted to energy resources: natural gas, grid electricity and district heat. Extending the evaluation list with other resources commonly found in the urban metabolism, for example waste water treatment, (organic) waste management and food, will change the inter-scenario proportions of the carbon inventory (ten Caat et al.,2020). A holistic FEW nexus evaluation of the emissions for all scenarios will further encourage integrative and symbiotic design, subsequently leading to a cumulative carbon footprint presumably in favour of the integrative greenhouse scenario. Conventional produce can be replaced with locally (and organically) produced crops, potentially diminishing embodied food miles. Conversion of bio-waste into biofuels can substitute fossil energy carriers. These are individual methods or technologies that fit the concept of circular farming and can be aggregated into the design of a modern urban rooftop greenhouse. Further research should develop an integrative assessment methodology for urban farming to inform policy makers and come up with a systematic design approach to couple agricultural flows with the urban flows with the aim to establish a symbiotic relationship that produces the lowest possible carbon footprint.

5.4.3.3. Agricultural Productivity

A greenhouse solar collector plugged into the center of a community combines the production of two desirable resources: healthy local food crops and renewable thermal energy. However, in accordance with the aim of this study, harvesting thermal energy has priority above agricultural yield. Carbon evaluation of all three scenarios point out that only when artificial growing lights are not used, the greenhouse solar collector becomes carbon competitive with the centralized district heating. According to this study, merely relying on natural sunlight to provide the desired PPFD drops the annual photoactive hours by 53%, from 5891 to 2775 h. A monthly breakdown reveals that during December and January, two months with the lowest outside temperatures and with the shortest daylight periods, less than 5% of the natural annual photosynthetic activity will occur, while at the same time, almost 60% of the heating demand takes place. From an energy-prioritizing perspective, it would be more efficient to shut down the greenhouse during these two months and use the stored energy to heat additional dwellings instead. Further research on crop growing cycles, possible use of alternative (cold climate) crops and also crop carbon accounting as described before, should lead to a balanced use and climate configuration of the greenhouse regarding the combined optimization of agricultural productivity, as well as thermal energy yield.

5.5 Conclusions

The metropolitan area of Amsterdam intends to become (nearly) fossil energy free by the year 2050. One of the adopted core strategies towards this goal is to disconnect the built environment from the natural gas supply and connect it to the existing city-wide heating grid. This paper aimed to demonstrate the value of considering local energy potentials and synergistic design at the city block level by evaluating and comparing the carbon emissions of an alternative scenario: employing a greenhouse solar collector. Comprehensive calculations and modelling of a case study show that it is energetically possible to substitute the natural gas demand of one tenement building (47 households) with solar thermal energy extracted from the rooftop greenhouse. This greenhouse solar collector fits within the rooftop area (851 m^2) of that same tenement building, is kept under specific interior climate set points to maintain a balanced system and is co-heated by excess energy from an adjacent supermarket.

Carbon accounting reveals that even after a disconnection from the gas supply is accomplished, the cumulative carbon footprint of the local solution exceeds the business-as-usual scenario with 28 tons/year. This is primarily due to emissions related with additional grid mix electricity demand consequential to applying crop lighting. Only when artificial lighting is deactivated entirely and crop photosynthetic activity is solely based on natural lighting, the greenhouse solar collector method becomes carbon-competitive with the Amsterdam district heating. Shortening the daily artificial photoperiod in order to lower the CO_2 emissions diminishes the photosynthetic active hours for crop growth. Setting a desirable photoperiod of 16 h per day leads to 5893 h of suitable crop growing conditions per year. Opting out of artificial lighting completely results in 2775 h of suitable growing conditions, a considerable reduction of 53%. This study points out that an urban rooftop solar collectors could be a suitable renewable alternative to conventional gas use or district heating. However, a system configuration to optimize energetic performance and minimize carbon emissions can lead to a reduction in greenhouse agricultural productivity.

Author Contributions: N.t.C.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft presentation, visualization, project administration. L.G.: Software, validation, resources, writing—original draft presentation. M.T.: methodology, validation, writing—review and editing, supervision. A.v.d.D.: conceptualisation, writing—review and editing, supervision, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Nomenclature: List of Symbols, Subscripts, Units and Abbreviations

Symbol	Unit	Description
ATES	-	Aquifer Thermal Energy Storage
BAU	-	Business as Usual
CO2e	-	Carbon dioxide equivalent
COP	-	Coefficient of Performance
DHW/SH	-	Domestic Hot Water/Space Heating
GH/DW/SM	-	Greenhouse/Dwelling/Supermarket
hh	-	household
PAR	-	Photo Active Radiation
PPFD	-	Photosynthetic Photon Flux Density
σ	W/m2K	Hemispherical Stefan-Boltzmann constant: 5.67 × 10−8
p	Pa	Water vapour pressure
a+b	-	Climate specific standard values. For a sea climate, a = 0.55 and b = 0.005
ρcon	kg/m3	Density concrete: 2500 kg/m3
ρair	kg/m3	Density air: 1.21 kg/m3
ηrec	-	Recovery efficiency ATES storage, set to 0.75
ηcar	-	Heat pump Carnot efficiency, set to 0.5
η1	-	Heat exch. eff. SM flow > GH air (HE1, Figure 5.6), set to 0.9
η2	-	Heat exch. eff. ATES loop > GH loop and DW loop (HE2, Figure 5.6), set to 0.9
η3	-	Heat exch. eff. SM flow > DW loop (HE3, Figure 5.6), set to 0.9.
Wlights	W	Power crop growing lights (54 W/m2 in this study)
vwind	m/s	Wind velocity (NEN5060 data)
qinf	m3/m2/s	Air exchange with environment due to infiltration
Vair	m3	Air volume
Vinf	m3/s	Air exchange volume due to infiltration (supermarket calculations)
Vvent	m3/s	Air exchange volume due to ventilation (supermarket calculations)
U(n)	W/m2.K	Rate of transfer of heat through structure n
Tmin-P	°C	Minimum greenhouse indoor temperature, photoperiod.
Tmin-D	°C	Minimum greenhouse indoor temperature, dark period
Tmax	°C	Maximum greenhouse temperature

Tlow	°C	Approach temperature heat pump
Tin	°C	Indoor temperature greenhouse
Thigh	°C	Upgrade temperature heat pump
Te	°C	Outside ambient air temperature (NEN5060 climate data)
Tair	°C	Assumed air temperature of waste energy flow supermarket, set to 35 °C
rPAR	-	Coefficient to filter out solar radiation in the PAR range
ro	-	Façade orientation reduction coefficient (see Table A1.)
qtrans	W	Thermal energy flux due to temperature difference interior-exterior
qsun	W/m2	Thermal heat gain by solar irradiation
qsky	W/m2	Atmospheric long-wave irradiation
qper	W	Thermal heat load per person present
qlight	W/m2	Thermal heat load by active lights, supermarket
QLIDL_C	kWhT	Cooling energy demand supermarket, i.e., energy provided
qinf	W	Energy flux due to air infiltration through façade construction
QGH_C_ATES	kWh	Cooling energy demand greenhouse (GH), supplied by the ATES
qeq	W/m2	Thermal heat load by active equipment
qem	W	Energy flux due to sky emissivity
np	-	Number of workers/customers present
M( )	kg	Mass
Isun	W/m2	Total incoming global horizontal irradiance (NEN5060 climate data)
gglass	-	Solar transmittance coefficient.: fraction of the solar radiation that passes the glass
f(n)	-	Active/Inactive coefficient for GH and SM internal heat loads, set to (1) or (0)
E	kWhe	Required electrical investment heat pump
cLED	%	Efficiency crop growing lights
ccon	J/(kg.K)	heat capacity concrete, this study applies 840 J/kg.K
cair	J/(kg.K)	heat capacity air, this study applies 1005 J/kg.K
A(n)	m2	surface area, façade or floor (Aglass/Afloor)
∑QGH_H_ATES	kWht/year	Thermal energy demand greenhouse (GH) supplied by the ATES
∑QDW_H_ATES	kWht/year	Thermal energy demand dwelling (DW), supplied by the ATES
∑QATES_H	kWht/year	Total thermal energy stored in the ATES
∑QATES_C	kWhc/year	Total cooling energy stored in the ATES
ε_glass	-	Emissivity of greenhouse cover material. Set to 0.97 for single pane glazing
T_sky	°C	Sky temperature at (t)
RH(t)	-	Relative Humidity at (t), retrieved from NEN5060 climate reference data
P_max	Pa	Saturated water vapour pressure
F_(sky)	-	Sky view factor. Set to 0.5 for an unobstructed hemispherical dome

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6

Towards carbon free cities

Towards carbon free cities - Grasping the urban food production pentalemma during the design process by using the FEWprint platform

Chapter five described the integration of a greenhouse solar collector on a high spatio-temporal resolution. Even though the output was highly contextual and offered the possibility for optimisation according to system integration or agricultural productivity, this level of detail requires considerable technical, data and time resources in order to complete a correct analysis of the resource and carbon implications. Based on the experiences of this chapter, an alternative approach to UFP design was developed that is less complicated to integrate into the FEWprint method and platform.

This chapter proposes a space-based approach to urban food production design. In order to control the comprehensive effort of food production and evaluation, the *pentalemma* is introduced, which consists the five relevant aspects of 1) demand, 2) space, 3) yield, 4) resources and 5) impact. The *design* component was applied in a student-expert workshop to test the interaction between platform operator and designer. The outcomes of the workshop and the decarbonisation impact are extensively discussed in this chapter.

The Introduction start by addressing the role of food consumption to the total carbon footprint of a community and how previous studies have addressed this sector in their carbon accounting studies. It also addressed the environed position and role of the platform during the urban design process. The method section commences by recalling the FEW nexus principles and how these connect with synergistic urban farming solutions (section 6.2.1), followed by an explanation of the design approach (6.2.3), after which the *pentalemma* framework is proposed to control five relevant UFP aspects when designing a food system (6.2.4). The results section describes an elaborative case study application of the *design* component, that start by explaining the position of the FEWprint platform in the design process (6.3.1). The discussion goes deeper into the limitations of the developed method (6.4.2) and how both the FEWprint *design* component and the design process can be improved (6.4.3).

6

Towards carbon free cities

Towards carbon free cities - Grasping the urban food production pentalemma during the design process by using the FEWprint platform

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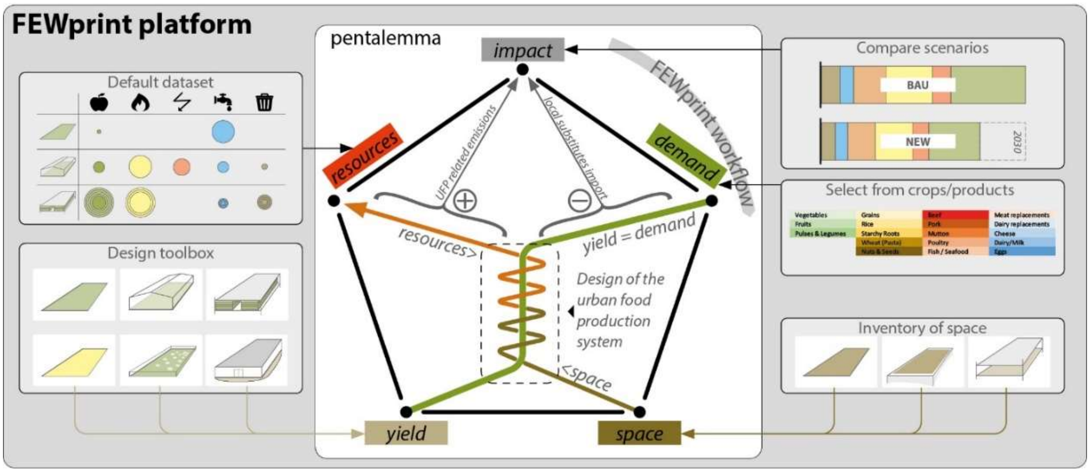
6. Towards carbon free cities - Grasping the urban food production pentalemma during the design process by using the FEWprint platform

Abstract

The production of food in cities is often supported with claims addressing its environmental benefits. Urban farming is said to reduce carbon emissions associated with transportation, land use change and food losses. However, food production implementations also impose a new demand for energy and water resources to the existing infrastructure, subsequently adding to the community's footprint. This article highlights five inter-dependent aspects that require a balanced configuration during the design process to inform holistic decision making: demand, space, resources, yield and impact, coined the pentalemma. The FEWprint platform is introduced to support the non-agriculturist urban designer with this pentalemma and provides a framework that reduces food production complexity into comprehensible elements. In a design workshop format, the implementation of the platform was tested through the conceptualization of a food-centred redesign strategy for a neighbourhood in Amsterdam to reduce its carbon footprint. It revealed a challenging aspect of its operation: the operator's ability to keep pace with an ad-hoc design process, particularly during out-of-the-box thinking and with design team unfamiliarity with the platform. Overall, the study recommends a combined approach of on-the-go feedback and interim moments of in-between evaluations to foster effective operator-designer collaboration.

Keywords

carbon emissions, water-energy-food nexus, sustainable cities, food production, design process, decision support platform



__Graphical abstract__. Pentalemma of food production aspects. The FEWprint provides the framework and toolbox to support urban food production strategies with preliminary performance data on yield, resource use, space use and impact.

6.1 Introduction

In tandem with population growth and increasing urbanisation, the transportation of food commodities went through a technological and logistical evolution in the previous century. Combined with the rise of refrigerated and standardised container shipping, food production moved from communal subsistence farming towards the city perimeter, subsequently further out into the arable hinterlands and even across borders. Even though on average 80% of the food is still supplied domestically, the global share of cross-border trade has increased from 10% to 14% from 1995 to 2017 alone (Geyik et al., 2021), a trend that is forecasted to continue due to the developing countries' growing reliance on imports until 2050 (FAO, 2017). In order to minimise the yield gap, resources like water, gas, fuel, electricity, synthetic fertiliser, manure and topsoil are paramount – each presenting their own carbon emission intensity when produced and/or used. Nowadays, two decades into the 21st century, on-farm emissions and land-use/land-use change related emissions are responsible for roughly 18% of global greenhouse gas emissions (FAO, 2020a). The food sector as a whole — adding refrigeration, processing, packaging and transport of food — has become the driver of more than a quarter of the anthropogenic greenhouse gas emissions worldwide (Poore & Nemecek, 2018).

At the level of the city, food demand can be responsible for a significant portion of the greenhouse gas emissions. However, whether or not agriculture-related emissions are included in a carbon analysis of a city is a matter of inventory and scoping — a sensitive methodological decision that can have considerable ramifications on the resulting environmental footprint (Chen et al.,2020; Ramaswami et al., 2008). The protocol set by the World Resources Institute offers a model and framework to urban carbon accounting, which classifies emissions in relation to the spatial boundary of a city and accounts for direct, indirect and process-related emissions (World Resources Institute, 2014). Briefly, scope 1 emissions occur within the boundaries of the context, also referred to as the territorial emissions. Emissions occurring during the production of grid mix electricity are placed in scope 2. Finally, scope 3 covers the extra-urban emissions associated with the production of good and services used in cities, to which food goods are attributed. In industrialised or service-based economies or cities, agriculture tends to be outsourced to external ecosystem services (Pincetl et al., 2012). As such, the majority of the food sector emissions predominantly occur outside the geographical boundaries of the urban context. Therefore, studies focussing only on territorial (scope 1) and grid mix electricity-related emissions (scope 2) and do not account for this extra-urban impact (scope 3), potentially report an environmental footprint that is not reflective of the true impact (de Souza Leão et al., 2020; Wei, Wu, & Chen, 2021).

The *consumption-based* approach towards carbon footprint analysis can be used to acquire a more encompassing estimation on the footprint of a city. It states that resources-related emissions are driven by the end-user and should therefore be attributed to them by means of a full scope assessment that captures the entire life cycle of resources, goods and services (S. Chen et al., 2020; Mi et al., 2019). The impact of food consumption by an urban population was previously included when estimating the carbon emission footprint of cities or communities; for example, Hillman & Ramaswami (2010), Heinonen (2011) and Moore (2013) used an *aggregated data* approach to food assessment. A disaggregated approach provides an insight on the food group or product level impact, as has been conducted by Codoban & Kennedy (2008). Tracking material and energy flows of the city — a metabolic analysis — forms the accounting basis of greenhouse gas emissions assessment, as was previously done for urban communities by Kennedy et al. (2010; 2009), Dobbelsteen et al. (2018) and Pulselli et al. (2021; 2019), although none of these studies addressed the food sector or urban redesign strategies in their evaluation.

In the consumption-based approach, life-cycle assessment data is used to describe the carbon intensity of the food production process, making the food sector carbon impact an exclusive derivative of food demand. Inherently, carbon reductions can then only be achieved through dietary change, i.e. changes in the demand and not in the production process (Caat et al., 2022). In par with the scope and boundaries of the consumption-based approach, the provision of food should be relocated within the urban system in order to obtain control over the food sector emissions (Goldstein et al., 2016b). The production of food goods is archetypically an industry that takes place in locations with sufficient areal potential to tap into the efficiency and efficacy of upscaling and — in a globalised system — takes place on locations with favourable climate conditions. Urbanising – and the thereby unavoidable downscaling – of food production should therefore not merely be considered as a transition of agriculture into the city. Instead, it should be approached as an incentive to identify, map and quantify the various material and resource flows and to design a system that is mutually beneficial for the farm and a city (Specht et al., 2014).

Farming and marketing of food resources within the geographical boundaries of a city has the potential to mitigate food emissions. To start, the close proximity to the consumer results in reduced *food miles* (AEA Technology Environment, 2005) and less food waste (Priefer et al., 2016). Secondly, inner-city or peripheral production also reduces the need to expand agricultural land in existing nature area in overseas nations, commonly referred to as *land use/ land use change* (Winkler et al., 2021). A food production system could operate as a *node* in the urban resource *host* infrastructure. A metabolic understanding and quantification of both the food production processes and the urban system could disclose anchor points for system coupling and integration, hence further adding benefit to urban food production. For example, plugging in food producing entities to the (existing) urban resource network introduces a demand for auxiliary farming resources (water, electricity, heat, feed, nutrition and manure) that successively impose new emissions to the carbon balance of the context. In tandem, produced food can be translated into *negative emissions* as they no longer have to be imported and subtracted from the carbon balance, provided it is consumed by the host-community. To be able to holistically determine the impact of local food production strategies and verify the net-effect to the carbon balance, the consumption of food should already be included in the baseline carbon emissions profile of a city or community during the *business-as-usual* scenario assessment.

Despite the growing popularity of urban farming and the realisation of countless urban food production initiatives (popular examples are *Gotham Greens* in New York City or *DakAkker* in Rotterdam), high-capacity, symbiotically integrated and holistically evaluated UFP systems that reliably account for a portion of the community's dietary needs do not yet exist in the industrialised world. Understandingly, such a profound overhaul of the existing food system would likely be borne out of severe instability and disruptions of the status-quo and requires incentives that go beyond the decarbonisation aim endorsed in this work. However, also the complexity of multi-sectoral holistic considerations and the comprehensiveness of a multi-method/multi-product approach could be one of the possible reasons that impede *research by design* explorations on the potentially positive impact of food production in cities on its carbon footprint. In response to the latter, this work introduces the design component of the *FEWprint platform*, a parametric design and evaluation platform developed for urban planners and designers to provide rapid feedback to design moves during the conceptual phase of the design process. With this platform, urban design strategies that contain elements of food production can be substantiated earlier in the design process with a numerical perspective to the changes in the carbon balance and agricultural output and therefore be used to steer the design process.

The *UFP design* component of the platform has been developed throughout a series of six living labs in various cities around the world, where each case offered a set of site-specific physical, socio-economic and environmental challenges and goals. The workshops were organised as a five-day intense design sprint session, in which a multi-disciplinary team of academic experts, students, residents and other actor-stakeholders engaged in a cooperative effort to quickly produce a (re)design of the context (Yan & Roggema, 2019). Characteristic to this process is the ad-hoc design method, during which out-of-the-box schemes or designs are pitched by projection on the site map in a round-the-table setup. Discussions between stakeholders were conducted through the stacking of tracing paper, each layer building upon the previous until a design is compounded that contained the desired conditions of all actors involved. On the last day of the workshop, ideas were translated into renders, schemes and a narrative for presentation and further discussion.

The FEWprint platform supports this ad-hoc design process by providing rapid feedback after design moves, thereby facilitating a *trial-and-error* form of an iterative process (Roggema, 2021). The time-constrained setting of the workshop means that design liberties have to be taken from situational constraining factors to be able to proceed forward. Therefore, the outcomes do not necessarily show actionable design solutions, but rather an emulsion of various narratives and ideas about the future of an urban context, composed into a final design proposition. This collective vision could be compared and attuned with existing local development plans, policies or climate goals for it to become conductive in continued debates. A team of academic experts and designers streamline the discussion, while the platform can be used to inform on the aspects of food demand, food yield, space required, resources implications and carbon impact: the pentalemma of UFP design.

In this article we introduce and demonstrate the *UFP design* component of the platform. The objective of this work is to develop an accessible, iterative, multi-product and multi-method design protocol for the integration and holistic ex-ante evaluation of food production in the urban context with the aim of lowering the carbon impact of a community. In the *Materials & Methods* section, the general functioning, interface and the underlying theory behind the aforementioned pentalemma is discussed. The FEWprint has been employed in a student-expert design workshop that challenged the participants to come up with a long-term redevelopment plan for a neighbourhood in Amsterdam in which local food production is explored.

6.2 Method & Materials

The FEWprint platform operates as a scenario comparison tool, in which the *BAU* (Business As Usual) scenario assessment sets the benchmark condition, to which the *new* scenario is compared. The BAU scenario constitutes a carbon assessment of the present situation without any carbon mitigating policies or implementations installed, which is demonstrated for six urban communities in Caat et al. (2022a). A *new* scenario can be established by means of three approaches: 1) urban FEW redesign, 2) dietary shift and 3) UFP design; see figure 6.1. FEW redesign pertains to an alternative method of resource provision and/or management for a community. *Diet shift* entails a reconsideration and change of the food consumption patterns of the community, which is demonstrated in Caat et al. (2022b). *UFP design* investigates food production implementations, in which imported goods are substituted with local production. The platform has been developed for the combined application of the three components; however, individual use is also possible.

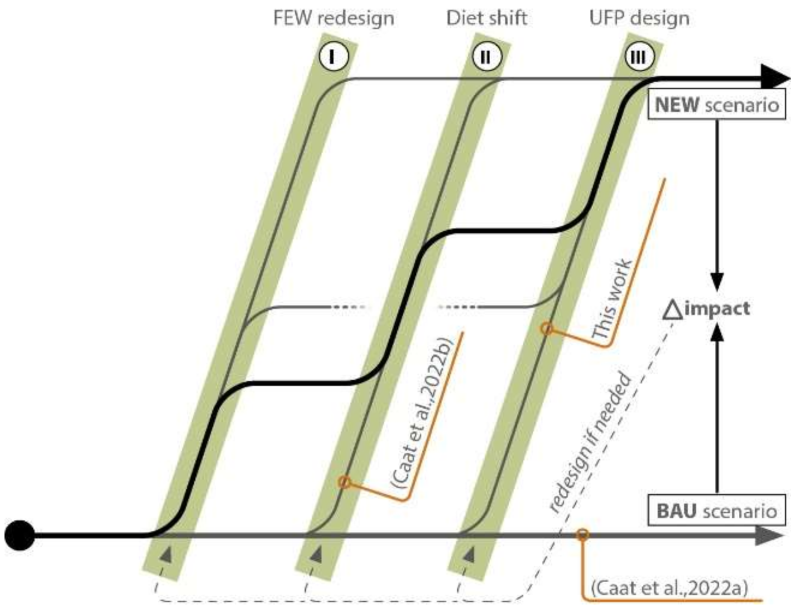


Figure 6.1: *Scenario comparison platform - testing changes to the carbon balance.*

6.2.1 FEW nexus theory

The development of the FEWprint has been conducted along the principles of the Food, Energy & Water (FEW) nexus paradigm, a systems-theory that focuses on the cross-sectoral interactions, inter-dependencies and potential synergies when managing resources (Hoff, 2011). One of the principles of the FEW nexus is an inclusive multi-sectoral attention towards the system's impact during resource management (Leck et al., 2015). This necessitates a quantified insight of resource interlinkages and a recognition that technologies or policies installed to manage one resource sector could cause knock-on effects in the others.

A farm can be considered a materialisation of the FEW nexus since through the principles of circularity, the city's residual resources (e.g. rainwater, nutrients, excess thermal energy) can serve as input for the farming system and vice-versa. This reduces the need to import virgin materials or resources across city boundaries. Secondly, closing resource loops of waste flows reduces the emissions associated with conventional waste management solutions, as was for example demonstrated by Tsai (2008). Even with the aforementioned proximity benefits included, urban crops are more likely to show carbon figures higher than their conventional counterparts on a weight basis (Goldstein et al., 2016; Kulak et al., 2013), however, symbiotic integration and holistic assessment of the systems could result in mitigation of the cumulative system-wide environmental impact.

6.2.2 *Design UFP* component

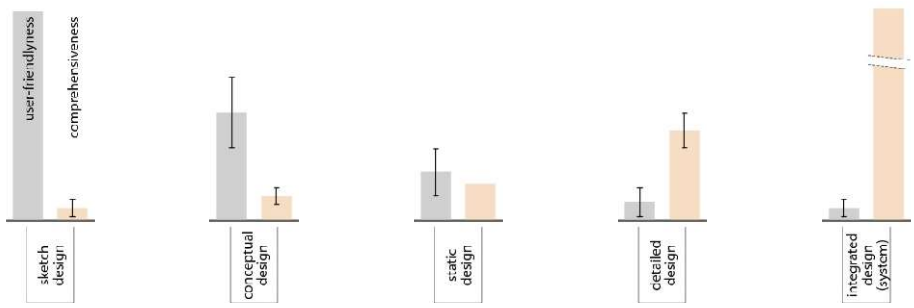
This platform is one of the first multi-product and multi-technique models to integrate strategic sizing of urban farming components in order to interact with community demand and generate carbon indicators. The platform's *UFP design* component offers a framework and workflow to manipulate the UFP pentalemma through an iterative design process. In essence, the design of an UFP system is achieved through a trial-and-error process in which a user-specified food demand is satisfied by assembling a composition of various agricultural elements, whilst not exceeding the spatial constraints of the urban context. The FEWprint operates as a platform that runs instant assessments based on pre-inserted secondary data surrounding various aspects of food production. As such, it can be used by operators without agricultural background knowledge.

In order to provide a meaningful experience and useful results, both operational user-friendliness and the comprehensiveness of the output have to be optimised with respect to each other. A user-friendly experience is fostered by securing simplicity and accessibility to non-experts in the field of food production, but will also depend on information provision and interface, data availability, software accessibility and inter-connectivity of the platform's subcomponents. Comprehensiveness of the output is — in this work — defined by the scope, granularity and situational applicability of the data, the contextuality of an analysis/assessment and the extent to which synergistic design solutions can be investigated and evaluated. Naturally, there is an inverse relationship between user-friendliness and outcome comprehensiveness as more thorough investigations require increasing time, knowledge and/or financial capacity.

An overview of five approaches to UFP design and evaluation in order of increasing comprehensiveness is given in table 6.1 and provides a superficial description on the extent to which a FEW nexus informed design solution could be achieved. The five approaches are not distilled from a systematic review of literature on UFP or FEW nexus theory, but rather have been drafted based on previous experiences with urban food design exercises and around the general principles of the FEW nexus paradigm. Primarily, the applied approach to urban food production design develops from the intended goal or desired analysis output. The FEWprint has been developed to inform urban designer-planners that intend to ex-ante substantiate UFP strategies with a perspective on the environmental implications, with the aim to lower the carbon impact of communities and neighbourhoods.

Table 6.1 An overview of five approaches to urban food production design. The middle column represents FEWprint functionality. Provided information and its position on each spectrum is indicative and a simplified representation of the complex nature of UFP assessment. X-axis: 5 approaches to UFP design and evaluation, in order of decreasing user friendliness and simplicity of the method(s) and increasing output accuracy and representability.

indication



Aim	Sketch design | visual	Conceptual design | hand calculations	Basic design | Holistic assessment	Detailed design | sectoral optimisations	Integrated design | synergies
Description of approach:	*Assigning farming functions to urban surfaces for visual impressions and drafting a spatial/functional organisation.*	*Design and planning to guide strategies and grasp the order of magnitude of food yields and climate impact.*	*Context specific assessment by using secondary data (if available) with consideration of embodied resources and system-wide impact.*	*Context responsive design that produces tailored solutions with the support of specialised software.*	*System-integrated design for context specific, balanced subsystems and optimised overall performance.*
Demand	Not considered.	Figures per macro food group or food category, based on general recommended diets.	Contextual figures based on secondary data, predominantly on food group level. High-impact groups, like animal products, considered on product level.	Contextual figures based on secondary data at product level.	Contextual figures, possibly based on empiric consumption data at product level.
Space	Not quantified. Patchwork-design.	Quantified overview of available space. No conditions apply on suitability	Quantified overview of available space based on manual measurements. Few conditions apply.	Quantified overview of available space, based on advanced spatial analysis software that includes multiple	Quantified overview and in-depth analysis of available space, based on advanced spatial analysis software that

				conditions (e.g. GIS software)	includes multiple conditions.
Yield	Rough estimations with heuristic data.	Category-level data used for preliminary estimations of agricultural yield.	Product-level data, specific for growing climate, used for more accurate estimations of agricultural yield. Secondary contextual data used where available. Synergistic opportunities are manually explored.	Situational product-level data, specific for growing climate + production method, used from crop growth simulations or agricultural models. Yield depends on local climate. Synergistic opportunities are manually explored.	Highly accurate and situational figures on output, based on crop growth conditions optimised to foster local synergies or other system-wide conditions or potentials.
Resources	Not considered.	Farming resource demand minimally considered with general data and manual calculations.	Embodied resources considered at product level, specific for growing climate where secondary data is available. Instant feedback on embodied resources to foster holistic design decisions.	Considered at product level, specific for growing climate + production method and based on location-based optimal growing conditions determined by crop growth models and/or simulations.	Highly accurate and situational figures on embodied resources. Crop growth conditions, and associated resource demand, are based on the optimisation of system's performance, local synergies or other system-wide goals.
Impact, local produce	Not considered.	Local food considered to be carbon neutral.	Considered at food group level, based on secondary and contextual LCA data when available or national data when unavailable.	Considered at food product level, based on secondary contextual LCA data when available.	Local produce is mechanically carbon-accounted by LCA studies.
Impact, resources	Not considered.	Resource implications considered with general heuristics.	Resource implications and associated carbon footprint are accounted for at product level. Carbon footprints [CO_2eq/unit] are based on regional or national indicators.	Resource implications + carbon footprint considered at product level. Carbon footprint indicators are based on location-specific infrastructure.	Local produce is mechanically carbon-accounted by LCA studies.

The required functionality and level of holism of the intended functionality of the FEWprint will concentrate mostly in the central column: *basic design - holistic assessment*. This approach-level offers insight to cross-sectoral resource implications and the subsequent impact based on a pre-installed framework of resource interconnectivity and does not require preparatory actions by the user. Reasonable output accuracy can be achieved by inputting secondary footprint, productivity and embodied resources data that pertains as close as possible to the considered context, product and farming method. However, in line with the accessibility aspect of the platform, a library of universal default data is linked to the design component for a preliminary outlook on the system performance. Finally, the FEWprint comes with a framework to explore and assess onsite management of (domestic) organic waste resource.

6.2.3 A space-based approach

To connect with the discourse of urban planner-designers and resonate with the ad-hoc rapid design process, the platform enables a space-led design approach to food production design, schematically drawn in figure 6.2. In order to reduce complexity of the design component and to be able to better comprehend the resource nexus behind food production, the platform does not simulate interactions between invested resources or their effect on the crop growing climate and the subsequent agricultural output. Instead, it links secondary data regarding farming input-output for a typical farming method with a specific crop. This means that the metabolic interactions of three typical food production methods are expressed in spatial units (m^2 or ha). Consequently, increasing the agricultural output of the system becomes a process of upscaling the selected farming method, changing the product or opting for a more productive farming element, instead of investing additional resources.

The user can assert control over the resource implications by entering custom *scaffolding* data that provides a more accurate representation of the situational climate conditions, a specific growing environment, specific growing methods or practises or a combination of the above.

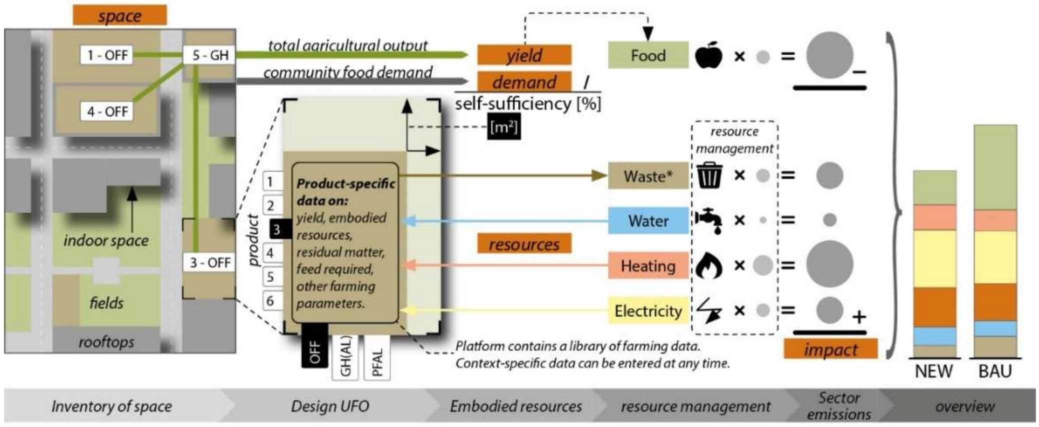


Figure 6.2: *The parametric design component of the FEWprint allocates food production functions to vacant urban surface. Based on the selected crop [3], size [m2] and farming method [OFF], the platform calculates the added resource demand (electricity, thermal energy, water, animal feed) and organic waste production. The resulting impact is based on user-defined management options for resource infrastructure. Agricultural yield is translated into a negative carbon impact and subtracted from the carbon balance.*

6.2.4 Urban Farming Design: grasping the pentalemma

A holistic design and evaluation of (urban) food systems through the lens of the FEW nexus confronts the designer-planner with various considerations that all have a direct or indirect influence on the overall environmental impact or agricultural performance of the system. In conjunction with redesigning the neighbourhood in order to tackle situational urban challenges, the designer is challenged to compose the UFP system in such a configuration, that the proposed targets are met with reasonable spatial and resource investments and a net reduction or the carbon footprint. During the design living labs and the development of the platform, five aspects have been identified that are considered important to control in UFP design: *demand*, *space, yield*, *resources* and *impact,* shown in figure 6.3 below and discussed in the next section.

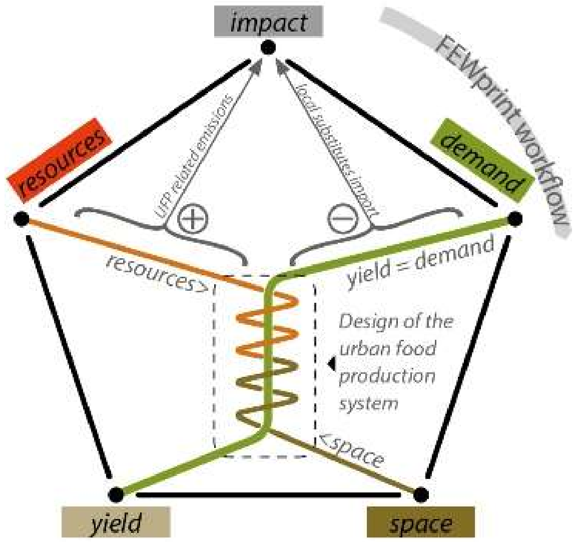


Figure 6.3: *Scenario comparison platform - testing changes to the carbon balance.*

The five aspects in the pentalemma describe spatial and physical potentials and/or constraints. In reality however, there are additional aspects to consider, for example: capital investments, maintenance costs, financial feasibility, market demand, community support, availability of (skilled) labour, zoning laws, development plans, policy and legislation, structural suitability of the substructure to support farming activities, farm accessibility and/or micro-climate and soil conditions to grow the desired crops are equally important aspects that individually could make or break farming implementations in an urban context. Naturally, it is desirable to gain preliminary insight in all of the above aspects early in the design process and foster cross-disciplinary and thorough multi-facetted holistic decision making (also see section 6.4). However, incorporating these aspects would over-complicate the platform and it would detach the framework from the intended purpose, namely investigating local food production strategies as a method to mitigate the carbon footprint of the urban environment.

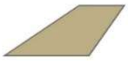
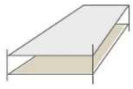
6.2.4.1. Demand

Food *demand* constitutes the full or partial community food requirement, based on the combination of 18 representative staple food groups. The design of the local food system is guided by a combination of production target(s), i.e. a percentage of the demand, specified per food group. Excess production of goods is not considered as a way of carbon emission offsetting, as is usually the case with a consumption-based carbon accounting approach. An overview of the 18 food categories and the sub-products provided as default options in the UFP design components can be found in Appendix 6B.

6.2.4.2 Space

Space refers to the availability of suitable in- and outdoor surface area that can be used for agricultural purposes without sacrificing existing nature area or indispensable urban functions. Early in the design process, an inventory of the available urban space should be made that forms the *space budget* for the food system that is to be designed afterwards. As in reality, the built environment is a patchwork of various uses of space, the potential suitable space is reduced to three generic sub-surface types in the platform: *open field*, *rooftop area* and *indoor space*, which are briefly addressed in table 6.2.

Table 6.2 Description of the space typologies used as potential subsurface for an food production element.

type 1: open space 	type 2: rooftop space 	type 3: floor space 
Plots of space at ground level with considerable dimensions, suitable for conventional farming practices or to place greenhouse structures.	Unused surfaces located on flat/horizontal rooftops of (existing) buildings with considerable dimensions and regular shapes.	(Semi) indoor floor space, available for controlled indoor agriculture, also known as plant factories, possibly practised in the form of vertical or stacked farming.
Examples of surfaces: parking spaces, sports fields, unused space, brownfields, roadside greenery, squares, courtyards, gardens, banks,	*Examples of surfaces:* supermarket rooftops, rooftops of factories/industry, rooftops of parking garages, rooftops of tenement dwellings, sports venues.	*Examples of surfaces:* parking garages, (part of) empty buildings, basements, new structures intended for food production, former industrial halls.

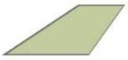
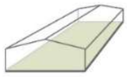
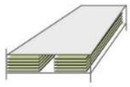
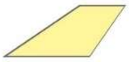
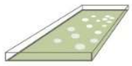
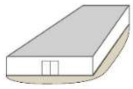
6.2.4.3 Yield

The underlying motivation of current-day urban farming practises varies between initiatives. The production of local and healthy food would be the typical purpose of a farming system in the urban context. However, it is not uncommon to find initiatives with a social, commercial, architecturally aesthetical or even an experimental or protest incentive. The notion of *urban farming* is broad, and the array of examples and methods is wide. This article adheres to the definition of Veen et al: '*the production, processing and marketing of food and food-related products and services in the urban and peri-urban areas, making use of urban resources and waste'* (2012). Veen emphasises that this definition does not discriminate any UF methods or scales so long as the food production becomes an integral part of the urbanity. This study, however, only informs on professionally organised farming methods that operate on a considerable capacity and prioritise agricultural output as opposed to farming initiatives that have a social aim or that are organised on an individual or household level.

Yield reflects the cumulative agricultural output from all the food-producing elements and should match the *demand* at food group level. By default, agricultural yield is expressed in absolute values per food group [ton/yr] and relative values [%/group demand]. Yield could also be noted in terms of locally produced protein ($gram_{prot}$/cap/day) or protein availability relative to the daily need of a person (%), which would require minimal additional hand-calculations by the user. Crop yield is determined by combining space [m^2] with productivity of a farming method for product (n) [kg(n)/m^2]. To estimate the output of livestock farming (meat, dairy, eggs), several key factors are taken into account, for example lifecycle of an animal [days], carcass weight [kg/animal] and productivity [$kg_{dairy/eggs}$/animal/day]. This data is part of the scaffolding data and can be adjusted if considered necessary. Appendix 6B gives an overview and explanation of the default scaffolding data and Table A6.1 lists all the default food groups + products used on the platform.

The array of methods for food production is broad. In addition to controlling environmental aspects of indoor temperature [°C], light intensity [PPFD] & duration [hrs], humidity [g/m^3] and CO_2 concentration [PPM] through closed growing environments, the farmer can optimise nutritional and water uptake in the root zone of the plant by opting for *hydroponic* farming (open vs. closed systems, no substrate vs. with substrate), which has become the standard in most European highly-productive systems (Maucieri et al., 2019). Hydroponic farming can take different forms, most common hydroponic examples being *nutrient film technique* and *deep flow technique*, next to *aeroponic* systems, but the platform does not facilitate assessment on this level of detail. The FEWprint distinguishes three crop growing environment methods for UFP design: standard outdoor field farming (OF), greenhouse horticulture (GH) and plant factories (PF). In addition, information is provided on three agricultural land use types that are not part of the primary design process. An overview can be found in table 6.3.

Table 6.3. Overview and description of the standardised farming components

type A: FF field farming 	**type B: GH(AL)** greenhouse horticulture 	**type C: PFAL** plant factory artificial lighting 
Farming element manually set by user.	*Farming element manually set by user.*	*Farming element manually set by user.*
Standard outdoor field farming can be practised on open fields as well as rooftop subsurface. By default, FF does not require any electrical or thermal resources, however user can enter custom values. Water demand for irrigation is accounted for.	Greenhouses (artificial lighting) can be placed both on rooftop surfaces and on ground level space. GH require both thermal and electrical energy for conditioning and water demand is accounted for. Artificial light <u>can be added</u> to prolong the photoperiod in the greenhouse. In practise, GH farming can take up various forms and resource demand/yield is variable.	Plant factory elements can only be placed in indoor spaces, where <u>only</u> artificial light is used to stimulate photoperiod activity. In general, PFAL require more electrical energy and zero thermal energy. Water demand is accounted for. Hydroponic crop growing beds are stacked to multiply yields per surface area.
type D: animal feed farming AFF 	**type E:** animal outdoor space AOS 	**type F:** animal housing AH 
*Semi-calculated**	*Auto-calculated by platform*	*Auto-calculated by platform*
Outdoor field farming, assigned for the production of animal feed crops.	Open field farming, assigned for livestock outdoor space (includes grazing).	Animal housing, indoor space used for the housing of livestock.
**semi-calculated:* Platform calculates and recommends minimum required cropland are in order to feed the livestock, based on standard animal diets and average productivity values of animal diet products. Quantity of livestock is auto-calculated based on the demand for animal products. The user can specify the final space assigned to a required crop.	Space requirements are directly based on number of animals present in the UFP system. Livestock that is kept under organic- or enhanced animal welfare conditions generally use more space per individual animal.	Space requirements are directly based on number of animals present in the UFP system. Livestock that is kept under organic- or enhanced animal welfare conditions generally use more space per individual animal. Note that housing only includes space used for animals and excludes service, storage, traffic and auxiliary spaces.

6.2.4.4 Resources

The agricultural productivity of a specific crop depends on various variables and farming parameters. Climate conditions and crop genetics determine the potential yield of a crop, i.e. the maximum obtainable yield in a specific geographical location. In practice, the farmer will endeavour to close the yield gap by means of adequate farming management, by improving the potential yield though growing more productive genetic variations of the crop, or by providing a growing environment that is closer to the desirable growing conditions of the plant (Stanghellini et al., 2018). Switching from outdoor farming to an enclosed indoor growing space, commonly carried out in the form of polytunnels or greenhouses, allows the farmer a first degree of control over the temperature, light intensity and humidity. From here, further optimisation of the climatological elements is possible through for example hydroponic production, artificial growth lighting, cooling and heating and CO_2 fertilisation. Creating an artificial growing environment is a resource-intensive process, especially under ambient climate conditions that deviate considerably from the desirable indoor climate. Therefore, in greenhouse and PFAL farming there is a general correlation between the quantity of invested resources (gas, fuel, electricity, water, nutrients) and the remaining size of the yield gap.

Resources refers to the embodied or invested resources required to operate the farm and to obtain the intended productivity. The FEWprint applies a stratification of invested resources with a maximum of four tiers, shown in figure 6.4. The *demand* for food is derived from the average community diet and is considered the final resource. Bio- or organic waste refers to the inedible organic material of the crop yield and is expressed as a fraction of the on-farm actual yield. *Feed* refers to the crops required to feed the livestock and is assumed to be produced on field farming; hence an irrigation factor is included.

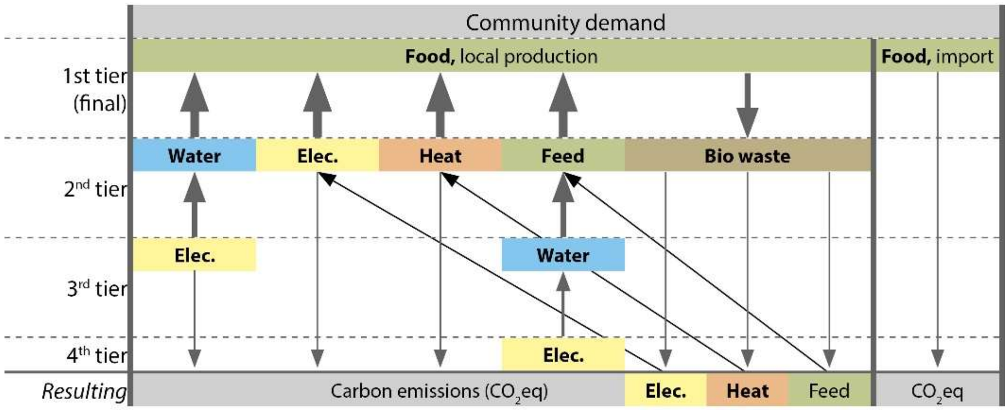


Figure 6.4. *Four-tiered stratification of embodied resources.*

6.2.4.5 Impact

Finally, the *impact* is the resultant based on the configuration of the other four aspects *demand, space, yield* and *resources* and expresses the carbon emission changes within the food sector and subsequently the difference the composed food system can make to the total carbon balance of the community. The carbon footprint in the new scenario is calculated with equation 1:

$$C(Food)_{new} = C(Food)_{import} + C(UFP)_{FEW} + C(UFP)_{proc} \quad [1]$$

Where $C(food)_{new}$ represents the total food sector emissions [ton/yr], $C(food)_{import}$ notes the emissions of the imported food resources that also remain imported in the new scenario. $C(UFP)_{FEW}$ describe the emissions associated with the invested resources, mainly energy, electricity and water. Finally, $C(UFP)_{proc}$ accounts for the emissions occurring at the *off-farm* food stations (a.k.a. farm gate-to-fork emissions) of locally produced food goods. The ratio on-farm/off-farm emissions and the food-station categorisation follows the mean global indicators determined by Poore & Nemecek (2018). The underlying equation framework is further discussed in appendix 6E.

Finally, the FEWprint offers a framework for two approaches to design and assess food production in the urban environment: the community and the *moveable* approach (table 6.4), the latter is a reference to the project title. *Moveable* refers to an autonomous state, independent from an existing urban context or community with whom no exchange of resources could take place. The choice of approach has consequences for the way food production targets are specified and how the UFP system is assessed.

Community approach. In a *community assessment* approach to system design and assessment, the food system is considered as an integrated component of the community in which it is physically localised. The resource implications and corresponding carbon emissions are considered part of the community, i.e. the farm produces food only for the community and it withdraws resources from existing resource infrastructure. This means that the evaluation of farming activities is done from the perspective of the community, in which UF implications are settled to establish a NEW scenario.

Moveable approach. The *moveable* option has been added to broaden the usability of the evaluation platform. In cases when there is no community present from which a food *demand* could be derived, a *moveable* approach is more suitable. This method considers only UFP system emissions and evaluates it as an autarkic entity. This option is also suitable in scenarios where the food system provides for a group of people that are not dwelling in the area, for example a farming system on university campus grounds or in a commercial area. Table 6.4 compares the functionality of the two systems.

Table 6.4. Two main approaches to UFP evaluation supported by the platform.

	Community Approach	**Moveable Approach**
Production target(s):	% of the daily intake of 1 community member [%] (expressed per food group, value between 0-100%)	Annual production target(s) [ton/year] (specified per food group)
Scope	FEW use of community + FEW demand UFP system + UFP food yield	FEW demand UFP system + UFP food yield
Description BAU scenario:	The baseline scenario in a *community approach* is formed by a FEWprint carbon assessment of the community, without any UFP implementations, dietary shift or other policies installed.	The baseline scenario in a moveable approach is set by calculating the virtual emissions of all the food quantities entered under the *demand* aspect. In other words: the production target is translated into import emissions.
Description NEW scenario:	FEWprint assessment + carbon assessment of UF activities and agricultural output (dietary changes optional)	Carbon assessment of farming system's resource demands plus remaining food chain emissions.

6.3 Redesign of a neighbourhood: Kattenburg and the Marine establishment

This chapter demonstrates an application of the platform during a 1-day (re)design workshop for a neighbourhood in Amsterdam, which took place in April 2022 at the Faculty of Architecture and the Built Environment in Delft. A group of building engineering and architecture students was composed, together with two academic experts in the field of urban farming and city design, to come up with a redesign strategy that pivots around sustainable production of food. The objective of the workshop was to validate and test the FEWprint-steered design approach in which feedback on system and UFP performance is rapidly provided after every design move. The workshop's output, a design proposal for the case area that is numerically substantiated with preliminary figures on resource demand, food yield, self-sufficiency and carbon impact, is described below.

6.3.1 Workshop design process

The participants were instructed to come up with a transformation plan for an artificial island in the centre of Amsterdam, which currently includes the residential neighbourhood of Kattenburg and the former naval base called the Marine Establishment/Marine Terrain, which are jointly named KBMT, shown in figure 6.5. Ownership of the MT will be transferred to the municipality, after which it is scheduled for redevelopment into a mixed residential-educational-commercial area. At least 800 new houses, 1400 workplaces and 1400 study places are planned for the island (Stuurgroep Marineterrein, 2021). Past stakeholder meetings highlighted and confirmed several local challenges, which are turned into design spearheads for the workshop and are further discussed together with additional relevant requirements in Appendix 6A. The baseline FEWprint for Kattenburg is based on the consumption data mentioned in table A6.2 and the carbon emissions footprints listed in table A6.3.

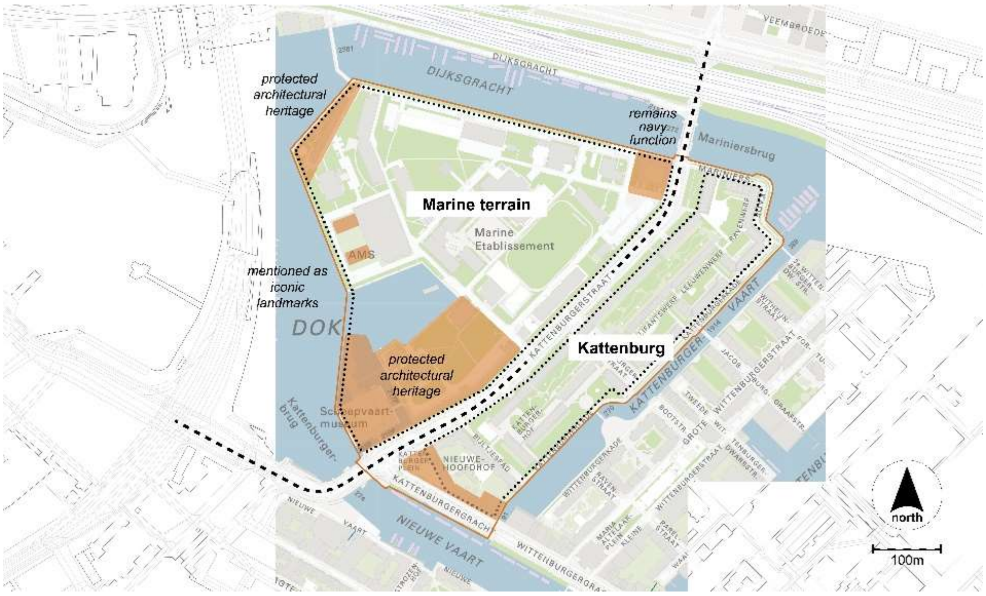


Figure 6.5*: KBMT case study. To the left of the main road is the Marine terrain (MT) and to the right is Kattenburg (KB). one of the umbrella challenges during redesign is to integrate the two sides.*

The workshop followed an abbreviated version of the 13-step iterative design process (figure 6.6.) described by Roggema (2021), which was developed to streamline the discussion between diverging discourses in order to produce a FEWprint-assessed design proposal in a short period of time, i.e. 3-5 days. The design team was asked to come up with a design that responds to situational challenges and projected population growth — presented at the start of the workshop — by urban (re)design in combination with establishing a food-centred community. As the goal of this assignment was to come up with a design for a food producing system under the support of the FEWprint framework and platform within a very brief period, no emphasis was put on architectural style and the urban design proposals or strategy remain programmatic, diagrammatic and numerical, and any visualisations remain volumetric and abstract. To avoid start-up hiccups and maintain a steady design flow throughout the workshop, a completed business as usual assessment was provided from the beginning and the platform was operated by the first author of this paper. More information about the workshop is provided in Appendix 6A.

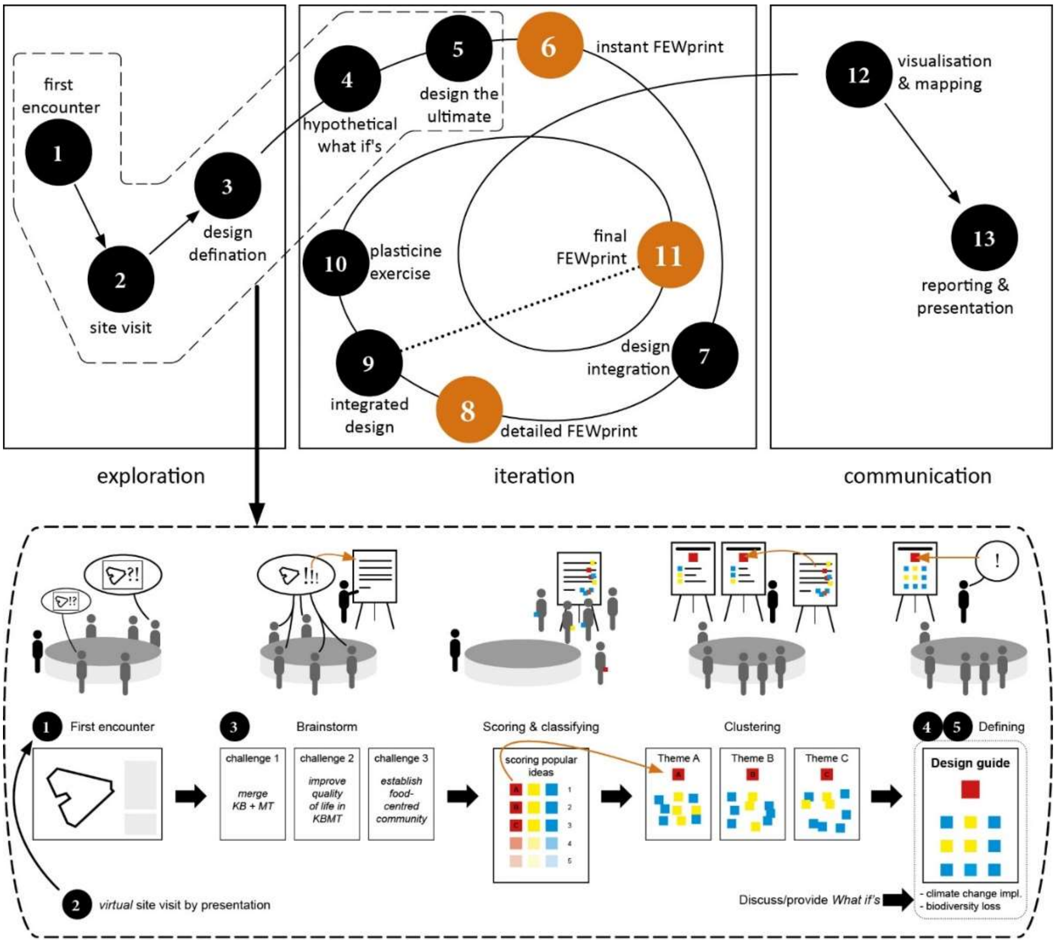


Figure 6.6. *Design workshop approach. The top scheme shows the original workflow conceptualised by Roggema (2021). For the design workshop in this study, the five-day approach has been compressed into a one-day exercise, for which step (2) and (10) had to be omitted. The bottom scheme visualises how within 1.5 hours, a design guide was formulated.*

Based on previous meetings with stakeholders and desktop research, vulnerabilities to the quality of life on the KBMT island were identified and aggregated prior to the workshop. Spearheads for redesign were extracted from the *note of principles for design* report which extensively describes, visualises and advises on the (future) spatial quality of the island (Stuurgroep Marineterrein, 2021). Spearheads and challenges are listed in Appendix 6A. Three broader but local challenges were presented to the design group to kick-off brainstorming: 1) the merging of the KB and the MT part of the island under future changes, 2) securing and improving the quality of life and 3) transforming KBMT in a food-centred community. Two so called *What ifs* were introduced as external threats to the community: biodiversity losses and climate change implications, in this context referring to heat waves, long droughts, extreme precipitation events and sea level rise. The former implies the protection of existing green area — for simplicity assumed as the marker for biodiversity — and the latter steering towards increased self-suffiency of food to enhance resilience against future food chain disruptions. Through an intense session of brainstorming and discussion, a guiding theme was distilled for further design.

6.3.2 KBMT Design proposal

The team embraced an *archipelago park* design theme for the future of KBMT, see figure 6.7. Morphological changes to the land and substituting roads with canals allows water to penetrate deeper into the island, creating more space for peak precipitation attenuation, capture and storage, leading to an overall higher water concentration on the island that aids the mitigation of the urban heat island effect and sustain any food production with rainwater during a long period of drought. The new urban programme was planned around these land changes, where a large concatenation of mixed residential and commercial city blocks forms the north wall of the island, an architectural solution that is commonly applied to former industrial areas in the vicinity. A cluster of 8 mid-rise buildings on the central-East part of the island provide the remaining space for the future program. The team proposed to bring the dividing road underground, making space for additional parks and agricultural land, thereby adding incentive to use this new space and increase the number of connections between KB and MT. This makes the island car free and fosters reliance of water-based public transportation, as is for example observe in the port city of Rotterdam with water taxis and ferries.

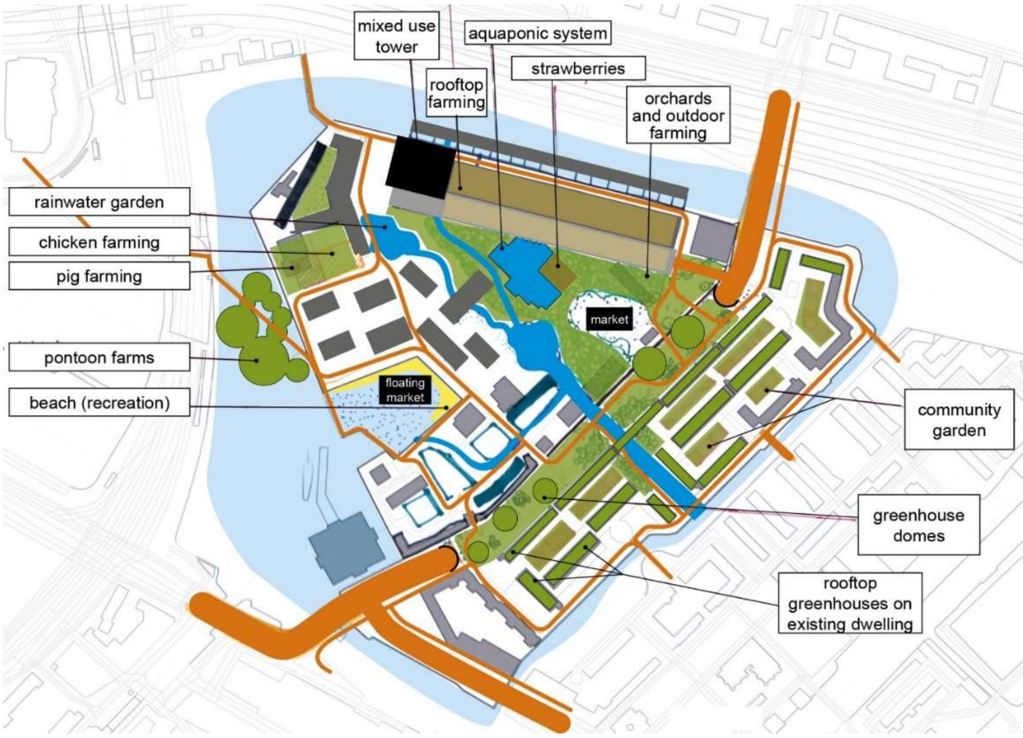


Figure 6.7*: Final design proposal for the KBMT workshop (plan has been embellished digitally after workshop but follows the proposals and outlines by the design team)*

In line with the food-centred community goal, the team assigned agricultural functions to all extends of the island, with a large central food production plain in the centre. In addition, additional space was created on floating pontoons at the perimeter of the island to grow the remaining requirement of livestock feed. The excavated basement of a demolished building is reused as a large, enclosed fish farming facility, providing 100% of the present demand for fish. Vegetables, potatoes, fruits and pulses are produces on the rooftops and at ground level fields around the island, yielding a varied combination of local produce, up to 100% of the total vegetable demand of KBMT. A small organic pig and poultry farm is added to the island. Animals are fed a combination of processed KBMT domestic organic food waste and local produce.

Assessment of the designed food system shows that substituting regular imported food with local produce reduces the per capita emissions in 2030 with an estimated 7%, or ±221 kg/cap*yr. This reduction includes both the avoided emissions due to recycling organic waste for animal feed and the lower impact of local production vs. imported food goods. The reduction does not contain the projected reduction of grid mix electricity carbon footprint (assumed 0.427 > 0.300 kg/kWh_f). The total food system yields about 216 tons of crops, 52 tons of meat, chicken and fish and 8 tons or eggs per year. The system is designed according to the present average consumption of KBMT, which means the production of vegetables is capped at 131 gram/cap*day, i.e. the total requirements of one person. About 338 ton of domestic organic waste is converted into animal feed annually, which drops the required land to grow livestock feed crops from about 27 ha down to about 4 ha. The FEWprints of both scenarios are compared in figure 6.8 below.

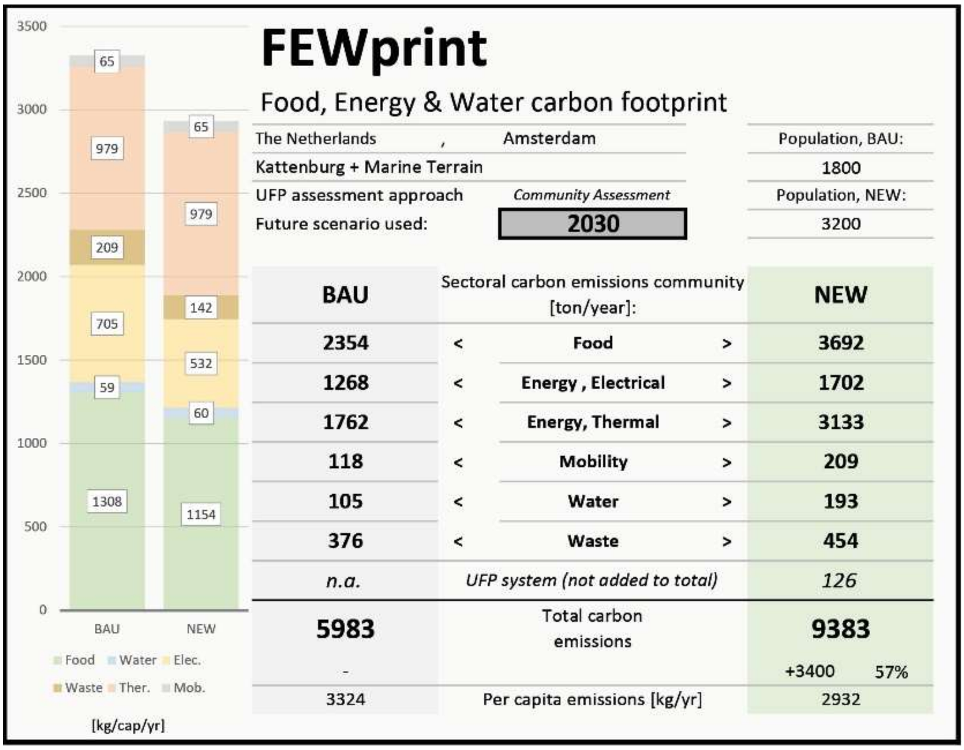


***Figure 6.8**. FEWprint of KBMT. The BAU columns shows the 2020 carbon emissions, the NEW column shows the 2030 estimations. The NEW scenario includes the projected population increase, the assumed carbon footprint reduction of grid mix electricity and the influence of the food producing system, including the emissions avoided by averting the incineration of organic domestic waste.*

6.4 Discussion

6.4.1 FEWprint in the design process

In urban neighbourhoods, exchanges between individual flows, linkages across scales and the benefits of establishing synergies between resource systems could illuminate unexpected advantages for urban life, urban resilience and environmental pressure. This can be explored through an unrestrained design approach, like the 13-stepped approach proposed and methodically described by Roggema (2021). A non-linear *research-by-design* process, informed by indigenous values and risks, allows to navigate unconventional spatial solutions to outline new transformative pathways and create unexpected perspectives on the future of a neighbourhood (Roggema, 2016). Awareness of the FEW nexus interlinkages is an opportunity to make these systems and their advantages visible in the urban space instead of degrading them as hidden drivers of urban processes. Stakeholder-engaged and bottom-up design collaborations though the lens of the FEW nexus paradigm challenges the multi-actor design team to make integrated resource infrastructure a visible and tangible element in the urban landscape as a method to experience sustainable progress and/or self-sufficiency. Under the umbrella of this design ethos, the *Design UFP* component in the FEWprint guides the integration of food systems in cities.

The platform has been developed as an integrated step of the FEW nexus iterative design approach and streamlines on a high spatio-temporal resolution the design and assessment of local food production. As such, it finds useful application at the interface of environmental engineering, sustainable urban design-planning, agriculture and building engineering. At present, the discourse discussing this interface has been rather niche and primarily of explanatory and theoretical nature, this work included. In addition to carbon emission accounting of the resource flows in the neighbourhood, the FEWprint can aid commercial, educational and governmental bodies in navigating the complex task of introducing UFP systems in already well-established urban settings or evaluate UFP as an autonomously operating entity.

Lessons learned

Based on the experiences and lessons learned during the discussed design workshop, advice is given for future application of the decision support platform. For organisational purposes, the workshop was condensed into one day instead of multiple days. This leads to concessions to the design freedom of the team, as local challenges and design values are presented as facts and boundary conditions. The omission of actual discussion within a multi-disciplinary team of stakeholders means less attention is given to the dynamics behind and links between challenges or values. As such, a design objective remains rather objective, testable and 'cold', whereas a multi-day design collaboration with stakeholder engagement at the front and backend of the workshop would establish design goals that are likely more in pursuit of conceiving a new *urban atmosphere* as the design workflow is more immersive through conversation. The actual design time was reduced to 2 x 90 minutes, following step (7) and step (9) of the design approach. In reality, it is difficult to grasp the context, get acquainted with the boundary conditions and 'building blocks' of the FEWprint, gain design momentum, design the neighbourhood, integrate the food system and have at least one round of iteration in such a short period of time. Hence, a certain visual refinement of the design proposals not possible, and the design propositions remain superficial.

The primary goal of the workshop was to test the interaction between platform operator and the design team. The design team was first introduced to the platform during the introduction presentation, and information regarding the FEWprint's control over the pentalemma was provided on separate information sheets that could be applied during the design stage. It was challenging for the operator to keep up the with speed of the design process and provide instant feedback on system performance during the workshop. This is a consequence of two organisational decisions. First, the short time frame. Sufficient time should be reserved at the start of the workshop to familiarise the team with the platform's (im)possibilities, scope, food inventory, design elements and performance indicators for a smooth kick-start. Preparedness could be improved further by sharing accessible documentation (e.g. a manual) with the team prior to the commencement of the workshop. Second issue is a discourse misalignment between the operator and the designer team and is directly related to the level of preparedness of the design team. Once the design process is set in motion, the design team needs to be aware of the terminology of the operators and vice-versa and interruptions for explanation should be avoided.

To better inform the design process, we propose a combination of instant on-the-go feedback and isolated assessment moments, figure 6.9. To start, we assume a longer design period in which the design process is divided into several multi-hour blocks and that one or two members of the team are assigned as platform operators. The operator initially acts as a part of the design team and advises the process according to the capabilities of the platform. When the design team is on a break, for example during the lunch or evening, the operator makes a snapshot of the current progress, assesses it, and starts the succeeding design block by presenting an interim status report and advice on possible design course adjustments needed to obtain goals. This process can be repeated between design blocks and the design becomes more defined and detailed over time. As the workshop proceeds, the operator gradually shifts the focus on the evaluation of the proposals and less on the design itself. In parallel, the design team increases its interaction with the platform as the team's understanding of it improves by experience. This method makes use of the pauses in the design flow, allowing time for the operator for assessment and creates a window to steer the designers before they regain momentum, after which it is more difficult to offer guidance.

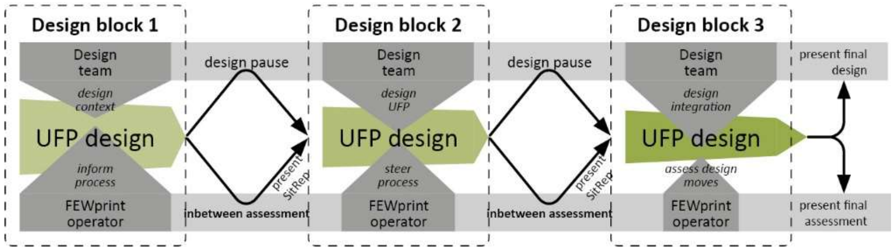


Figure 6.9. *We advise to schedule multiple interim assessments of the design strategy and provide situational reports (SitRep) to the design team for effective steering. The number and duration of each design block depends on the organisation and can be more than three.*

Accessibility

The FEWprint has been developed around accessibility to the non-expert user. As such, it is hosted on a public web domain (www.m-nex.net, version 10.2 on 4-4-2022) and can be downloaded without registration or costs. The FEWprint operates on the Microsoft Excel 2016 format and is provided with a step-by-step user-guide which provides detailed information about the three components, the various aspects of the FEW nexus and manual to explain in detail the functionality of the platform. The platform requires no coding skills. Transferability is possible by inserting new location-specific input data and no structural change to the framework has to be applied. A customisable and expandable library of default resource management services and resources has been added to the platform to streamline the insertion of new data. Scalability is possible through the increase of a population in combination with inserting updated average end-user consumption indicators, for example an upscaling from a neighbourhood population assessment to a district population assessment.

6.4.2 Limitations.

At present, the platform lacks a geospatial component such as GIS integration, which would benefit data accuracy and limit data insertion errors. Even though the internal library of default data can be used for quick estimation on the carbon footprint of a community or for a preliminary perspective on the carbon implications of an UFP strategy, contextual data is required to control the sensitivity of the outcomes and produce well-informed design solutions. Aggregation, processing and entering new data can be a time-consuming and meticulous assignment. A database plugin from an external source could overcome this issue but would lead on its turn to a reduced controllability of the input data.

In a computerised world, there is often a decision support platform for a specific design problem or challenge. A recurring limitation of a decision support platform such as the FEWprint is the misalignment between the expectations from the user and the information provided by the system. The platform calculates changes to the carbon emission balance of an urban community, based on parametric changes to resource demand, based on modifications surrounding the resource provision methods, based on applying different carbon intensities and finally due to adding the net emissions (positive or negative) associated with an urban food production strategy. The FEWprint does not generated and recommend optimal design strategies centred around user-defined parameters, but rather tests the impact of a programmatic design proposal formed during a design effort. The platform cannot be used to produce a meticulous analysis of the resource implications of urban farming practises, nor is the model an operational tool that can be employed to make real-life changes to respond to emerging externalities or support everyday farming management decisions.

The quality and/or relevance of the FEWprint output is as good as the quality of the data input. Internally, the platform organises and links the end-user resource consumption data or the resource input of farming elements with carbon emission intensities of resource infrastructure in the local context. The contextuality of data depends on the data aggregation or measuring level of the responsible agency which supplies the data. Aggregated data cannot be correlated with specific local activities, demand or people and is likely to depict a consumption profile deviating from the local reality (Chrysoulakis et al., 2013). In parallel, scaling up individual properties to the neighbourhood population might equally lead to an unrealistic perception of neighbourhood flows and cancels out individual differences. Carbon emission intensity of consumer goods, resources or services is preferably noted with figures representing a full-scope assessment, which is not always possible or feasible to verify. Finally, it should be remarked that the future shape and program of a city is designed and assessed based on today's data. It is difficult, if not impossible for some figures, to embed evidence-based projections on demographics, resource consumption, carbon intensity and agricultural data in input values, causing a certain sensitivity in the output data.

6.4.3. Outlook and future work

Assessing food production

The metabolic flows surrounding the production of food —in this work being electricity demand, water demand, heating demand, agricultural yield and organic waste — are retrieved from secondary data sources, of which an overview is provided in appendix 6B and 6C. This method does not allow to simulate the interaction between resource input and agricultural output. In other words, the agricultural yield of a farming method cannot be manipulated by amending the resource input. To an extent, it can be assumed that a dataset already describes a reasonably maximised situation when the yield value is described as a derivative of the quantified invested resources. The means that all data should preferably come from the same dataset, describing the performance of the same farming system. This would be difficult to find for most contexts, especially across the entire inventory of food products.

Crop growth or horticultural simulation software can be used to overcome data insecurities and uses a combination of farming parameters and site-specific climate data to calculate the yield for a designated context. Embedding this specialised software in the interface and framework of the platform would lead to concessions in terms of user accessibility due to specific knowledge required to operate such advanced simulation models and grasp the substantiating theory. Alternatively, the FEWprint could be expanded with an extensive library of input-output data describing best-practise situations of specific food crops, for the three basic production methods and tailored to different climate classes. This method would yield the closest approximation to reality whilst still operating on existing data. However, populating a database with mechanistically acquired indicators for farming would require considerable time investments at the front-end. In addition, this method would still lack the possibility for more thorough simulations of farming management alternatives.

Towards a triple-bottom assessment

The current version of the FEWprint has been developed around the *pentalemma*—five relevant aspects for the integration of food production in the urban environment— with performance indicators that directly or indirectly revolve around the carbon impact of cities or communities. Platform (sub)components that evaluate additional aspects could be added to the current version of the platform that provide additional perspectives at the early phase of the design. For example, coupling current and local market value indicators with end-user domestic resources (kWh, m^3 gas, m^3 water, kg food), agricultural output of farming elements and land prices would expand the nexus-pentalemma assessment with approximations on economic feasibility, especially when further expanded with indicators on capital investment, maintenance expenses and/or hourly labour costs. Finally, an auto-calculated translation of agricultural yield into popular nutritional indicators like a daily availability of vegetables, fruits, pulses or (plant) protein to provide a perspective on healthy food availability within a community would complete the triple-bottom (people, planet, profit) quantifiable substantiation of an urban food production strategy.

Further smaller expansions of the platform would be to include *neo-farming* products as alternative protein sources, for example insect farming. Alternatively, it could expand with a *façade farming* element for more design freedom and assessment during the design process. Finally, it could broaden the output with alternative environmental indicators. These would include the *virtual water* and *embodied land* shadowing (food) resources, impacts that both are routinely captured with LCI assessment studies and can therefore be added to the platform. Since both conventional domestically used resources as well as popular sustainable alternatives—including resources associated with UFP— have direct and/or indirect implications to the aforementioned indicators, a comparative assessment between a BAU and new scenario can be conducted in a similar fashion as the CO_2eq emissions assessment.

6.5 Conclusion

This work introduces and demonstrates the Urban Food Production (UFP) component of the FEWprint platform. This component can be used to aid decision making around UFP during the early and conceptual stages of the urban design process and evaluate UFP strategies regarding its carbon impact and agricultural output. This work discusses five inter-linked key aspects required to be balanced while designing agro-cities or neighbourhoods: *demand, space, yield, resources* and *impact.* The platform is used to control these aspects and numerically substantiate UFP strategies with preliminary figures. The FEWprint is developed to provide instant feedback of design moves and to be operated in parallel to the design process. Application of the FEWprint in a design workshop for a case study in Amsterdam underlined the complex task for the platform operator to keep up with the ad-hoc design flow and support effectively. It is therefore advised to follow a mixed role of the FEWprint: to provide instant feedback during the design process by the operator and scheduled moments of reflection on the design, informed by a snapshot analysis, to effectively steer the design team.

6.6 Acknowledgment

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PART IV

Conclusion

7

Conclusion

The urban Nexus - dissertation

7. CONCLUSION

7.1 Introduction

When analysing the carbon footprint of urban residential neighbourhoods, food-related carbon emissions can be responsible for a considerable part of the total emissions. This doctoral research explored how urban food production can be applied as a strategy to *decarbonise* cities. In other words: how can food production systems within the urban boundaries be used to mitigate the carbon emissions footprint consequential to urban resource consumption and resource supply chains.

Relocating food production within the geographical boundaries of an urban neighbourhood has the potential to reduce the food-sector emissions due to producer-consumer proximity related benefits, also referred to in this work as the direct reductions. Simultaneously, *urban food production* imposes additional resources demand on the existing urban resources infrastructure, consequentially driving up carbon emissions of the community, referred to as the direct implications. To add more ballast to the *decarbonisation* effect of UFP, the indirect impact should be taken into account – meaning the urban emissions avoided when conventional urban resources infrastructure or systems are substituted with food production related *ecosystem services*. On that aspect, this work mainly investigates the positive impact of recycling organic waste streams.

The complexity and comprehensiveness of food production makes it difficult to provide rapid holistic evaluations during the urban design process. Along the principles of the FEW nexus systems theory, this research presents a method and platform called the *FEWprint*, to guide the implementation of food production into the urban context. The platform can be used by the *agro-urban* designer during the conceptual and explorative phase of the design process to navigate various options and alternative scenarios for food-centred communities and assess the carbon benefits and implications derived from this.

The platform has been developed through a series of Living Labs organised for the *Moveable Nexus* research project (section 1.6.1) and various other smaller applications by building engineering/architecture students and the main author. At the final stage, a student-expert design workshop was organised around the application of the platform to test and optimise the interaction between the design team and the platform operator.

This final concluding chapter summarises and discusses the main outcomes of the dissertation. First, it responses to the research questions discussed in the introduction, starting with the sub-questions and their specific findings as partial outcomes that support the main research question. Furthermore, this chapter defines the scientific contributions and limitations of the study. Finally, this chapter will propose recommendations for future developments and research regarding the application of food production in the urban context and the application and continued development of the FEWprint platform.

7.2 Answers to the sub-questions

How could a representative carbon emissions profile of urban resource use be made that includes the activities of urban food production?

At the tail-end of resources supply chains, cities form dissipative entities that use large quantities of energy and materials to make life possible. A carbon emissions profile categorises and lists carbon equivalent emissions associated with urban resources infrastructure and forms the accounting basis to ex-ante estimate the impact of alternative resources management strategies and/or local food production implementations. Such a profile should be sufficiently comprehensive to depict a representative reflection of the present urban carbon impact and remain equally suitable when urban food production elements are added to the context. Three methodological aspects have been defined to answer this sub question: 1) resources scope, 2) food assessment inventory, 3) assessment depth. To answer the sub-question, an exploratory study was performed.

resources scope. To establish a suitable carbon analysis scope, i.e. the resource sectors that are included during carbon accounting, an exploratory study was conducted. This study describes the implementation of a livestock farm within the geographical perimeters of a residential neighbourhood and focussed on a single food product, *pork*, to get acquainted with the FEW nexus approach towards food system design. The study first used existing literature to estimate the embodied resources required to operate the farm. Second, it looked at the practice of pig rearing and reduced this activity into a handful of key parameters to make it computable and to determine the farm's output. Third, input-output analysis identified the potential overlap between the urban resources infrastructure and the metabolism of the farm and pinpointed opportunities for material recirculation. Finally, additional infrastructure and/or systems required to bridge the gap between the farm and the neighbourhood was studied, including transportation/processing losses and embodied resources of this infrastructure. The urban resources that were either directly or indirectly influenced by the implementation of the UFP system demarcated the carbon accounting scope of the study's assessment. Tertiary implications surrounding UFP were not assessed in the platform, for example auxiliary resources needed for support infrastructure.

Based on the experiences and insights of this study and the principles of the FEW nexus paradigm the carbon analysis resource scope was set: only resources that apply to both the farming system as well as the urban system are considered. As such, all resources analysed during the carbon assessment of an urban context, should have the ability to be influenced by installing the UFP systems. For example, this means that the carbon footprint of crop fertilisation is not included in the carbon analysis as nutrient resources do generally not apply to an urban context. The *status-quo* analysis of the context serves as the initial condition to start from and test holistically assessed urban farming strategies towards community decarbonisation.

food inventory. Chapter 3 introduced, discussed and demonstrated the *assessment* component. The platform supports a semi-disaggregated approach to food carbon emissions analysis. *Semi* implies a *food group* assessment granularity of food consumption (e.g. fruit, beef, pork), residing between the aggregated *macro* level (e.g. grains, meat, produce) and the more granular *product* level (e.g. full fat yoghurt and Greek yoghurt). Processed food groups and drinks are excluded as the production process of such items are difficult to grasp and require an industry that is not easily conceivable in an urban context as part of a wider urban food production strategy. The semi-disaggregated approach secures sufficient detail to isolate high-impact groups and the inventory remains comprehensible when designing a food system. In addition, the data input required —meaning data research, interpretation and insertion— of average food consumption and carbon intensity figures remains manageable, as became evident when assessing the six cases of the M-Nex project. A sensitivity analysis on the chosen food inventory pointed out that the exclusion of processed food groups leads to a food sector impact that is coming short of reality.

assessment scope. Finally, a full scope *consumption-based approach* towards carbon emission analysis is paramount to be able to perform a comparative analysis between a conventional and an UFP scenario. The consumption-based approach attributes resources related emissions to the end-user. As such, to include the predominantly extra-urban emissions associated with the food supply chain, the analysis should include scope1, scope 2 and scope 3 emissions (World Resources Institute taxonomy applies). When urban food production is conducted and the crops yield constitutes part of the community demand, agriculture related resources demand is transferred within the urban boundaries, automatically assigning them to scope 1 or scope 2 emissions.

<u>How could the demand for food be swayed in order to reduce the accompanying carbon emissions?</u>

The scientific community has reached consensus about the lower carbon emission footprint of diets that are predominantly based on plant-based products as opposed to diets that contain more animal-sourced products. The *diet shift* component of the FEWprint platform can be deployed to rapidly generate preliminary estimations on the carbon mitigation potential of a community-wide protein transition, in which the animal-based proteins are substituted with plant-based alternatives. In addition, when taking into consideration the high *on-farm land use* associated with conventional livestock farming, diets that are inclined towards plant-based food inherently offer more potential for self-sufficiency in space-limited urban centres or peripheries.

During the development of the platform, three essential questions had to be tackled:

1. How is the nutritional quality of a diet affected when substituting animal-based food products with plant-based alternatives?
2. How should this quality loss be quantified and compensated for to achieve equilibrium with the original diet? (in other words: Are plant and animal protein mutually substitutable?)
3. How should this process be incorporated in the UFP design protocol?

Both plant and animal-based food products supply nutritional protein when consumed. Animal products are typically considered as the protein sources in a human diet as they contain, in higher quantities, the full range of essential amino acid combinations required by the body. Both protein availability and protein quality are in general lower for plant-based products. As such, a diet shift that considerately replaces animal products with plant-based alternatives, is likely to cause a diminished protein uptake. The protein content of food products/food groups can be retrieved from various public databases. With this data, additional consumption of, preferably high-protein, plant-based alternatives can be calculated to counteract the emerging protein intake deficiencies after a transition. However, this does raise the question on the extent of which animal and plant protein are mutually substitutable with regards to nutritional quality.

The quality of food-borne protein depends on the digestibility of the protein and the composition and bioavailability of essential amino acids in the food. To account for protein quality at the product or diet level, the *Digestible Indispensable Amino Acid Score* (DIAAS) has been developed. This index considers amino acids as individual nutrients and the nutritional quality of protein, a food product, or a dish is dictated by considering the least digestible or available amino acid within that item. First DIAAS studies show that plant-based food products generally have (significantly) lower scores than animal-based food products. However, plant-derived proteins usually have large amounts of some to most essential amino acids but have little or no amounts of some essential amino acids. This consequently leads to lower scores with the DIAAS method.

In chapter 5 it is argued that in order to produce a meaningful evaluation of the nutritional quality with regard to the protein intake of a new diet, it should be carefully evaluated at the amino acid level where each of the ten essential amino acid combinations is quantified separately per product. With this data, food products should be strategically combined into dishes, resulting in much higher DIAAS index scores and thereby providing a suitable alternative to animal-based products.

Unfortunately, a readily available and extensive database of amino acid contents is not available at present. When following the previously applied strategy of adding surplus consumption to overcome protein quantity deficit, incorporating the aggregated DIAAS score to secure protein quality equilibrium between diets would lead to unreasonably high consumption excesses as the least available amino acid has to be compensate with disproportionate amounts of food consumption to reach the healthy uptake level. In addition, amino acids level assessment per food product and the strategic food combining that follows would complicate the mechanics and data requirements of the platform considerably, which would require resource input from the user that currently is unreasonable with regard to the intended aim and objective of the FEWprint method and platform. Since the platform has been developed on the values of inter-component integration and scope comprehensiveness, whilst securing simplicity and functionality, it abridges the assessment by only considering the protein content of food(groups) and applies the total daily protein intake as the quality indicator [$gram_{prot}$/cap*day].

To implicitly secure protein quality when using the *diet shift* component (in this case meaning without numerical validation), it is recommended to use sufficient variation in crop alternatives when compensating for the emerged protein shortage after a dietary change. For example, when testing the impact of a pesce-pollotarian, pescetarian, vegetarian and vegan diet on the carbon balance of a case study community in Amsterdam, Belfast and Detroit, the calculated required surplus consumption was evenly distributed over 1) *pulses & legumes,* 2) *grains,* 3) *nuts & seeds* and 4) *meat replacers.* This study estimated that a community-wide protein transition could reduce the food sector emissions by 51% in Belfast, 67% in Amsterdam and up to 79% in Detroit community. With regard to the total carbon footprint of a neighbourhood, reductions are possible from 7% in Detroit, 15% in Amsterdam and up to 25% in Belfast.

Finally, food consumption is often deeply rooted in cultural behaviour or identity; people have been omnivorous for many generations and arbitrary impositions of dietary change on a community are unlikely to yield the intended desirable shift as food consumption should always remain a personal choice. The change to a more plant-based diet is usually a personal decision driven by intrinsic and/or extrinsic motivations; therefore, the community’s engagement is very important. Informing about the carbon mitigation potential of a community wide behavioural change could instil inspiration and incentivise a movement to further explore opportunities for urban farming design, which could be of great value in the process of future urban farming design.

<u>How can the fields of urban design-planning and food production design be bridged?</u>

This research is written from the viewpoint of urban designers and planners, who are also referred to as the *agro-urban designers* as they explore urban food production strategies for urban decarbonisation. As such, bridging the mentioned discipline gap was unilateral, in which the extensive and complicated practice of food production was made comprehensible and applicable for urban designers. The carbon accounting scope of resources, assessment approach and the food inventory were defined in section 7.2.1. As was stated in the introduction, in order make urban food production an interesting decarbonisation strategy to explore, the designer's toolbox should offer multi-product and multi-method elements to deliver sufficient design freedom to navigate various design options. Through the two explorative UFP propositions discussed in the scaffolding chapters and multiple applications of FEWprint beta-versions during living labs, three aspects pivoting around this sub question are addressed:

1. What is a suitable design approach?
2. What is a suitable level of detail when approaching UFP design?
3. Which indirect carbon implications should be included (and how)?

research by design. In urban neighbourhoods, exchanges between individual flows, linkages across scales and the benefits of establishing synergies between resource systems could illuminate unexpected advantages for urban life, urban resilience and environmental pressure. A non-linear *research-by-design* process, informed by indigenous values and risks, allows to navigate unconventional spatial solutions to outline new transformative pathways and create unexpected perspectives on the future of a neighbourhood. Characteristic to this process is the ad-hoc design method, during which out-of-the-box schemes or designs are pitched by projection on the site map in a round-the-table setup. Stakeholder-engaged and bottom-up design collaborations though the lens of the FEW nexus paradigm challenges the multi-disciplinary design team to make integrated resources infrastructure a visible and tangible element in the urban landscape – food production being the added element in this work. The platform streamlines on a high spatial resolution the design and assessment of local food production.

level of detail. Chapter 5 investigated the capacity of a greenhouse double-functioning as a solar collector for an inner-city residential neighbourhood, thereby providing the double-service of renewable energy and food production and having both the direct and indirect carbon emission implications. By solving hourly energy balance equations with hourly weather data and including various interior climate and operation parameters, a detailed insight was obtained that could be used to identify simultaneous and mismatched discrepancies between energy excess and demand. Through modelling, various parameter alterations were tested in order to achieve a balanced micro-grid and energy-autonomy. A comparative assessment of the carbon emissions pointed out that method performs better than conventional heating systems and is potentially carbon-competitive with district heating systems.

Even though this study delivered in detail and accuracy an elaborate example of a novel double-use of urban greenhouses, the technical complexity, knowledge requirement, site-specific data needed and overall level of detail were challenging to simulate as a separate model, let alone to integrate in the digital framework of the tool. Therefore, the meticulous approach of this explorative study did not resonate with the intended objective, aim and user-friendliness of the FEWprint platform. Instead, it was decided to capture the performance of food producing entities in spatial units and facilitate a space-based approach with the FEWprint method, as opposed to an energy balance-based approach.

space-based approach. To connect with the confer of the agro-urban designer and facilitate the ad-hoc design process, the platform enables a space-led design approach to food production design. In order to reduce complexity of the design component and to be applicable on the intended consideration level, the platform does not simulate interactions between invested resources or their effect on the crop growing climate and the subsequent agricultural output. Instead, the platform links to secondary data regarding farming input-output for a typical farming method with a specific crop. This means that the metabolic interactions of three typical food production methods are expressed in spatial units (m^2 or ha). This results in a workflow in which the agricultural output of the system can be controlled by up- or downscaling the selected farming method(s), changing the product(s) or opting for a more productive farming element.

design framework. Grasping the multi-facetted and cross-sectoral implications of UFP systems is a comprehensive challenge. In the platform, five inter-dependent aspects are highlighted that can be controlled during the design process to inform holistic decision making: *demand*, *space*, *resources*, *yield* and *impact*, coined the *pentalemma* of urban food production (fig. 7.1). The FEWprint supports the non-agriculturist urban designer with this pentalemma by facilitating a step-by-step iterative design sequence and provides a framework that reduces food production complexity into comprehensible elements.

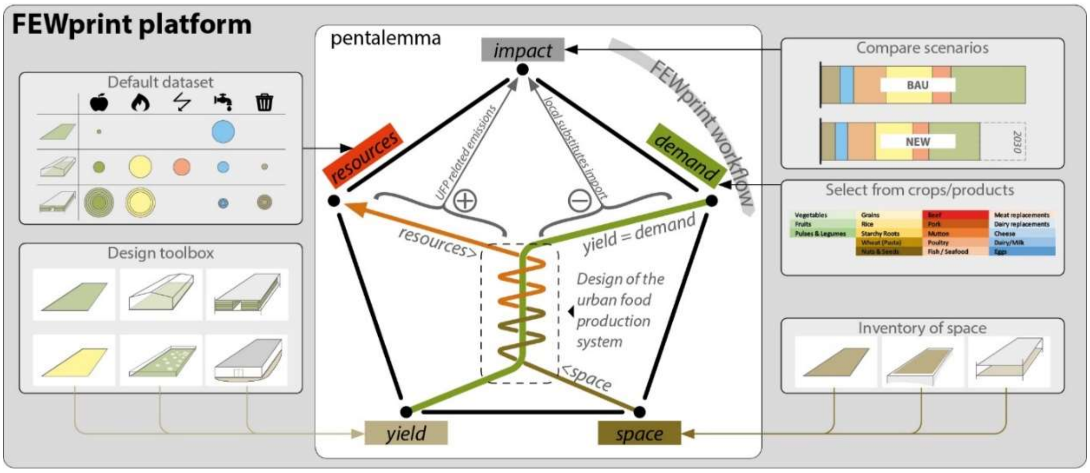

__Figure 7.1__: Under 'Demand', the designer composes from an inventory of standard food items a production target. Under 'space', the designer first makes an overview of the available and suitable land that could be used for UFP, and then allocates a production method under 'yield'. 'Resources' provides a dataset of default values for the 6 production methods for each of the items in the food inventory. The designer can first check if production targets are met, and second, if the added carbon emissions caused by the UFP components are acceptable - visualized under 'impact'.

Direct, indirect and tertiary carbon implications. The *reuse* step of the macro strategy concerns both inter- and intra-system resource circulation, see figure 7.2 on the next page. Two resource conversion methods — meaning the infrastructure required to connect residual (urban) output with input — were studied and applied in chapter 3 and have been added to the platform. The conversions are: 1) turning organic residual material into animal feed and 2) turning remaining organic waste material into renewable energy. Turning organic waste flows into animal feed averts it from being processed through more carbon intensive and destructive processes like incineration or landfilling. A knock-on effect is that it lowers the land requirements for animal feed crop farming. Through anaerobic digestion, biogas can be produced and applied internally for the farming systems or can substitute conventional fossil-based natural gas.

In chapter 3, both conversion systems were modelled and added to the input-output analysis as they proved to push considerable carbon reductions. This scaffolding study assessed the carbon implications of end-user resources as demanded by the urban dweller as well as the farm, the *direct* implications, but also the avoided emissions due to resources circulation – the *indirect* implications. In addition, resources required by the aforementioned conversion infrastructure were also assessed and added to the carbon balance, which are referred to as the *tertiary* implications. However, these latter were not added to the platform as its calculation was considered too complex for generic integration in the platform.

The platform was developed to be operated alongside the design team and provide rapid feedback regarding the aspects of the pentalemma after every design move. However, to foster effective feedback loops, it is advisable to assign one platform operator that has a degree of familiarity with the software and to thoroughly inform the design team about the platform's toolbox, design approach, output and boundary conditions. Finally, based on the experiences of a student-expert workshop, the design process, which is envisioned as an intense multi-day workshop, would benefit from several moments of snap-shot assessments followed by an operator-led feedback moment to effectively guide the process.

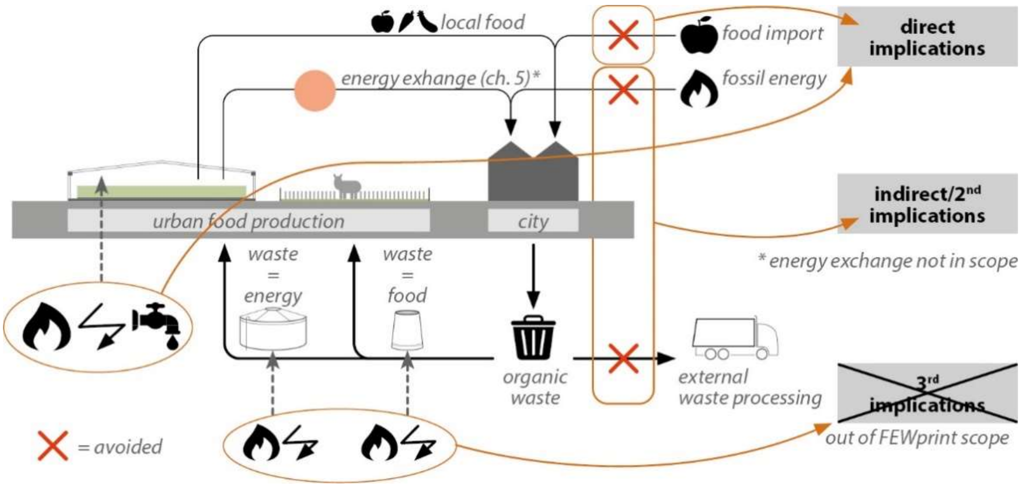

Figure 7.2: *Three tiers of carbon implications. Direct implications are associated with the resource demand directly driven by adding food production elements to the urban environment. Secondary implications are caused by establishing circulation links between food producing and urban functions, leading to less demand for external resources (e.g. gas) or services (waste processing). Third, or tertiary, implications are caused by the energy demand of new auxiliary infrastructure to operate resource circulation. Third implications are excluded from the scope of the platform, but have been accounted for in the two scaffolding studies.*

7.3 General Conclusion

<u>How could the urban food production design process be harmonised with the FEW nexus principles in order to lower the carbon footprint of the city?</u>

Carbon emissions occurring at the food supply chain are often responsible for a considerable portion of the total greenhouse gas emissions of the urban dweller. This research aimed to develop and disseminate a method and platform that can be used by agro-urban designers during the conceptual stage of the design process to explore the decarbonisation potential of urban food production. The method and platform have been developed along the principles of the FEW nexus theory – an integrative approach towards resource system design and assessment.

The demand for resources is increasingly concentrating in cities due to population increase and fast-growing urbanisation. This makes cities interesting study objects for sustainable resource management. Urbanising the production of food has the potential to lower the carbon emissions of cities in a direct and indirect way. Direct carbon emissions reductions are related to producer-consumer proximity benefits, although the extent of this impact varies per system and can even be adverse. Indirect carbon implications emerge from new methods of resources circulation fostered by system integration and pivot around recirculation of waste materials.

A non-linear *research-by-design* process, informed by indigenous values and risks, allows to navigate unconventional spatial solutions to outline new transformative pathways and create unexpected perspectives on the future of a neighbourhood. However, the diversity and inherent complexity of (urban) food production makes it difficult for non-experts to provide holistic evaluations, especially during the exploratory phase of design when performance assessment needs to keep up with rapid trial-and-error based decision-making. The platform should streamline this *research-by-design* process with iterative feedback loops, keep up with ad-hoc design moves, and provide output meaningful to urban designers.

Through literature research, the principles and research gaps of the FEW nexus theory was investigated. Key principles of the FEW nexus approach applicable in the biophysical sphere of resource management are:

1) actively consider cross-sectoral resource implications;
2) prioritise system performance above sectoral performance;
3) identify and use an all-sector performance indicator;
4) apply circular flows where possible;
5) explore synergistic opportunities;
6) maximise resource self-sufficiency.

Since the conception of the paradigm, research has mainly captured the nexus between resources at the regional or national level, whereas the local scale has been investigated much less. The intrinsic complexity of the nexus concept trickles down into the availability and suitability of tools that intend to provide a perspective on the various resources inter-dependencies. The cross-disciplinary nature of the nexus concept requires the attuning of data, methods, tools and indicators in order to obtain the shared language necessary to pursue synergetic design, a process that becomes more difficult at smaller scales.

The overarching master strategy applied as the backbone of the protocol follows the steps *research*, *reduce*, *produce* and *reuse (figure 7.3)* which is an adaptation of the urban energy master planning framework *New Stepped Strategy*, which finds roots in the principles of circularity.

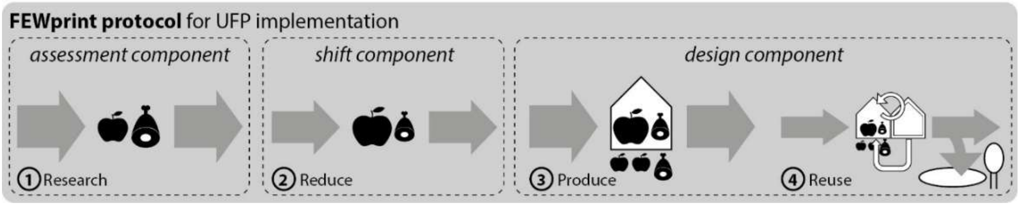

Figure 7.3: *FEWprint master strategy, adapted from Dobbelsteen.*

Step one, **research**, is covered in the *assessment* component of the platform. This step provides a status-quo analysis of the resource consumption and resulting carbon equivalent footprint of the urban community. This subsequently forms the baseline condition to start from and test holistically assessed urban farming strategies towards community decarbonisation. In order to make a comparative carbon analysis between the present and the urban food production scenario, a *consumption-based approach* of carbon accounting is necessary that includes the outer-boundary emissions of food production. The carbon analysis scope includes the following resource infrastructure: electricity production (includes cooling), energy carriers for heating, water production and treatment, energy carriers for personal mobility, domestic waste processing and food consumption. The assessed food inventory follows a semi-disaggregated method, resulting in 18 representative staple foods. Carbon analysis of six diverging case studies reveals that the fraction of food related emissions is mainly dictated by the emissions occurring in the other resources sectors.

Step 2, **reduce**, refers to community-wide dietary alterations that could reduce the food sector carbon impact. The *reduce* step is organised in the *shift* component, and simulates the effect of dietary changes without compromising the nutritional quality of the diet, in this study indicated with the total daily protein intake. This study demonstrates and assesses the implications of a protein transition for three case studies, i.e. assuming a full vegan diet. A complete shift from animal-based protein sources to plant-based alternatives can diminish the total carbon footprint of a community in Amsterdam, Belfast and Detroit with respectively 15%, 25% and 7% per year.

Step 3, **produce**, is found in the *design* component of the platform. A food system can be designed by combining various food production elements from a multi-method and multi-product design toolbox until a desired proportion of the demand is met or the intended decarbonisation targets are obtained. The platform enables a space-led design approach, which means that the metabolic interactions of three typical food production methods are captured in spatial units (m^2 or ha). This research highlights five inter-dependent aspects that reduces food production complexity into comprehensible elements and that can be configured during the design process to inform holistic decision making: demand, space, resources, yield and impact, coined the *pentalemma*.

After composing a food system, resource circulation between the urban system and the food system can be explored - **reuse.** Two resource conversions are added to the platform: waste > food and waste > energy. The required bridging infrastructures to connect output with input are digitally embedded in the platform and can be designed with. Through resource circulation, indirect carbon benefits can be added when evaluating urban food production as a decarbonisation strategy.

Under the umbrella theme of urban food production, this research contributes to the smaller-scale FEW nexus discourse. The main research output consists of a method and platform that can be employed to explore the food, space, resources and carbon implications of local food production and streamlines the discussion around the sustainable redesign of the city of the future. This platform is publicly disseminated under the name *FEWprint*. Simplicity and user-friendliness were the key priorities during its development, secured by component integration, accessible interface, step-by-step user guidance, scope-alignment, a semi-aggregated food inventory, establishing a common currency for system evaluation and a data library.

7.4 Scientific Contribution

7.4.1. Urban food production design and assessment

The demand for food can constitute a significant portion of the greenhouse gas emissions of an urban dweller. However, whether or not agriculture-related emissions are included in a carbon analysis is a matter of inventory and scoping — a sensitive methodological decision that can have considerable implications on the resulting environmental footprint of cities. New about the FEWprint framework is the detailed assessment of end-user level resources consumption combined with a *consumption-based approach* to evaluate carbon emissions of an urban dweller, which is necessary as agricultural activities in industrialised nations rarely take place within the city borders anymore. This analytical and inclusive carbon profile forms the accounting basis for urban decarbonisation propositions and is essential to test the direct and indirect carbon implications of urban food production.

This work acts as a pathfinder for future research on sustainable urban transformations and can be used or expanded on when investigating the decarbonisation potential of food production.

7.4.2. FEW nexus theory

In times when food, energy and water resources are perceived as infinite, the interlinkages are overlooked or not relevant. When one or more elements in the FEW trilemma encounter stressors and limitations, or the impact of exhaustive resources consumption is revealed through various outings of climate change, the links between them become relevant and it becomes apparent that all three resources are co-depending on each other.

Since its conception as an integrative framework to comprehend resources inter-dependence, the scientific discourse has mainly prevailed at the higher scale levels of consideration, meaning regional (e.g. river basin), national or international. The effect of this knowledge gap extends towards the FEW nexus tools that have been developed over the past decade, which mostly provide a perspective on the FEW nexus at the supra-national level. However, it is at the local level where policies and strategies turn into physical interventions and where policy makers can combine public, private and civic interventions to mitigate or respond to climate change.

By adhering to the general FEW nexus principles during urban food production design and evaluation, this research implicitly adds to the thus far under-perceived resources inter-connectivity at the local level, meaning the household, building, neighbourhood, city and city-region scale. This work and its output adds to the void within the FEW nexus theory at the smaller scale by providing elaborated examples and a platform that is publicly available for download on www.m-nex.net/FEWprint or on the publisher's website (Caat et al. 2022b).

7.5 Recommendations - Urban Food Production design

triple bottom line evaluation

The *triple bottom line* evaluation is a concept used in sustainable development and covers the three elements *people, planet* and *profit* (Jeurissen, 2000). The ambition is to harmonise the three elements to secure durability in sustainability efforts and the concept assumes that when harmonisation fails, one or more sectors will be negatively affected. The FEWprint frames the urban food production design process through the pentalemma, which are five aspects in the biophysical sphere of resource management. To provide a perspective on *planet,* environmental impact is measured with indicators that directly or indirectly revolve around the carbon impact of cities or communities. This could be expanded with other indicators that apply to multiple resource sectors, such as *virtual water* or *embodied land*.

Early consideration of the remaining two elements, people and profit, will reinforce the integrity of UFP strategies. For example, coupling up-to-date and local market value indicators with end-user domestic resources (kWh, m^3 of gas, m^3 of water, kg of food), agricultural output of farming elements and land prices would expand the nexus-pentalemma assessment with approximations on economic impact, especially when this is further expanded with indicators on capital investment, maintenance expenses and/or hourly labour costs.

Finally, an auto-calculated translation of agricultural yield into popular nutritional indicators, such as a daily availability of vegetables, fruits, pulses or (plant) protein to provide a perspective on healthy food availability within a community, would complete the triple-bottom quantifiable substantiation of an urban food production strategy. Especially in *food-deserts* or *food swamps*, UFP design propositions should be informed with local surveys to establish a detailed insight of desired food items.

form follows nutrition: amino acid level quality assessment

In this work, the national quality of a diet after modifications is secured by maintaining a daily protein intake equilibrium. Protein intake is assessed by observing the protein content of a semi-disaggregated food group – a method that increases the sensitivity of the outcomes (chapter 5.4.1). An amino acid level assessment of meat-substituting dishes or diets could pinpoint and quantify with higher accuracy which food elements are required to maintain a healthy diet after a protein transition. Such a *shopping list* could subsequently inform the design process to make sure that the right crops are grown in abundance in the locality. However, for this an extensive and unambiguous catalogue of food nutrition profiles must be available and coupled with the platform, meticulously describing the availability-digestibility score of the ten essential amino acids.

expand food inventory: neo protein sources

In the shadow of the overarching themes of sustainable diet shift, sustainable food production and producing food sustainably, there are novel, yet feasible alternative farming techniques and products available that could be included into an UFP strategy. Many modern premade meat-substitutes are based on tofu, tempeh, mushrooms, peas, chickpeas and beans. Tempeh and tofu are based on soybeans, which are, despite their sustainable character, space and water intensive during production and are therefore less attractive for inner-urban locations. *Fungiculture* (e.g. mushrooms) requires specific cool, dark and humid growing environments that do not need many energy resources to maintain. In addition, agricultural output per surface area is high due to many crop cycles per year and the necessary substrate can be provided by organic waste streams in the urban area (Dorr, Koegler, Gabrielle, & Aubry, 2021). Recent statistics show that the global demand for mushrooms is rising (Royse, Baars, & Tan, 2017), a trend that urban food production could cater for. Finally, insect farming has proven to be a viable high-protein, low-impact, high output alternative to meat production (Baiano, 2020). Farming is done indoors, does not require sunlight and can be done in relatively small spaces. Similar to mushroom farming, urban organic waste flows can be processed into insect feed. General cultural acceptance of insect consumption is slow, but first consumer products have made their way onto the regular market and the product is slowly moving away from its niche consumer base.

indirect impact: expand on ecosystem and ancillary farming services

This work applies two resource conversions to foster indirect carbon emission benefits: waste > (animal) food and waste > energy. These two services are embedded in the FEWprint platform and parameters can be configured according to the user's insight. With regard to quantifiable resource management solutions that could mitigate urban carbon emissions, urban farms could provide two additional services that are currently not included in the FEWprint: rain and storm water drainage (implicitly present, but the effect is not auto-translated into carbon emissions) and sewage water treatment. Modelling the impact of these surfaces and embedding them in the form of sub-components would add design tools at the disposal of the agro-urban designer. Especially urban areas with energy intensive sewage infrastructure could benefit from ecological filtration systems in terms of carbon footprint reduction.

In addition, and elaborately researched in this dissertation, a greenhouse solar collector plugged into the centre of a community combines the production of two desirable resources: healthy local food crops and renewable thermal energy. The second resource service was not added to the platform as it proved too complicated to embed, it was highly contextual and required substantial climate data to model the thermal output. However, the study also addressed the carbon reduction potential of the method. Further research could aim to build a user-friendly, accessible, robust, scalable and transferable greenhouse energy model, possibly connected with an external climate database and preferably using the same graphical and technical language as the FEWprint, following the space-led design approach connecting with the pentalemma framework.

7.6 Recommendations - FEWprint platform in the design process

Based on the experiences and lessons learned during the discussed design workshop, advice is given for future application of the decision support platform (discussed in chapter 6.4.1 and 6.4.3). This section discusses briefly the recommendations derived from the workshop and then suggest more general research courses that could improve the design process.

The primary goal of the workshop was to test the interaction between platform operator and the design team. To better inform the design process, we propose a combination of instant on-the-go feedback and isolated assessment moments. This implies a design period in which the design process is divided into several multi-hour blocks and that one or two members of the team are assigned as platform operators. The operator initially acts as a part of the design team and advises the process according to the capabilities of the platform. Throughout the process, the operator makes a snapshot of the current progress, assesses it, presents an interim status report and advises on possible design course adjustments needed to obtain goals. This process can be repeated between design blocks and the design becomes more defined and detailed over time. As the workshop proceeds, the operator gradually shifts the focus on the evaluation of the proposals and less on the design itself. In parallel, the design team increases its interaction with the platform as the team's understanding of it improves by experience.

Conditions apply to be able to work effectively with the platform as described above - materialised in the form of proper preparedness by both the design team and the platform operator. Designer preparedness can be improved by sharing accessible documentation (e.g. a manual) with the team prior to the commencement of the workshop. Once the design process is set in motion, the design team needs to be aware of the terminology of the operators and vice-versa and interruptions for explanation should be avoided. In addition, preparatory desktop research by the FEWprint operator is required in to start the session with the baseline assessment.

Future research could aim to include the needs of a wider variety of stakeholders in the platform. This dissertation uses the *agro-urban designer* as the subject, which in practise are the urban designers, urban planners, architects and building engineers. A triple bottom approach, as discussed in chapter 6.4.3, could foster this ambition to an extent. In addition, multiple applications of the platform plus the method will gain experience in juggling and balancing the priorities and ambitions of a multi-disciplinary team and systematically gathering user experiences after design sessions will help with this. A structured workshop program is paramount to rapidly gain design momentum and keep the design team in par, as the discussion and design course can deviate from the identified target, especially in a multi-disciplinary team. Further platform application could apply and test minor differences in the process to over time distil an optimal workflow for different combinations of stakeholders.

7.7 Limitations

Several limitations arose when conducting this research and/or apply to the research outcomes, which are briefly described below.

- **FEW nexus assessment**
  As was stated in chapter 6.2.3, the FEWprint design process apprehends a space-based approach when composing a food system, which means that the metabolism of a farm is captured in spatial units. Even though this has been well considered decision to maintain a comprehensible design experience for the operator of the platform, this approach is also a rather one-dimensional strategy as *space* is the single workable parameter to control a farm's productivity. In reality, farming output is a result of total arable land and the interactions between the input resources (light, heating or cooling, nutrients, water and also growing period, farmers experience, technology). The current approach does not capture the *nexus* connectivity in the practise of farming.

- **Mobility resources**
  Briefly, the resource analysis scope is based on mutual applicability for a farming entity and the urban resource system and – by means of conversion infrastructure – resources must have the ability to be affected through circulation. Personal mobility-related resources play a significant role in the carbon footprint of a community - between ±4% and ±33% of total footprint of the cases studied in this dissertation - and cannot be omitted from the assessment. However, mobility resources only have an implicit role and do not get directly affect when composing a food system. More explicit emphasis on this particular resource on the impact/resource demand implications could help the designer better when designing for urban contexts that are considered *food deserts*.

- **Nutrients not included**
  In line with the idea behind the resource scope of this work, crop fertilisation is not included in the input-out analysis and carbon assessment of the FEWprint. However, it would provide a more holistic evaluation if this essential resource were assessed and included as a design parameter when composing a farming system.

- **semi-aggregated food inventory**
  The FEWprint uses 18 food categories to frame UFP design and assessment. To secure inter-component integration, the platform's food scope is limited to unprocessed and minimally processed food products, while drinks, with the exception of milk products, have been excluded. Therefore, the range of food products provided by the datasets has to be transformed and aggregated (or disaggregated) into a single representative indicator per category. This process of data clustering applies to all three key factors in the carbon analysis of food in this work, namely food consumption, carbon intensity of food and protein content, and can have implications on the representability of the outcomes. One particular example is when regular tap water consumption (highly consumed but near-zero carbon impact) is assigned under a clustered drinks carbon indicator, hence driving up the emissions in that category.

- **limited food inventory**
  The limited food inventory excludes drinks and processed food groups. Even though this is a well-considered choice, a sensitivity analysis performed in chapter 3.4.4. for the Amsterdam case study highlights the considerable consequences this methodological decision has on the resulting food sector impact.

- **Ambiguity of food taxonomy**
  Data collection for this study revealed discrepancies between countries when comparing food inventories and datasets individual food items or food groups. Food categorisation is not similar between datasets, which usually means that certain food items are assigned to different food groups or sometimes form their own semi-aggregated level. This consequentially diminishes the comparability between cases. The question arises whether the cause of observed consumption- or carbon impact differences can be assigned to data collection and interpretation methods or to actual differences in food consumption in reality. In addition, the macronutrient content between similar food products can vary significantly because of climate, geography, agricultural practises, crops genetics, or processing influences during the food production and preparation stages. Food consumption patterns lead to country-specific foods, recipe compositions, and food brands. For a representative output, each diet simulation and/or urban food production strategy should be conducted local data that has been collected and processed according to clear standards.

- **Situational applicability of data**
  The quality and/or relevance of the FEWprint output is as good as the quality of the data input. The contextuality of data depends on the data aggregation and/or measuring level of the responsible agency which supplies the data. Aggregated data cannot be correlated with specific local activities, demand or people and is likely to depict a consumption profile deviating from the local reality. In parallel, scaling up individual properties to the neighbourhood population might equally lead to an unrealistic perception of neighbourhood flows and cancels out individual differences. Optimally, the data boundaries overlap with the boundaries of the urban context seamlessly. Alternatively, it is recommended to seek and use aggregation levels that are closest to the desired scale, which was visualised for the cases in this work in figure 3.2.

- **A technocratic approach in the biophysical sphere**
  This work applies a technocratic approach to comprehend urban food production and performance is expressed in measurable indictors that apply in the biophysical sphere. The political, legislative, socio-economic or behavioural side of reorganising the production of food resources in the urban context are not addressed.

- **Designing with numbers.**
  Based on the experiences of the workshop conducted for this dissertation, we advise caution when working with a smaller and homogeneous design team, especially the design period is short. The design assignment is more prone to become superficial and is likely to solely become conductive to the stated (testable) design goals when this situation applies (see chapter 6.4.1). For example, when vegetable production is (one of) the design spearheads, it is possible that the design propositions will pivot primarily around this performance indicator and other design values are diluted and become secondary. Variation within the design team can help avoiding this pitfall.

- **Design for the future with present data**
  Finally, it should be remarked that the future shape and programme of a city is designed and assessed based on today's data. It is difficult, if not impossible for some figures, to embed evidence-based projections on demographics, resource consumption, carbon intensity and agricultural data in input values, inherently causing a degree of sensitivity in the output data.

7.8 References

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KUNTRY GARDENS
$1.99/lb
Certified Organic
Tantré Farm
Certified Organic
Tantré Farm
Strawberries
Certified Organic
Kapnick Orchards
Strawberries
Schwartz Family Farm
Strawberries
$7.00/quart
SNAP PEAS
$3/pt

PART IV

Appendices

PART V: Appendices

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Appendices Chapter 2

Pig farming vs. Solar farming: exploring novel opportunities for the energy transition.

No appendices are used for chapter 2.

Appendices Chapter 3

Emission assessment of food and resources consumption with the FEWprint carbon accounting platform

Appendix 3A: Carbon footprint values - 6 case studies

Table A3.1. Inventory per urban context of carbon footprints (CF) relevant to this study. Food CF are specified in table 3.1 in the main chapter. Default data is noted with (D). Where CO_2 is written, CO_2eq is meant.

Sector	Component	Product/Activity	CF	Unit	Note (source)
Kattenburg, Amsterdam (AMS)					
Energy	Electrical	grid mix	0.526	kg CO_2/kWh_e	Country specific value. (Otten & Afman, 2015)
	Thermal	natural gas	1.884	kg CO_2/m^3	(Zijlema, 2018)
Water	Domestic demand	centralised production	0.360	kg CO_2q/m^3	(STOWA, 2008) Country specific value
		centralised treatment	1.140	kg CO_2/m^3	(STOWA, 2008) Country specific value
Waste[1]	Unrecycled fraction	waste-to-energy	0.652 (D)	kg CO_2/kg	Based on IPCC Waste model (Pulselli et al., 2019)
		waste-to-landfill	1.160 (D)	kg CO_2/kg	Based on IPCC Waste model (Pulselli et al., 2019)
		waste-to-compost	0.091 (D)	kg CO_2/kg	Based on IPCC Waste model (Pulselli et al., 2019)
Mobility	Personal mobility	petrol (gasoline, E95)	2.800 (D)	kg CO_2/L	European value. Assumed η_{fuel}= 15. (NEN-EN, 2012)
		diesel	3.240 (D)	kg CO_2/L	European value. Assumed η_{fuel}= 18. (NEN-EN, 2012)
		electric	0.526	kg CO_2/kWh_e	Assume CS grid mix electricity. Assumed η_{fuel}= 15
Food	Various	Various	Varies	kg CO_2/kg	See table 3.1
Inner-East, Belfast (BEL)					
Energy	Electrical	grid mix	0.339	kg CO_2/kWh_e	Country specific value. (DAERA, 2020)
	Thermal	natural gas	2.023	kg CO_2/m^3	(DEFRA, 2020b)
Water	Domestic demand	centralised production	0.139	kg CO_2/m^3	(N.I. Water, 2019)
		centralised treatment	0.433	kg CO_2/m^3	(N.I. Water, 2019)
Mobility	Personal mobility	petrol (gasoline, E95)	2.800(D)	kg CO_2/L	European value. Assumed η_{fuel}= 15. (NEN-EN, 2012)
		diesel	3.240 (D)	kg CO_2/L	European value. Assumed η_{fuel}= 18. (NEN-EN, 2012)
		LPG	1.900 (D)	kg CO_2/L	European value. Assumed η_{fuel}= 10. (NEN-EN, 2012)
		electric	0.339	kg CO_2/kWh_e	Assume CS grid mix electricity. Assumed η_{fuel}= 15
Food	Various	various	varies	kg CO_2/kg	See table 3.1
Tamaplaza, Tokyo (TOK)					
Energy	Electrical	grid mix	0.442	kg CO_2/kWh_e	Country specific value. (TEPCO, n.d.)
	Thermal	City gas (natural gas)	2.230	kg CO_2/m^3	(Japan LP Gas association, 2020)
	Thermal	Light oil products	0.247	kg CO_2/L	(Japan LP Gas association, 2020)
	Thermal	LPG	1.530	kg CO_2/L	(MoE Japan, 2017)
Water	Domestic demand	centralised production	0.270	kg CO_2/m^3	(Bureau of Waterworks Tokyo, 2020)
		centralised treatment	0.397	kg CO_2/m^3	(Sano, Masuda, Li, Nishimura, & Harada, 2012)
Mobility	Personal mobility	petrol (gasoline, E95)	2.320	kg CO_2/L	(MoE Japan, 2017)
		diesel	2.580	kg CO_2/L	(MoE Japan, 2017)

		LPG	1.530	kg CO_2/L	(MoE Japan, 2017)
		electric	0.442	kg CO_2/kWh$_e$	Assume CS grid mix electricity. Assumed η_{fuel}= 15
Food	Various	various	varies	kg CO_2/kg	See table 1.
Oakland Avenue Farms, Detroit (DET)					
Energy	Electrical	grid mix (comp. elec.)	0.890	kg CO_2/kWh$_e$	(Carlson et al., 2014) Includes T&D losses
	Thermal	Natural gas	1.910	kg CO_2/m^3	(Carlson et al., 2014),
Water	Domestic demand	centralised production	0.510	kg CO_2/m^3	Based on peak time emission (Jin et al., 2015)
		centralised treatment	0.960	kg CO_2/m^3	Base case WWT Plant (Cashman et al., 2014)
Mobility	Personal mobility	petrol (gasoline, E95)	2.316	kg CO_2/L	(US EPA, 2020)
		diesel	2.693	kg CO_2/L	(US EPA, 2020)
		LPG	1.499	kg CO_2/L	(US EPA, 2020)
		electric	0.890	kg CO_2/kWh$_e$	Assume CS grid mix electricity. Assumed η_{fuel}= 15
Food	Various	various	varies	kg CO_2/kg	See table 3.1
Qatar University Campus, Doha (DOH)					
Energy	Electrical	grid mix	0.596	kg CO_2/kWh$_e$	Country specific value. (Ecometrica, 2011)
Water	Domestic demand	centralised production	11.23	kg CO_2/m^3	Multi Stage Flash desal. (Darwish & Mohtar, 2012)
		centralised treatment	2.810	kg CO_2/m^3	SWRO (Darwish & Mohtar, 2012)
Mobility	Personal mobility	petrol (gasoline, E95)	2.900 (D)	kg CO_2/L	European value. Assumed η_{fuel}= 15. (NEN-EN, 2012)
		diesel	3.240 (D)	kg CO_2/L	European value. Assumed η_{fuel}= 18. (NEN-EN, 2012)
		electric	0.596	kg CO_2/kWh$_e$	Assume CS grid mix electricity. Assumed η_{fuel}= 15
Food	Various	various	varies	kg CO_2/kg	See table 3.1
Western Sydney, Sydney (SYD)					
Energy	Electrical	grid mix	0.810	kg CO_2/kWh$_e$	Country specific value. (DISER, 2020)
	Thermal	Jemena gas (nat. gas)	1.930	kg CO_2/m^3	Own assessment[2]
Water	Domestic demand	centralised production	0.210	kg CO_2/m^3	(Sydney Water, 2019)
		centralised treatment	0.380	kg CO_2/m^3	(Sydney Water, 20s19)
Mobility	Personal mobility	petrol (gasoline, E95)	2.305	kg CO_2/L	(DISER, 2020)
		diesel	2.698	kg CO_2/L	(DISER, 2020)
		LPG	1.577	kg CO_2/L	(DISER, 2020)
Food	Various	various	varies	kg CO_2/kg	See table 3.1

1) Mean carbon emissions indicators are applied similarly for all case studies but are only tabulated for the Amsterdam case.

2) Source reports only emissions from activities (i.e. chain related emissions, or Well-to-tank), which is 1.77 ton CO_2/TJ (Jemena, 2020). Based on assuming 1 GJ = 26.14 GJ, we can estimate the scope 3 emissions to be around 0.067 kg/m^3. To account for territorial emissions, we assume that 1m^3 of natural gas produces 42.3 mol CO_2, or 1.86 kg. Combined gives 1.86 + 0.067 = 1.93 kg CO_2eq/m^3.

Appendix 3B: List of Default values provided in the FEWprint platform

Not all countries release accessible, accurate or available data that could be used for carbon assessment and in order to overcome these data gaps, the platform offers a set of default data. All values specified below can be adjusted by the user on the platform and new methods can be added. The platform offers a selection of common fuels for car mobility (listed in table B1, item 1-8), energy carriers for home heating (item 9-18), district heating methods (item 19-23) and electricity sources, both renewable, fossil and nuclear (item 24-35). CF data on energy provision describe either European averages or represent generic indicators from literature. The processing of domestically produced waste through the three key methods of incineration, landfilling or composting (item 36-39) can be expressed in carbon emission equivalents. This study adapts the values applied by Pulselli et al. (2019) and are based on the IPCC Waste Model mean global values. The carbon footprint of drinking water infrastructure denotes only process related (scope 3) emissions (or scope 2 emissions should water management takes place within the system borders) and various methods of water production and treatment are possible. Water infrastructure is strongly contextual and most of the default values are estimates. The CF is split up in upstream (provision + distribution, item 40-53) and downstream indicators (collection + treatment, item 54-60). Finally, the FEWprint provides default food CF data for a selection of countries plus the global average, based on the United Nations FAO database (table 1).

Table A3.2. List of default carbon footprints provided in the FEWprint tool. Where possible, global/European averages are used. CS = Country Specific, i.e. no default values apply. Carbon assessment is done with the full-scope footprint (scope 1+2+3) , to which the $ef(n)$ terms mentioned in appendix 3E refer to. Values/methods can be changed, added or replaced at any time within the platform. The carbon impact factors of food categories are listed in table 1.

Estimations for greenhouse gas emissions associated with water management (item 40-60) are based on an grid mix carbon footprint of 0.500 kg/kWh$_e$

•	Product/Activity	Scope 1	Scope 2	Scope 3	Unit	Note (Source)
	Energy - Personal mobility (commonly found fuels)					
1	Petrol (gasoline, E95)	2.30	-	0.50	kg CO_2/L	European value, E95 type. Assumed η_{fuel}= 15. (NEN-EN, 2012)
2	Diesel	2.67	-	0.57	kg CO_2/L	European value. Assumed η_{fuel}= 18. (NEN-EN, 2012)
3	LPG (Liquefied Petroleum Gas)	1.70	-	0.20	kg CO_2/L	European value. Assumed η_{fuel}= 10. (NEN-EN, 2012)
4	CNG (Compressed Natural Gas)	2.68	-	0.39	kg CO_2/kg	European value. Assumed η_{fuel}= 7. (NEN-EN, 2012)
5	Biofuel (Diesel)	0.00	-	1.92	kg CO_2/L	Assumed η_{fuel}= 18. (NEN-EN, 2012)
6	Biogas (CNG, green gas based))	0.03	-	0.35	kg CO_2/m^3	Estimation for the Netherlands. Assumed η_{fuel}= 7. Adapted from (CE Delft, 2015)
7	Electricity (full/hybrid)	CS	CS	CS	kg CO_2/kWh	Assume CS grid mix electricity. Assumed η_fuel= 15
8	Hydrogen (green based)	0.00	-	0.64	kg CO_2/ m^3	Estimation for the Netherlands Assumed η_{fuel}= 7. Adapted from (CE Delft, 2015)
	Energy - Primary energy for heating + energy carriers.					
9	Natural gas / CNG / LNG	1.79	-	n.d.	kg CO_2/m^3	Dutch reference value (Zijlema, 2020)
10	Propane (for home heating)	1.53	-	0.20	kg CO_2/L	[add source]
11	Wood combustion, dry wood	0.01	-	0.05	kg CO_2/kg	Average value of various wood forms. (AVIH, 2018)
12	Cokes coal	2.69	-	n.d.	kg CO_2/kg	Dutch reference value (Zijlema, 2020)
14	Charcoal (bricks)	3.36	-	n.d.	kg CO_2/kg	Dutch reference value (Zijlema, 2020)
15	Residential fuel oil	3.19	-	n.d.	kg CO_2/L	Dutch reference value (Zijlema, 2020)
16	LPG	3.02	-	n.d.	kg CO_2/L	Dutch reference value (Zijlema, 2020)
17	Biogas (conventional digester)	0.00	-	0.74	kg CO_2/m^3	Dutch reference value. Based on 23,4 kg CO2eq/GJ and a caloric value of 31,65 MJ/m3. Input material: domestic organic waste (CE Delft, 2019a)

18	Lignite	2.02	-	n.d.	kg CO_2/kg	Not very common anymore. (Zijlema, 2020)
19	District heating - CCGT	-	32.50	3.40	kg CO_2/GJ	Combined Cycle gas Turbine power plant. (CE Delft, 2016)
20	District heating - Industry residual heat	-	20.60	0.90	kg CO_2/GJ	No co-firing. (CE Delft, 2016)
21	District heating - Waste Incineration	-	23.10	3.40	kg CO_2/GJ	(CE Delft, 2016)
22	District heating - Geothermal	-	23.40	1.60	kg CO_2/GJ	(CE Delft, 2016)
23	District heating - Biomass	-	15.30	10.50	kg CO_2/GJ	Based on imported pellets. (CE Delft, 2016)
	Energy - Electricity					
24	Grid mix - National grid mix	CS	CS	CS	kg CO_2/kWh	Country specific value, based on grid mix composition.
25	Grid mix - European average	-	0.38	?	kg CO_2/kWh	European electricity grid mix - 2015 values (Pulselli et al., 2019)
26	thermoelectricity - GAS based	-	0.44	?	kg CO_2/kWh	Various combined cycle turbines (Sovacool, 2008)
27	thermoelectricity - PETROL based	-	0.78	?	kg CO_2/kWh	Various generator and turbine types (Sovacool, 2008)
28	thermoelectricity - COAL based	-	1.05	?	kg CO_2/kWh	Various generator types with scrubbing (Sovacool, 2008)
29	Nuclear electricity	-	0.07	?	kg CO_2/kWh	Mean value (Sovacool, 2008)
30	renewable - photovoltaic	-	-	0.03	kg CO_2/kWh	Polycrystalline silicone based. (Pehnt, 2006)
31	renewable - wind energy	-	-	0.01	kg CO_2/kWh	2.5MW turbine offshore. (Pehnt, 2006)
32	renewable - hydroelectric energy	-	-	0.01	kg CO_2/kWh	Reservoir based.(Pehnt, 2006)
33	renewable - geothermal energy	-	-	0.04	kg CO_2/kWh	80MW capacity. (Pehnt, 2006)
34	renewable - biomass incineration	-	-	0.04	kg CO_2/kWh	Short rotation forestry, reciprocating engine(Pehnt, 2006)
35	renewable - biogas combustion	-	-	0.01	kg CO_2/kWh	Anaerobic Digestion. (Pehnt, 2006)
	Waste - Domestic waste processing					
36	Waste-to-recycling	-	-	0.00	kg CO_2/kg	No emissions accounted for recycled fraction.
37	Waste-to-incineration	-	-	0.65	kg CO_2/kg	For the production of energy. (Pulselli et al., 2019)
38	Waste-to-landfill	-	-	1.16	kg CO_2/kg	(Pulselli et al., 2019)
39	Waste-to-compost	-	-	0.09	kg CO_2/kg	Organic fraction (Pulselli et al., 2019)

Water - Production & distribution

	Production method/source	**kg CO_2eq/m^3**	**kWh/m^3**	**Note (ref. carbon footprint) / Note (ref. embodied energy)**
40	ext.: desalination - reverse osmosis	2.20	4.30	Range 0.08-4.3, ± 2.2 (Cornejo et al., 2014) / Range 4.0-4.5, ± 4.3 (Cornejo et al., 2014)
41	ext.: desalination - multi stage flash	17.70	18.50	Range 0.3-34.7, ± 17.7 (Cornejo et al., 2014) / Range 13.5-23.5, ± 18.5 (Cornejo et al., 2014)
42	ext.: desalination - multi-effect distillation	13.60	8.00	Range 0.3-26.9, ± 13.6 (Cornejo et al., 2014) / Range 6.0-10.0, ± 8.0 (Cornejo et al., 2014)
43	ext.: desalination - other	5.00	10.00	Range n.a., estimation / Range n.a., estimation
44	ext.: underground aquifer	1.00	2.00	Estimation / Estimation for pumping energy
45	ext.: surface water (basin/lake)	0.36	0.72	Dutch reference value - LCA study, upstream emissions (STOWA, 2008) / Estimation
46	ext.: unknown	0.25	0.50	Estimation / Estimation for pumping energy
47	local: recirc. waste water (filtered & treated)	2.50	5.00	Estimation / Estimation for pumping and processing energy
48	local: surface water (untreated)	0.25	0.50	Estimation / Estimation for pumping energy
49	local: surface water (filtered)	0.50	1.00	Estimation / Estimation for pumping energy + filtration energy
50	local: ground water (untreated)	0.38	0.75	Estimation / Estimation for pumping energy
51	local: ground water (filtered)	0.63	1.25	Estimation / Estimation for pumping energy + filtration energy
52	local: rainwater (untreated)	0.13	0.25	Estimation / Estimation for pumping energy
53	local: rainwater (filtered)	0.38	0.75	Estimation / Estimation for pumping energy + filtration energy
	Water - Collection and treatment			
54	External: conventional sewage treatment	1.14	2.20	Dutch reference value - LCA study, downstream emissions (STOWA, 2008) / Estimation

55	External: no treatment (to surface water)	0.25	0.50	Estimation / Estimation for pumping energy
56	External: constructed wetlands	0.25	0.50	Estimation / Estimation for pumping energy
57	External: unknown	0.25	0.50	Estimation / Estimation for pumping energy
58	local: recirc. waste water (filtered & treated)	2.50	5.00	Estimation / Estimation for pumping and processing energy
59	Local: constructed wetlands	0.13	0.25	Estimation / Estimation for pumping energy
60	Local: storage basin (untreated)	0.05	0.10	Estimation / Estimation for pumping energy

Appendix 3C: Subdivision of food groups - 6 cases studies

Table A3.3. Subdivision of food groups. The diet profile applied in this study does not reflect the complete dietary intake of a consumer. Only food groups and/or subgroups/products are used that are processed minimally and the idea of producing these products in the urban context is conceivable without complicated food processing steps in between.

Additional remarks: frozen products are included. Milk & yoghurt are pasteurized but are accounted for.

Kattenburg, Amsterdam			
●	**Food group**	**gr/day**	**Subgroups / products**
1	Vegetables	131.0	All vegetable types, including: unclassified + mixed vegetables/salads (11.8), leek, onion, garlic (11.8), mushrooms (2.9) ,cabbages (19.4), root veg. (12.3), fruiting veg. (48.4), leafy veg. (19.2), grain- & pod veg. (2.5) and stalk vegetables (2.6). *Excluding: vegetable juices, tomato sauces*.
2	Fruits	113.8	Fruits (113.4), unclassified mixed fruits and others (0.4). *Excluding: fruit juices, jams & jelly, marmalade*.
3	Pulses & legumes	4.5	Legumes (4.5).
4	Grains (bread)	138.3	Bread (125.6), Crispbread-rusks (5.3), Breakfast cereals (7.4). *Excluding: dough & pastry and flour, starches, flakes, semolina.*
5	Rice	0.0	No sub-specification available, rice included in group 15.
6	Starchy roots	72.2	Potatoes (71.6), Unspecified tubers (0.5).
7	Beef (+veal)	12.6	Beef (12.2), Calf (0.4). *Excluding hot- & cold processed beef, offal, game.*
8	Pork	13.0	Pork (13). *Excluding: hot- & cold processed pork.*
9	Mutton (+lamb & goat)	0.6	Mutton/Lamb (0.6). *Excluding: hot- & cold processed mutton*
10	Poultry (+turkey)	16.6	Chicken, hen (15.9), Turkey, young turkey (0.4), Duck (0.3) *Excluding: hot- & cold processed poultry*
11	Fish (incl. sea food)	12.9	Fish (11.5), Crustaceans & molluscs (1.4). *Excluding: unspecified fish and combined fish products, amphibians and reptiles, fish in crumbs.*
12	Cheese	32.6	Cheeses - including spread cheeses (32.6).
13	Dairy (milk & yoghurt)	254.3	Milk-fermented (200.6), Yoghurt (53.7). Excluding creams, sorbets, ice creams, non-dairy products, Fromage blancs.
14	Eggs	12.7	Eggs (12.7).
15	Pasta (Durum wheat)	47.1	Pasta, rice and other grain (47.1).
16	Nuts and Seeds (+olives)	6.3	Nuts, Peanuts & Seeds (5.7), Olives (0.6). *Excluding: spreads, e.g. peanut butter.*
17	Meat replacements	1.5	Meat substitutes (1.5).
18	Dairy replacements	8.4	Milk substitutes and substituting products (8.4).
	total	878.4	

general note: Data retrieved from the Dutch National Food Survey 2012-2016 (RIVM, 2020a). Data constitutes the average values for female + male food consumption in the age group 1-79.

Inner-East, Belfast, U.K.			
1	Vegetables	92.0	All vegetable types, including: unclassified + mixed vegetables/salads (48.5), onions, leeks & shallots (15.4), cucumbers (7.3), mushrooms (5.1), tomatoes (11.9). *Excluding vegetable juices, tomato sauces*.
2	Fruits	114.0	Fruits (114). *Excluding: fruit juices, jams & jelly, marmalade, dried fruit*.
3	Pulses & legumes	3.0	Legumes (3).
4	Grains (bread)	106.0	Bread (84.3), Oatmeal and oat products (3.86), Breakfast cereals (17.5). *Excluding: dough & pastry and flour, starches, flakes, semolina.*
5	Rice	15.0	Rice (15).
6	Starchy roots	93.0	Potatoes (60.2), carrots (14.5), turnips (1.66) and other root vegetables (7.61).
7	Beef (+veal)	21.0	Beef (21), *Excluding hot and cold processed beef, offal, game.*
8	Pork	31.0	Pork (31). *Including joints, chops, steaks, bacon and sausages.*
9	Mutton (+lamb & goat)	5.0	Mutton/Lamb (5). *Including joints and chops.*
10	Poultry (+turkey)	36.0	Chicken – whole or pieces (36). *Including hot and cold when purchased.*
11	Fish (incl. sea food)	22.0	Fish (22). *Including white fish, blue fish, shellfish, tinned fish, ready meals and takeaway fish products.*

12	Cheese	18.0	Cheeses (18). *Including spread cheeses.*
13	Dairy (milk & yoghurt)	262.0	Liquid wholemilk (42.4), skimmed milk (151), condensed milk (2.36), infant milks (7.38), yoghurt (26.9), cream (3.75) and other milks and dairy desserts (20.4).
14	Eggs	15.0	Eggs (15).
15	Pasta (Durum wheat)	14.0	Pasta (14).
16	Nuts and Seeds (+olives)	5.0	Nuts, edible seeds and peanut butter (5).
17	Meat replacements	n.d.	n.a.
18	Dairy replacements	n.d.	n.a.
	total	852.0	
	general note: Data retrieved from *Family food statistics* survey by Department for Environment, Food and Rural Affairs (DEFRA, 2020a). Data consists of three-year U.K. average for quantities of food and drink purchased.		
Tamaplaza, Japan			
1	Vegetables	283.0	Tomato(21.2), Carrot(18.5), Spinach(11.6), Green Pepper(3.6), Other Green and Yellow Vegetables(35.6), Cabbage(30.0), Cucumber(9.9), Radish(22.0), Onion(31.6), Chinese Cabbage(19.8), Other Pale Vegetables(50.0), *Including: Fruit Juice(17.8)*
2	Fruits	108.0	Strawberry(0.1), Orange(20.7), Banana(17.0), Apple(17.6), *Including: fruit juices, jams*
3	Pulses & legumes	63.0	Soy(61.6)
4	Grains (bread)	103.0	Bread(35.2), Muffin and Doughnut(4.7), Udon and Soba(a kind of noodles)(47.0), Wheat(3.5)
5	Rice	291.0	Rice(291.0)
6	Starchy roots	46.0	Sweet Potato(5.5), Potato(24.8), Other Potatoes(15.7), *Including: Starch*
7	Beef (+veal)	14.0	Beef(13.9) *Excluding hot and cold processed beef*
8	Pork	45.0	Pork(45.4) *Excluding: Sausage*
9	Mutton (+lamb & goat)	n.d.	n.a.
10	Poultry (+turkey)	32.0	Poultry(32.1)
11	Fish (incl. sea food)	66.0	Fish (66). *Including raw fish, ready meals and takeaway fish products.*
12	Cheese	4.0	Cheese(4.1)
13	Dairy (milk & yoghurt)	130.0	Milk(81.1), Other Dairy(48.5)
14	Eggs	38.0	Eggs(38.0)
15	Pasta (Durum wheat)	12.0	Pasta(11.9)
16	Nuts and Seeds (+olives)	n.d.	n.a.
17	Meat replacements	n.d.	n.a.
18	Dairy replacements	n.d.	n.a.
	total	1235.0	
	general note: National Health and Nutrition Survey. Retrieved from (MHLW, 2018).		
Oakland Avenue Farms, Detroit			
1	Vegetables	99.7	All vegetable types- fresh and frozen including: artichokes(0.43), asparagus(0.73), bell peppers(5.77), broccoli (5.90), brussels sprouts(0.72), cabbage (4.03), cauliflower (1.12), celery (2.72), collard (0.24), sweet corn (3.61), cucumber (3.70), eggplant (0.47), escarole (0.07), garlic(1.41),kale (0.31), lettuce (18.67), lima beans (0.17), mushroom (2.19), mustard green (0.18), okra (0.26), onion (14.05), pumpkin (1.28), snap beans (2.38), spinach (1.47); squash (3.04); tomatoes (15.39); turnip (0.06); carrot (5.86); radish (0.24); green peas (1.06); other (2.17) *Excluding: vegetable juices, tomato sauces, dehydrated, and canned vegetables.*
2	Fruits	77.5	Fresh Fruits (73.6), Frozen Fruits (3.9). *Excluding: dried fruits, canned fruits, fruit juices, jams & jelly, marmalade*.
3	Pulses & legumes	11.6	Legumes (11.6).
4	Grains (bread)	150.8	Total wheat flour- white and whole wheat flour and durum flour (115.3), Rye flour (0.46), Total corn products- corn flour and meal, hominy and grits, and starch (30.8), Barley products(0.67), Oat products (3.61)
5	Rice	n.d	No sub-specification available
6	Starchy roots	57.7	Potatoes Fresh (32.3), Potatoes Frozen (25.42)
7	Beef (+veal)	51.8	Beef (51.7), Calf (0.1). *Accounts for edible weights adjusted for loss.*
8	Pork	39.4	Pork (39.4). *Accounts for edible weights adjusted for loss*

9	Mutton (+lamb & goat)	0.7	Lamb (0.7). *Accounts for edible weights adjusted for loss*
10	Poultry (+turkey)	75.1	Chicken, hen (65.0), Turkey (10.1). *Accounts for edible weights adjusted for loss*
11	Fish (incl. sea food)	8.1	Fresh and Frozen Fish (4.2), Fresh and Frozen Shellfish (3.9). *Excluding: Canned and Cured fish.*
12	Cheese	34.2	Cheeses – all types of processed cheese (29.8), cottage cheese (1.9) Cream cheese (2.5)
13	Dairy (milk & yoghurt)	138.6	Total fluid milk - Beverage milk and refrigerated yogurt (138.6). *Excluding: Butter, Frozen dairy products- ice cream, evaporated and condensed milk, dry milk products, half and half cream, eggnog*
14	Eggs	27.3	Eggs (27.3).
15	Pasta (Durum wheat)	n.d.	Included in grains
16	Nuts and Seeds (+olives)	13.9	Peanuts (8.2), Almonds (2.1), Hazelnuts (0.1), Pecans (0.5), Walnuts (0.5), Macadamia nuts (0.1), Pistachio nuts (0.4), Other tree nut (1.1), Coconut (0.9)
17	Meat replacements	n.d	n.a.
18	Dairy replacements	n.d	n.a.
	total	786.5	
	general note: Data retrieved from Food Availability (Per Capita) Data System-Loss Adjusted food availability (USDA ERS, 2017). The data is not specific for Oakland Avenue, Detroit but a USA per capita consumption estimate.		
Qatar University Campus, Doha			
1	Vegetables	209.0	Tomato (48.2), cucumber (19.5), pepper (13.5), squash (7.2), cabbage (8.9), cauliflower (9.9), onions (84.7), lettuce (6.7), eggplant (10.2)
2	Fruits	187.0	Banana (40.3), apples (29.7), citrus (60.5), (water)melon (24.4), dates (32.4)
3	Pulses & legumes	41.0	Legumes (41)
4	Grains (bread)	211.0	Wheat (211)
5	Rice	184.0	Rice (184)
6	Starchy roots	59.0	Potato (59)
7	Beef (+veal)	7.0	Beef (7)
8	Pork	n.d.	n.d.
9	Mutton (+lamb & goat)	53.0	Sheep meat (53)
10	Poultry (+turkey)	119.0	Fresh poultry (22.1), frozen poultry (96.9)
11	Fish (incl. sea food)	46.0	Seawater fish (40.8), other seafood (5.3)
12	Cheese	n.d.	n.d.
13	Dairy (milk & yoghurt)	232.0	Milk (232)
14	Eggs	32.0	Eggs (32)
15	Pasta (Durum wheat)	n.d.	n.a.
16	Nuts and Seeds (+olives)	n.d.	n.a.
17	Meat replacements	n.d.	n.a.
18	Dairy replacements	n.d.	n.a.
	total	1380.0	
	general note: Data retrieved from the Qatar National Food Security Strategy 2018-2023. Ministry of Municipality and Environment (MME) - Food Security Department (MME Qatar, 2020). Data are commodity-based.		
Sydney, Australia			
1	Vegetables	110.5	Cabbage, cauliflower and similar brassica vegetables (9.9), Leaf and stalk vegetables (7), Peas and beans (7.1), Tomato and tomato products (14.4), Other fruiting vegetables (20), Other vegetables and vegetable combinations (16.9), Dishes where vegetable is the major component (35.2)
2	Fruits	142.3	Pome fruit (46), Berry fruit (4), Citrus fruit (20.9), Stone fruit (17.1), Tropical and subtropical fruit (28.1), Other fruit (15.4), Mixtures of two or more groups of fruit (6.8), Dried fruit, preserved fruit (3), Mixed dishes where fruit is the major component (0.8)
3	Pulses & legumes	8.8	Mature legumes and pulses (2.5), Mature legume and pulse products and dishes (6.2)
4	Grains (bread)	131.9	Grains (bread) 131.9
5	Rice	32.2	Rice (32.2)
6	Starchy roots	61.1	Potatoes (46.3), Carrot and similar root vegetables (14.7)
7	Beef (+veal)	18.9	Beef (18.7, Veal (0.2)
8	Pork	6.0	Pork (6)

9	Mutton (+lamb & goat)	7.2	Lamb and mutton (7.2)
10	Poultry (+turkey)	25.6	Chicken (24.3), Other poultry (1.3)
11	Fish (incl. sea food)	29.9	Finfish (excluding commercially sterile) (7.6), Crustacea and molluscs (excluding commercially sterile) (1.3), Other sea and freshwater foods (0.5), Packed (commercially sterile) fish and seafood (5.5), Fish and seafood products (homemade and takeaway) (8.6), Mixed dishes with fish or seafood as the major component (6.1)
12	Cheese	11.4	Cheese (11.4)
13	Dairy (milk & yoghurt)	209.4	Dairy milk (cow, sheep and goat) (139.1), Yoghurt (23.5), Cream (1.8), Frozen milk products (14.6), Custards (2.5), Other dishes where milk or a milk product is the major component (3.3), Flavoured milks and milkshakes (24.7)
14	Eggs	8.6	Eggs (8.6)
15	Pasta (Durum wheat)	16.2	Pasta and pasta products (without sauce) (16.2)
16	Nuts and Seeds (+olives)	6.5	Seeds and seed products (0.5), Nuts and nut products (6)
17	Meat replacements	1.2	Meat substitutes (1.2)
18	Dairy replacements	8.3	Dairy milk substitutes, unflavoured (7.8), Dairy milk substitutes, flavoured (0.1), Cheese substitute (0.1), Soy-based ice confection (0.2), Soy-based yoghurts (0.1)
	total	836.0	

general note: Food consumption is retrieved from ABS (2014)

Appendix 3D: Description of case studies

The six sections below describe the data sources addressed to determine the per capita consumption of various FEW resources. All data comes from (online) publicly accessible sources. Table 2 provides an overview of all the consumption data used in the calculation of the FEWprint carbon profiles.

(1) Amsterdam, Kattenburg (population = 1721)

The residential neighbourhood of Kattenburg is located on an artificial island adjacent to Amsterdam's city centre. Throughout history, the neighbourhood has provided housing for workers in the shipbuilding industry and naval activities. In the 1970s, the original dwellings were demolished and replaced with large residential complexes, including gallery flats and tenement buildings that have not been changed since then. As of 2020, the Kattenburg community counts 1720 residents divided over 989 households. City statistical data note that the community is aging (20.9% = 65+), income levels are at city-average (€34,400 cap/yr) and the percentage of the population with a non-Western background (23,6%) is lower than in the rest of the city (OIS Amsterdam, 2020). In this study, a Halal fraction of 15% and a Carnivorous fraction of 20% are assumed for Kattenburg.

The consumption data used to contextualise the Kattenburg community are either from national (The Netherlands), province (Zuid-Holland), regional (Amsterdam + belt), municipality (Amsterdam), city (Amsterdam), neighbourhood (Kattenburg) or street-level registrations. All the Kattenburg consumption data used in this study is retrieved from online public sources. The average food consumption per person is retrieved from census data provided by the Dutch National Institute for Public Health and the Environment (RIVM, 2017). Data on electricity and gas consumption is provided at the address level (anonymised) by the network manager Liander (Liander, 2019). Car ownership data is released at the neighbourhood level and the average distance driven per year is at the province level: 300 vehicles per 1000 household (CBS, 2016) and 11,700 km/yr (CBS, 2017) respectively, of which the latter is reduced by 50% to account for the inner-city location where cars are less used in general. Data on car type based on fuel use is available at the national level. In a car fleet 80% uses petrol, 15% uses diesel and about 5% uses electric (CBS, 2019). Water consumption data is published by the local water provider (Waternet, 2016). The study assumes that water used/consumed is equal to the water treated afterward. Data on domestic waste production is provided at the municipal level, which is similar to the city level in the case of Amsterdam. Amsterdam residents produce 377kg annually, which includes fine and bulky waste (CBS, 2018). Official data on waste recycling is lacking (recycle fraction = 0%) and to the extent of our knowledge, all waste is incinerated. The platform offers default data for waste composition (organic, paper, plastic, glass, metal & other [%]) based on income level (low, lower-middle, upper-middle, high) as determined by the World Bank (2012). For Kattenburg, the high income level is used.

(2) Belfast, Inner-East district (population = 32.000)

Situated on the eastern bank of the Lagan River, Inner East Belfast was historically important in providing housing for workers of the shipyards, to the north and Sirocco works, to the west. Today, Inner East Belfast is a low-density neighbourhood with a wide variety of housing typologies, from mid-twentieth century terrace housing to detached bungalow housing from the 1990s. Consisting of six administrative wards of Ballymacarrett, Woodstock, The Mount, Bloomfield, Island and Sydenham, it has a population of 32.834 residents divided over 15.246 households. The total site area considered for this study spans 1322 ha, of which 322 ha is non-permeable area. The neighbourhood consists of a large percentage of one-person households (41.5%). A Halal fraction of 0% and Carnivorous fraction of 20% is applied to the diet of residents compared to the average GB diet.

The consumption information of residents is sourced from government data sources. Further, the consumption data used to contextualise Inner-East Belfast are either from national (United Kingdom), province (Northern-Ireland), county (Antrim and Down), city (Belfast), or neighbourhood (Inner-East) level. The average food consumption is drawn from the Family food statistics survey by Department for Environment, Food and Rural Affairs (DEFRA, 2020a). While food data is available at a regional level for N.I., the data used in this study is a U.K. average. Data on electricity generation and associated environmental factors are taken at provincial level with the electricity generation producing carbon at 0.339 kgCO_2e/kWh in 2018, demonstrating the high percentage of contribution from renewables in Northern Ireland (DAERA, 2020). The emissions factors for other fuel types are drawn from a national, U.K., level (BEIS, 2020). Electricity consumption and gas consumption are measured at a city level (DfE, 2020). Car ownership – 667 per 1000 people over the age of 17 – is high in Northern Ireland compared to the U.K., while the average person travels 6,369 km/yr (DfI, 2017). The fuel used for cars is 57% petrol, 42% diesel and 1% electric or hybrid (NISRA, 2016). Average water consumption data (53 m3/cap/year) is published by N.I. Water alongside the environmental factor of water treatment (0.139 kg CO2e/m^3) and wastewater treatment (0.433 kg CO2e/m^3) (N.I. Water, 2019). Waste is monitored at the Local Council Area level with the average resident in Belfast producing 416 kg of waste annually. Official data states the Belfast recycling and reuse rate is approximately 25% while as much as 40% is sent to landfill (DAERA, 2019). The income level is set to high.

(3) Detroit, Oakland Avenue Urban Farm (OAUF) (population= 427)

Situated in the North End of Detroit, Michigan, the OAUF neighbourhood is centred around a 2.4 ha urban farm. The farm serves as a community hub for social activities, education, and outreach concerning food sovereignty and justice while providing fresh food access to neighbouring communities. Currently, the farm consists of a series of garden plots and apple orchards, a farmer's market, community public art projects, a performance area, a community house, and a farm store. Historically, the North End neighbourhood was an automobile industry in the 1920-30s, and the Oakland Avenue corridor was recognized for its jazz and entertainment. Since the mid-1950s, the neighbourhood has witnessed a gradual decrease in population and increased vacancy, due to the loss of manufacturing jobs, suburbanization, disinvestment, and closure of small businesses. Within the one-block radius of the farm, 5-10min walking distance, an estimated population of 427 divided over 197 households live within an urban footprint of 36.7 ha, of which 17 ha is non-permeable. The neighbourhood is predominantly comprised of single-detached homes. The median income of the census tract (5114) falls in the low-income bracket ($20,362) (USCB, 2018). The majority of the population in the census tract (19.8%) is between the age of 55-64 years (USCB, 2018). Considering that 3% of the population in the Detroit Metro area are Muslim, the study assumes a Halal percentage of 3% as well (Pew Research Centre, 2020). Further, based on the studies by the Centers for Disease Control and Prevention (CDC), 18.5% of adults (aged 18+) and 42.4% of children (between age 12-18 years) consume vegetables less than one time daily in Michigan, thus the study applies a cumulative carnivorous fraction of 21.75% (CDC, 2020).

The consumption data used to contextualise OAUF neighbourhood are either from national (USA), state (Michigan), regional (Midwest or South-East Michigan), county (Wayne), city (Detroit), or census tract (5114) datasets, retrieved primarily from public online sources. The estimated per capita food consumption is drawn from the national Food availability (per capita) data system using the Loss-adjusted food availability data for 2017 (USDA ERS, 2017). The Environmental Factors for the US diet is based on the Database of food impacts on the Environment for Linking to Diets (Heller et al., 2018). The energy consumption data per household member is generated from the regional data- annual household site consumption and expenditure in the Midwest, from the 2015 Residential Energy Consumption Survey: Energy Consumption and Expenditures (US EIA, 2015). The carbon footprints for electricity and natural gas are based on the report, City of Detroit Greenhouse Gas Inventory (Carlson et al. 2014). The annual vehicular distance travelled per capita within Detroit is 14215 km (USDOT, 2015). Within census tract-5114, there is an estimate of 752.6 vehicles per 1000 households (USCB, 2018). The fuel types used for light-duty vehicles, including passenger cars and light-duty trucks in the U.S., are 96.7% petrol, 2.9% diesel, 0.35% propane, and 0.04% electric (Davis & Boundy, 2020; EIA, 2017). The Great Lakes water authority (GLWA) is a regional system managing water supply and wastewater systems in seven Southeast Michigan counties, including Wayne County. The environmental factor applied for the water supply and wastewater treatment are proxy values from U.S. based studies due to limited data availability for GLWA (Cashman et al., 2014; Jin et al., 2015) The daily water consumption per person in Detroit is 219.5 litres (CDM Smith, 2015). The study assumes that all the water used for domestic consumption becomes wastewater in the calculation. Waste estimates for the City of Detroit are from the Wayne County Municipality Report 2015. Each Detroit resident produces 432 Kg of waste per year, out of which 1% is recycled, 71% is incinerated, 6% is composted, and 23% is sent to landfill (Wayne County, 2015).

(4) Doha, Qatar University Campus (QU) (population= 24.00)

Qatar University is a public university, north of Doha and 2 km from the Gulf shore, situated on an elevated site. In 2019 the university accommodated more than 23,000 students and 1000 staff members within a campus area of 80.9 ha, of which 7.2 ha is considered non-permeable surface. The student population consists mostly of Qatari citizens: 66% (Qatar University Publications, 2020). The campus is composed of residential and commercial buildings, a central library, a science centre, a park, as well as numerous colleges and student centres. Additional social and commercial activities take place in retail facilities including mini markets, shops, food outlets, health centres as well as recreation and athletic facilities. Qatar is among the richest countries globally with a GDP of 146.37 billion USD in 2020 (The World Bank, 2021), thus the national income level is classified as high and therefore the income level is set to high. Qatar being an Islamic country with approximately 67.7% of the population Muslims (World Population Review, 2021), the Halal fraction is set to zero as the national data represents this specific diet. Further, the study assumes a Carnivorous fraction of 20%, since Qatari diet is high in meat products (Al-Thani et al., 2017).

The consumption data used to contextualise the Qatar University Campus are either from the national (Qatar), or neighbourhood level (QU campus). The Qatar University campus consumption data used in this study are retrieved from public online sources, in collaboration with the Facilities & General Services Department (FGSD) at QU. The average food consumption per person is collected by the Food Security Department, Ministry of Municipality and Environment in Qatar (MME Qatar, 2020). For this assessment demonstration, this study assumes that all staff and students live on campus and that 100% of the staff, 75% of the Qatari student and staff and 50% of the international students own a car, resulting in a total of 16,295 cars on campus. This number is manually inserted to the platform. The average vehicular distance travelled is approximately 22,000 km per year (Cihat, Kucukvar, Aboushaqrah, & Jabbar, 2019). Data on electricity and water consumption were provided by the FGSD. Data on domestic waste production are given at a national level from the Planning and Statistics Authority in Qatar. In 2019, the domestic waste produced amounted to 1.41 kg per capita per day (Planning and Statistics Authority Qatar, 2019).

(5) Tokyo, Tamaplaza (population=84.850)

The Japanese population made a significant transformation from rural areas to large cities in the 1960s and 1970s due to labour demand in urban areas. To meet the enormous demand for housing, a policy of ownership with a focus on own-construction was promoted so that suburban areas were rapidly converted to residential areas by the private sector (Ishabashi & Taniguchi, 2005). Examples in Tokyo include Tama New Town and Tama Garden City, Tamaplaza is a part of these housing complexes. The Tamaplaza neighbourhood has a population of 84850 divided over 34918 households, residing within an urban footprint of 832 ha, of which 707 ha is non-permeable surface. Although there are no official statistics, the number of people following a Halal diet is considered to be extremely low. The study assumes an overall Halal fraction and Carnivore fraction of 0%. The income level is set to high.

The consumption data used to contextualise Tamaplaza are either from national (Japan), province (Kanto), regional (Tokyo Metropolitan Area), municipality (Kanagawa), city (Yokohama) or neighbourhood (Tamaplaza). Carbon footprints for electricity, gas and water are specified by law and from reports of the Water Department. For electricity and gas, the law stipulates a system for calculating, reporting, and announcing greenhouse gas emissions, and this study applies the prescribed coefficients in the calculations (ME Japan, 2020). Although water supply is managed at the prefectural level, the data for Kanagawa Prefecture (where Tamaplaza is located) remains inaccessible. Therefore, the study applies data collected by Tokyo Metropolitan Waterworks Bureau and results from other academic publications (Bureau of Waterworks Tokyo, 2019; Sano et al., 2012).

The resident consumption data are based on government and business data sources. Average food consumption is obtained at the regional level from the National Health and Nutrition Survey of the Ministry of Health, Labour and Welfare (MHLW, 2018). Data on per capita consumption of electricity, gas and water are prepared at the county level (ANRE, 2019; Bureau of Waterworks Tokyo, 2015). According to data generated at the ward level and published by the City of Yokohama, there are 704 cars per 1000 households (Yokoma City, 2020). The average distance travelled by cars is 7231 km, calculated at the city level (Yokohama City, 2010). The number of vehicles by fuel type is estimated using data provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT, 2010, 2018). Waste data is sourced from a report by the City of Yokohama, which informs that the annual per capita household waste generated is 222 kg (Yokohama City, 2019). In addition, the recycling rate of waste is 33.1% (YCRMB, 2017).

(6) Sydney, Western Parkland City (population= 1000000)

The Sydney case study is a futuristic project, for which the applied values are estimates. As part of the Greater Sydney Region Plan Metropolis of Three Cities (GSC, 2018a), Sydney will transform into three distinct but interconnected cities: the Eastern Harbour City, the Central River City, and the Western Parkland City. The city will be established on the strength of the new international Western Sydney Airport and Badgerys Creek Aerotropolis. Western Parkland City is the subject of the M-NEX Sydney Living Lab as it is currently sparsely populated and environmentally degraded. Previously the site was primarily used for grazing, hobby farming and industrial activities. The scale of the proposed development is unprecedented. The population of Western Parkland City is projected to grow from 740,000 in 2016 to 1,1 million by 2036, and over 1,5 million by 2056 (GSC, 2018b). The study assumes a population 1,000,000, divided over 384,615 households residing within an urban footprint of 808,661 ha, of which 485,196 ha is non-permeable. The income level of this future city is set to high. The study assumes an overall Halal fraction and Carnivore fraction of 0%.

The consumption data used to contextualise Western Parkland City are either from national (Australia), State (New South Wales), regional (Greater Sydney), city (Sydney), or neighbourhood (Western Sydney) level. The Western Sydney consumption data used in this study is retrieved from public online sources. The average food consumption per person is retrieved from the Australian Bureau of Statistics (ABS, 2014). Data on electricity and gas consumption is provided at the State level from the NSW Environmental Protection Agency's State of the Environment Report (US EPA, 2015). Car ownership data and average distance travelled per year are released at the state level: 536 vehicles per 1000 households (ABS, 2021) and 8700 km/yr (ABS, 2020), of which the latter accounts for the capital city area of operation. Car type based on fuel use is available from the same data set (ABS, 2020) at the State level. In a car fleet 72.7% uses petrol, 25.6% uses diesel, 1.7% uses LPG, and approximately 0.1% uses electric. Water consumption data is provided by the local water provider (Sydney Water, 2019). Data on domestic waste production is given at the state level. NSW residents produce 550 Kg per person annually (US EPA, 2020), 43% is diverted from landfills which comprise 22% recycled and 21% organic. No waste is incinerated and until recently most recycling was sent overseas to China.

Appendix 3E: FEWprint equation framework

This appendix section describes the applied equations used to establish a carbon assessment with the FEWprint platform. The impact of FEW management intervention is measured as the difference in carbon equivalent emissions between the baseline scenario and the designed *new* scenario. As such, this platform operates as a scenario comparison and evaluation tool. Not including any interventions surrounding the production of food, a *new* scenario is composed changing end-user resource demand, resource type or resource infrastructure (shown in figure 3.1). Therefore, discussed equations in this appendix apply for both the baseline scenario assessment as well as the *new* scenario assessment, where resource demand for new scenario is marked by a notion in the subscript, for example $PCC(n)_{new}$. This particular study does however not discuss any new scenario solutions.

The total carbon footprint of the community (CF_{tot}) is calculated with equation A1, and is composed of the separate sectoral footprints of food consumption (CF_F), electrical energy use (CF_{EE}), thermal energy use (CF_{TE}), the use of car fuel for mobility (CF_{ME}), water production and treatment (CF_W) and the emissions associated with the processing of domestic waste (CF_{DW}). The equations apply [ton/yr] as units, however, note that the results of this study are expressed in [kg/cap/yr] for inter-community comparability purposes.

$$CF_{tot} = CF_F + CF_{EE} + CF_{TE} + CF_{ME} + CF_W + CF_{DW} \qquad [A1]$$

Food

CF_F denotes the summed carbon footprint by the 18 considered food groups consumed in a community and can be calculated with equation A2. An overview of the considered food inventory is provided in table A3.3 in appendix 3C.

$$CF_F = N_{tot} * \sum(PCC(n)_{ctx} * \frac{365}{1000} * ef(n)_{kg}) \qquad \text{(apply } PCC(n)_{new} \text{ for a new scenario)} \qquad [A2]$$

N_{tot} represents the total number of people in the community. $PCC(n)_{ctx}$ denotes the contextualised daily per capita consumption [g/cap/day]. The contextualisation of the national diet is discussed in the section below. The carbon footprint of a food group is indicated by $ef(n)_{kg}$. Table 3.1 provides an overview of the country specific values applied in this study as well as a set of mean global default values.

Contextualising food consumption

The carbon assessment of food consumption is based on a selection of food groups and individual food consumption data is extracted from public datasets that usually represent the national average. Through on-site survey data, it is theoretically possible to get an accurate figure on the daily food intake of a considered context. However, data on this granularity is hardly available for a given urban context and it would be resource-intensive to produce. Some datasets connect consumption data with socio-cultural, economic or demographic aspects and present this data through customisable graphs and tables (for example the Dutch RIVM (2020a). Relevant aspects of the considered community can then be projected on the existing data, yielding a more accurate number on food intake. To narrow the misalignment between data aggregation levels, this work applies a basic method of contextualisation for the more environmentally intensive products: meat.

The FEWprint provides two neighbourhood-specific parameters that can be used attune the national base diet and make it representative for the considered context: the *halal diet* fraction and the *carnivorous* fraction. Even though varying between religions or cultures, halal diets exclude certain food products and prescribe specific procedures surrounding the preparation of meat products. The halal fraction in this study is limited to the reduction of pork meat and the removed amount of pork is for simplicity assumed to be equally substituted by beef, mutton, poultry and fish. The carnivorous fraction describes the number of people in the community that consume more than average amounts of meat. The resulting contextualised diet is denoted by $PCC(n)_{ctx}$ and can be calculated with the equations A3 for pork consumption and A4 for the other meat categories. The remaining food groups (1-6;11-18) are not affected by the halal and carnivorous fraction (equation [A5]).

$$PCC(pork\ (8))_{ctx} = PCC(pork(8)) * (1 - r_{hal}) * (1 + r_{car} * r_{add}) \quad [A3]$$

$$PCC(7{,}9{,}10)_{ctx} = (PCC\ (7{,}9{,}10) + \frac{PCC(pork)*r_{hal}}{4}) * (1 + r_{car} * r_{add}) \quad [A4]$$

$PCC(n)_{ctx} = PCC(n)$ for all remaining food groups. [A5]

PCC(n) is the per capita consumption of food group (n) according to the average national diet [gram/cap/day] and CS food intake data is listed in table 3.1. and Appendix 3C. The community fraction that follows a halal diet is represented by r_{hal}. The group of the community that consume more than average quantities of meat and fish can be accounted for with r_{car}. Their additional meat + fish consumption is included with the factor r_{add} and is set to +15% as a default value, which is roughly corresponding with an extra day of meat consumption per week. All before mentioned parameters can be adjusted while working with the platform. In case the national diet is expected to deviate strongly from the food intake at the community level, inserting a (partly) customised diet is more advisable.

Energy

The carbon footprint of electrical energy use (EF_{EE}) and thermal energy use (EF_{TE}) are calculated with respectively equations A6 and A7 and is based on the per capita use ($PCU(n)$, or $PCU(n)_{new}$) of the various inserted energy sources and/or carriers *n*. The corresponding default footprints of the various energy carriers, electricity sources or district heating systems ($ef(n)_{unit}$) can be found in table B1. The footprints applied in this study can be found in table A1.

$CF_{EE} = N_{tot} * \sum(PCU(n) * ef(n)_{kWh})$ (apply $PCU(n)_{new}$ for a new scenario) [A6]

$CF_{TE} = N_{tot} * \sum(PCU(n) * ef(n)_{unit})$ (apply $PCU(n)_{new}$ for a new scenario) [A7]

New energy scenarios can be designed and evaluated by changing the end-user demand and/or changing/decentralising energy provision.

Mobility

The carbon footprint of mobility, i.e. transportation carbon emissions from fuel combustion, is limited to personal transportation only. This limitation allows for a top-down assessment approach where data from local or national registrations are combined to produce a contextual estimation. This educated estimation is based five parameters: (1) community vehicle typology based on fuel input, (2) car efficiency (also called fuel economy), (3) car ownership, (4) annual distance driven and (5) carbon footprint indicators of fuel combustion. The impact of the mobility sector is estimated with equation A8:

$CF_{ME} = N_{tot} * \sum(PCU(n) * ef(n))$ (apply $PCU(n)_{new}$ for a new scenario) [A8]

The per capita use of car fuel $PCU(n)$ has to be calculated separately with equation A9:

$$PCU(n) = \frac{N_{hh} * \frac{c_{car}}{1000} * r(n)_{fuel} * d_{yr}}{\eta(n)_{fuel}} / N_{tot} \quad [A9]$$

N_{hh} denotes the total number of households in the community and c_{car} represents the car ownership, which should be expressed in number of cars per 1000 household. It is not unlikely that car ownership (c_{car}) is expressed in different terms, like for example per capita, in which case $[N_{hh} * \frac{c_{car}}{1000}]$ should be exchanged with $[N_{tot} * c_{car}]$ or any other elementary equation that can calculate the total number of car in the community. $r(n)_{fuel}$ notes the fraction of car types based on the fuel input *n*, see item 1-8 in table B1. The car type fractions applied in this study and the average distance driven per capita per year (d_{yr} [km]), are both listed in table 2. The efficiency of the car, expressed in kilometres driven per 1 unit of fuel, is approximated with $\eta(n)_{fuel}$, of which the applied default values in this study can be found in table A3.2 in appendix 3B.

Water

The total carbon footprint of urban water management is composed of the emissions related to the production and distribution of potable water (pw) and the emissions coming from the collection and treatment of wastewater (ww). Also, the emissions involved with the treatment of centrally collected rainwater (rw) are accounted for, which may be applicable in cities with mixed rainwater-sewage water pipes. All these processes require electrical energy, hence driving both upstream and downstream carbon emissions. The total carbon emissions occurring in the water sector are calculated with equation A10:

$$CF_W = CF_{pw} + CF_{ww} + CF_{rw} \quad \text{[A10]}$$

The emissions associated with drinking water production are calculated with equation A11:

$$CF_{pw} = \left(PCU(pw) * \sum\left(E(n_{prod}) * ef(n)_{kWh}\right)\right) * \frac{365}{1000} * N_{tot} \quad \text{[A11]}$$

The emissions associated with waste water treatment are calculated with equation A12:

$$CF_{ww} = \left(PCP(ww) * \sum\left(E(n_{trt}) * ef(n)_{kWh}\right)\right) * \frac{365}{1000} * N_{tot} \quad \text{[A12]}$$

The emissions associated with rainwater management are calculated with equation A13:

$$CF_{rw} = p * \sum A_{imp} * 0.623 * E(n_{trt}) * ef(n)_{kWh} \quad \text{[A13]}$$

The per capita use of potable water that is tapped from the regional water provision is noted by PCU_{pw} [L/day] and can be retrieved from public databases or estimated based on resident survey input. The per capita produced wastewater is denoted by PCP_{ww} [L/day]. For simplicity, potable demand and wastewater production are assumed to be similar in this work. The embodied electricity per cubic meter of water produced or treated is mentioned by respectively $E(n_{prod})$ and $E(n_{trt})$ [kWh/m^3] and is multiplied with the carbon footprint of the applicable electricity source $ef(n)_{kWh}$. Due to a broadly observed unavailability of embodied energy data on water production and treatment processes, it is also possible to calculate directly with emission footprints [kg CO_2e/m^3].

The emissions related to rainwater management are noted by CF_{rw} and are calculated by multiplying the annual rainfall *p* [m^3/m^2/yr] with the total amount of impermeable surface A_{imp} [m^2] within the designated urban area. A reduction factor (0.623) is included to account for the rainwater that precipitates in such small quantities that collection and disposal are not required and natural evaporation takes over (Texas A&M, n.d.).

Alternative scenarios can be designed by lowering the water demand, changing and/or decentralising the water provision, changing and/or decentralising water treatment methods and assigning renewable energy sources to the water infrastructure. Alternative rainwater resource management strategies in a new scenario can be assed be increasing the permeable surface area, switching rainwater treatment methods, increase rainwater capture + reuse or allocating renewable energy sources to the treatment systems.

Waste

The carbon equivalent emissions associated with processing domestically produced waste can be estimated with equation A12:

$$CF_{DW} = N_{tot} * PCP_{dw} * r_{rec} * \sum(r(n)_{waste} * ef(n)_{kg}) \quad \text{[A12]}$$

The per capita waste production PCP_{dw}[kg/yr] is first reduced with the recycling fraction r_{rec}. No emissions are assigned to the recycled fraction in this study. The remaining waste is sub-divided into the three waste processing methods applicable to the context with $r(n)_{waste}$ and multiplied with the corresponding carbon footprints $ef(n_{38-41})_{kg}$. This study limits to the three main methods of processing: waste-to-energy (incineration), waste-to-landfill and waste-to-compost. The domestic waste management methods can be expressed in carbon emission equivalents, which are adapted from Pulselli et al. (2019) and applied similarly to all case studies. The nature of the waste does not affect the carbon assessment of the baseline scenario in this work. However, the platform offers default data for waste composition (organic, paper, plastic, glass, metal & other [%]) based on income level (low, lower-middle, upper-middle, high) as determined by the World Bank (2012). Subdividing the total waste can be useful when designing a new waste management strategy for the context, since more tailored solutions can be proposed for the different waste streams.

Appendix 3F: Sensitivity Analysis

Table A3.4

Detailed overview of data entries for sensitivity analysis of selected food scope. Abbreviations: n.d. = no data; o.s. = Out of Scope.

Food consumption Limited scope and Full scope.					Carbon footprint	Carbon impact [kg/cap*yr]			
•	**Food group**	**Limited scope assessment (group based)**	**Full scope assessment (product based) (=). also included in limited scope. (+). added to scope**	**Note on consumed products**	**categorical (left) product (right)**	**Lim. scope / Categorical. indicator (LSCI)**	**Full scope / Categorical. indicator (FSCI)**	**Full. scope / Product indicator (FSPI)**	**Lim. scope / Product indicator (LSPI)**
1	Vegetables	Total 131.0	Vegetables total: 131.0	-	1.82	87.0	83.9	87.0	83.9
		- various products	= Mixed vegetables (11.8)	-	(n.d.)	-	-	7.8	7.8
		(as full scope column)	=Leafy Greens (19.2)	Includes spinach & chicory	1.00	-	-	7.0	7.0
			= fruiting vegetables (48.4)	Tomato. Bell pepper. cucumbers	2.47	-	-	43.6	43.6
			= Root vegetables & carrots (12.3)	Based on carrots	0.59	-	-	2.6	2.6
			= Cabbages (19.4)	Based on kale	1.60	-	-	11.3	11.3
			= Mushrooms (2.9)	Based on mushrooms	5.21	-	-	5.5	5.5
			= Peas. corn & broad beans (2.5)	Based on peas. corn & green beans	1.69	-	-	1.5	1.5
			= Onion. leek. garlic (11.8)	Based on onion (raw & cooked)	0.61	-	-	2.6	2.6
			= Stalked vegetables & Sprouts (2.6)	-	(n.d.)	-	-	1.7	1.7
2	Fruits	Fruits 113.4	Fruits total: 119.5	-	1.53	63.3	63.3	66.7	66.7
		- Fruit (113.4)	= Fruit (113.4)	-	*(n.d.)*	-	-	63.3	63.3
			+ fruit compote (+5.7)	-	*(n.d.)*	-	-	3.2	(o.s.)
			+ fruit-nut mix (+0.4)	-	*(n.d.)*	-	-	0.2	(o.s.)
3	Pul.& Leg.	Pulses & Legumes (4.5)	Pulses & Legumes total: 4.5	-	2.53	4.2	4.2	4.2	4.2
4	Cereals & Grains	138.3	Cereals & Grains total: 146.9	-	1.32	66.6	70.7	-	-
		+ Bread (125.6)	= Bread (125.6)	-	1.24	-	-	56.8	56.8
		+ Knackebrod (5.3)	= Cracker/Knackebrod (5.3)	-	(n.d.)	-	-	2.6	2.6
		+ Breakfast cereals (7.4)	= Breakfast cereals (7.4)	-	1.38	-	-	3.7	3.7
			+ wheat other (8.5)	-	(n.d.)	-	-	4.1	(o.s.)
5	Rice	n.d.	n.d.	-	1.71	n.d.	n.d.	n.d.	n.d.
6	Starchy R.	72.1	Starchy Roots total: 72.1	-	0.92	24.2	24.2	24.2	24.2
7	Beef	12..6	Beef total: 30.5	-	30.8	141.7	343	343.1	141.7
			+ Processed mix (18.3)	Mix of processed meat products (hot/cold)[1]	(n.d.)	-	-	-	(o.s.)

8	Pork	13.0	Pork total: 31.3	-	13.70	65	157	156.9	65.1
			+ Processed mix (18.3)	Mix of processed meat products (hot/cold)[1]	(n.d.)	-	-	-	(o.s.)
9	Mutton	0.6	n.d.	Consumption to low	(n.d.)	n.d.	n.d.	n.d.	n.d.
10	Poultry	16.6	Poultry total: 34.7	-	12.2	74.0	155.0	154.6	74.0
			+ Processed mix (18.3)	Mix of processed meat products (hot/cold)[1]	(n.d.)	-	-	-	(o.s.)
11	Fish & Seafood	12.9	Fish & Sea food total: 16.0	-	8.61	41.0	51.0	-	-
		- Fish (11.5)	= Fish (11.5)	-	8.23			34.5	34.5
		- Sea food (1.4)	= Sea Food (1.4)	CF based on shrimp	15.40			7.9	7.9
			+ Fish products (+3.2)	-	(n.d.)			10.1	(n.d.);(o.s.)
12	Cheese	32.6	32.6	-	11.30	*134.2*	*134.2*	*134.2*	*134.2*
13	Dairy (except cheese)	254.3	Dairy total: 310.6	-	2.31	214.0	262.0	-	-
		- yoghurt (53.7)	= Yoghurt (53.7)	-	*2.26*			44.3	44.3
		- fermented (147.4)	= Milk. fermented (147.4)	-	*1.50*			80.7	80.7
		- unfermented (53.2)	= Milk. unfermented (53.2)	-	*2.03*			39.4	39.4
			+ Other (1.7)	-	(n.d.)			1.4	(o.s.)
			+ Kwark (11.4)	-	*4.72*			19.6	(o.s.)
			+ Vla. porridge. pudding (26.3)	-	*2.03*			19.5	(o.s.)
			+ Ice cream (9.8)	-	(n.d.)			8.3	(o.s.)
			+ Cream. coffee cream (7.1)	-	(n.d.)			6.0	(o.s.)
14	Eggs	12.7	Eggs total: 12.7	-	4.32	20.0	20.0	20.0	20.0
15	Wheat (P)	47.1	Wheat (pasta) total: 47.1	-	1.52	26.1	26.1	26.1	26.1
16	Nuts & Seeds	6.3	Nuts & Seeds total: 6.3	-	4.16	10.0	10.0	-	-
		- Olives (0.6)	o Olives (0.6)	-	(n.d.)			0.9	0.9
		- Nuts & Seeds (5.7)	o Nuts & Seeds (5.7)	-	(n.d.)			8.7	8.7
17	Meat rep.	1.5	Meat replacers total: 1.5	-	n.d.	0.0	0.0	n.d.	n.d.
18	Dairy rep.	8.4	Dairy replacements: 8.4	(soy drink. natural)	0.76	2.3	2.3	2.3	2.3
19	Fruits & Nuts	n.a.	Fruits & Nuts total: 4.0	-	8.68	Out of scope	12.7	-	Out of scope
			Peanut Butter (4.0)	-				12.7	
20	Fats & Oils	n.a.	Fats & oils total: 22.0	-	7.02		57.0	-	
			Fats & Oils. other (1.6)	Based on category average	(n.d.)	Out		4.1	Out
			Plant oils (3.5)	Based on Sunflower & olive oil	6.09	of		7.8	of
			Butter (2.2)	Based on Butter. salted + unsalted	12.2	scope		9.8	scope
			Margarine & prep. fats (14.9)	Margarine	4.95			26.9	
21	Sugar & Candy	n.a.	Sugar & Candy total: sum	-	2.54	Out	28.0	-	Out
			Sugar & Candy. other (4.7)	As average.	n.d.	of		4.4	of

			Sugar (4.7)	-	0.84	scope		1.4	scope
			Marmalade products (5.1)	Jelly & Apple Sirope	1.68			3.1	
			Honey (0.9)	-	1.16			0.4	
			Chocolate spread (3.4)	Sprinkles and spread	2.56			3.2	
			Candy. no chocolate (5.8)	As average.	(n.d.)			5.4	
			Dessert sauce (0.7)	As average.	(n.d.)			0.6	
			Chocolate (4.8)	Milk chocolate	6.06			10.6	
22	Cake	n.a.	Cake & Cookies total: 41.2	-	3.33	Out	50.0	-	Out
			Cake. breakfast cake (24.1)	Based on breakfast cake & cakes	3.55	of		31.2	of
			Cookie & biscuit (17.1)	Based on various products	3.28	scope		20.5	scope
23	Non-alcoholic	n.a.	Non-alcoholic drinks total: 1707.5	-	0.64		399.0	-	
			Non-alcoholic. other (7.5)	As average.	(n.d.)			1.8	
			Fruit- & vegetable juice (55.4)	Various products	0.89			18.0	
			Lemonades. soda. sirops (349.3)	Cola. Ice tea. lemonades	0.47	Out		59.9	Out
			Coffee (392.5)	Coffee & Cappuccino	0.90	of		128.9	of
			Tea (225.7)	-	0.16	scope		13.2	scope
			Herb- & fruit tea (88.4)	as tea	0.16			5.2	
			Water. bottled water (588.7)	Essentially zero	0.01			2.1	
24	Alcoholic	n.a.	Alcoholic Drinks total: 138.8	-	1.93		98.0	-	
			Wine (38.4)	Wine red. rose and white	2.15	Out		30.1	Out
			Sherry. Port. Vermouth (1.6)	As average.	(n.d.)	of		1.1	of
			Beer (92.3)	-	0.71	scope		23.9	scope
			Strong spirits. liquor (4.2)	Base on Jenever drink	2.49			3.8	
			Other alcoholic drinks (2.3)	As average.	1.93			1.6	
25	Sauce & seasonings	n.a.	Sauces & Seasonings total: 35.4	-	2.68		35.0	-	
			Sauces & Seasonings. other (16.3)	As average (no seasonings included)	2.68	Out		15.9	Out
			Tomato Sauce (6.7)	-	1.17	of		2.9	of
			Mayonnaise & dressings (7.9)	-	5.52	scope		15.9	scope
			Bread spread. mayonnaise based (4.5)	As average	2.68			4.4	
26	Bouillon	n.a.	Bouillon total: 42.6	-	2.21	Out of scope	34.4	34.4	Out of scope
27	Savoury Snacks	n.a.	Savoury Snacks: 20.6	-	4.56	Out	34.3	-	Out
			Salty snacks. crisps. salt cookies (9.4)	Based on crisps and popcorn	2.89	of		9.9	of
			Snacks. deep-fried. snack breads (11.2)	Based on sausage bread. frikandel and kroket	6.23	scope		25.5	scope
Total impact:		871 g/cap*day	3048 gram/cap*day	Total impact:		2165	973	1911	854

[1] Mix of (1) Other meat products. (2) Processed meat for warm dinner & (3) Meat products (lunch) = + 18.3.

Appendices Chapter 4

Towards a More Sustainable Urban Food System—Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform

Appendix 4A: Country specific protein content.

Table A4.1. Knowing the protein content of food is relevant to calculate protein equilibrium after diet shift. For each case study, national datasets of protein content [$gram_{prot}$/100 g_{food}] have been collected. Where necessary, individual food products listed by the sources are combined or re-categorised in order to align with the 18 food categories applied in this study. Processed, non-staple food and drinks (except milk) are not included in this overview. As discussed in section 4.3.2, a considerable deviation in values becomes evident after data cleaning, which is visualised in figure A4.1. In order not to add an extra layer of variables and further compromise the comparability between the cities, the non-contextual FAO dataset is used for further assessment of the diet transition. Table B2 shows the processed FAO dataset. Values represent the average protein content of an extensive list of products, where (*n*) represent the number of aggregated individual items. The Detroit column only shows meat products as only these categories have been expressed in weight units (oz.) in the data source, whereas the (nearly) all other items are expressed in household unit that are difficult to convert (e.g., tablespoons, scoops). Values represent the retail weight of food. N.d. = no data. Food group 17–18 are not retrieved from the dataset but constitute assumed customary replacement products due to an unavailability of data.

Food Category		**Protein Content [$gram_{prot}$/kg_{food}]**			
•	**Food Group (*n*)**	**Amsterdam [3]**	**Belfast [4]**	**Detroit [5]**	**FAO [6]**
1	Vegetables	1.9 (207)	n.d. (n.a.)	n.d.	2.3 (36)
2	Fruits	1.1 (111)	n.d. (n.a.)	n.d.	1.0 (50)
3	Legumes & pulses	11.9 (32)	7.0 (4)	n.d.	24.3 (11)
4	Grains & Cereals	10.3 (223)	9.9 (4)	n.d.	9.7 (24)
5	Rice	5.6 (9)	2.6 (1)	n.d.	6.7 (4)
6	Starchy roots	2.6 (45)	n.d. (n.a.)	n.d.	1.3 (11)
7	Beef (& veal)	28.5 (44)	31.0 (1)	24.5 (26)	20.9 (7)
8	Pork	26.6 (30)	31.6 (1)	23.1 (31)	13.9 (6)
9	Sheep & Goat (+lamb)	26.2 (6)	29.2 (1)	22.5 (38)	14.2 (4)
10	Poultry & Turkey	25.1 (6)	32.0 (1)	25.3 (21)	15.7 (11)
11	Fish & Seafood	22.8 (73)	19.8 (7)	21.2 (26)	20.9 (37)
12	Cheese	21.8 (77)	23.6 (3)	n.d.	24.5 (5)
13	Dairy (Milk & Yoghurt)	4.2 (138)	4.1 (5)	n.d.	4.3 (21)
14	Eggs	13.1 (12)	12.5 (1)	n.d.	11.1 (4)
15	Pasta (durum wheat)	6.9 (17)	6.6 (1)	n.d.	11.8 (3)
16	Nuts & Seeds	18.5 (36)	16.6 (3)	n.d.	12.4 (39)
17	Meat replacements [1]	11.1 (33)	8.1 (1)	n.d.	13.0 (n.a.) [1]
18	Dairy replacements [2]	2.5 (10)	n.d. (n.a.)	n.d.	3.0 (n.a.) [2]

[1] Retail product assumed: Tofu, uncooked (33% water), 13 g protein/100 g product.
[2] Retail product assumed: Soy Drink, natural. 3.0 g/100 mL of product.
[3] Data source:(RIVM, 2019),
[4] Data source: (British Nutrition Foundation, 2012),
[5] Data source: (USDA, 2018),
[6] Data source: (FAO, 2001).

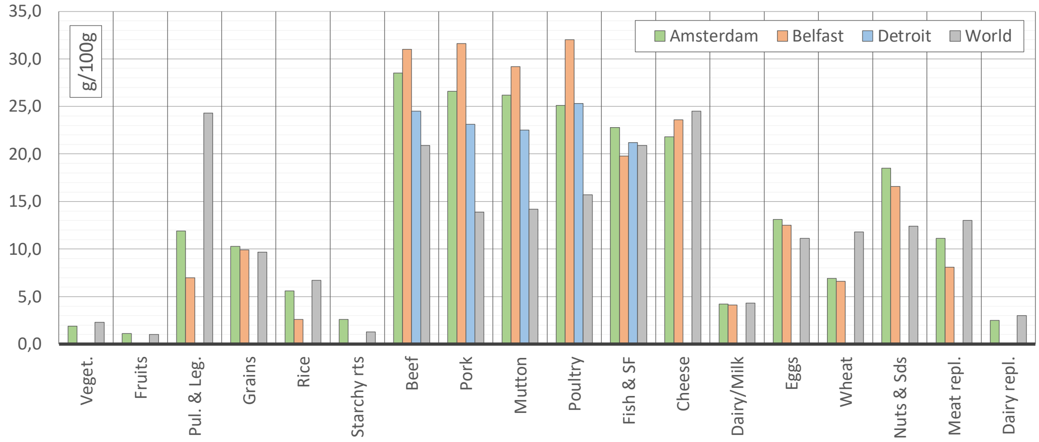


Figure A4.1. *Visualization of protein content [gramprot/100 gramfood—4 data sources.*

Appendix 4B: Protein content of food groups - data

Table A4.2 Processing of FAO dataset.

This work uses the FAO protein content of food (groups) for diet shift assessment. Listed items are considered to be consumed on a regular basis in developed economies globally. The raw data had to be recomposed to align with the taxonomy of this study and a number of product are left out of the assessment. The breakdown below forms the basis of aggregated indicators listed in Tables 3.2 and A3. Excluded items are noted by *rem.*, i.e., removed. Excluded food items/products/groups are:

- Processed items (with exception of the cheese category)
- Concentrates
- Starches/Malts/Flour/Gluten/Germs/Brans/Cakes
- Fruit/vegetable juices (=processed & drink)
- Non-staple foods categories

NES = Not Elsewhere Specified. Note: Retail product assumed for meat replacer: Tofu, uncooked (33% of water), 13 g protein/100 g product. Note: Retail product assumed for dairy replacer: Soy Drink, natural, 3.0 g/100 mL of product

Original dataset is retrieved from (FAO, 2001).

Cereal and Products	**g/100 g**	**Wheat (Pasta)**		**g/100 g**
Wheat	12,2	Macaroni		11,0
Flour of wheat	Rem.	Quinoa		12,0
Bran of wheat	Rem.	Bulgur whole meal		12,3
Germ of wheat	Rem.		Average**:**	**11,8**
Bread	8,2	**Rice**		
Pastry	7,4	Rice paddy		6
Wheat starch	Rem.	Rice husked		7,5
Wheat gluten	Rem.	Rice milled		6,7
Barley	11,0	Rice broken		6,7
Pot barley	9,6	Rice flour		Rem.
Barley pearled	9,0	Rice gluten		Rem.
Barley flour and grits	Rem.	Rice starch		Rem.
Malt of barley	Rem.	Bran of rice		Rem.
Malt extracts	Rem.		Average:	6,7
Maize	9,5	Roots, tubers and products		
Germ of maize	Rem.	**Potatoes**		**1,6**
Flour of maize	Rem.	Flour of potatoes		Rem.
Maize gluten	Rem.	Potatoes frozen		1,2
Starch of maize	Rem.	Potato starch		Rem.
Pop corn	9,5	Potato tapioca		0,5
Rye	11,0	Sweet potatoes		0,7
Flour of rye	Rem.	Cassava		0,9
Oats	13,0	Flour of cassava		Rem.
Oats rolled	16,0	Cassava tapioca		0,5
Millet	9,7	Cassava dried		2,8
Flour of millet	Rem.	Cassava starch		Rem.
Sorghum	10,1	Yautia (cocoyam)		1,7
Flour of sorghm	Rem.	Taro (cocoyam)		1,5
Buckwheat	11,0	Yams		1,3
Flour of buckwheat	Rem.	Roots, tubers nes		1,6
Fonio	8,0	Flour of roots and tubers		Rem.

Flour of fonio	Rem.
Triticale	11,6
Flour of triticale	Rem.
Canary seed	Rem.
Mixed grain	8,0
Flour of mixed grain	Rem.
Cereals nes	8,0
Wafers	9,2
Flour of cereals	10,0
Breakfast cereals	7,4
Cereals prepared nes	10,0
Mixes and doughs	6,2
Food preparations flour	7,5
Treenuts	
Brazil nuts	6,9
Cashew nuts	7,7
Chestnuts	1,8
Almonds	8,0
Walnuts	6,4
Pistachios	10,3
Kolanuts	9,0
Hazelnuts	6,0
Arecanuts	4,9
Brazilnut shelled	14,3
Cashew nuts shelled	15,3
Almonds shelled	20,0
Walnuts shelled	14,3
Hazelnuts shelled	13,0
Nuts nes	7,0
Prepared nuts	15,5
Groundnuts in shell	18,7
Groundnuts shelled	25,7
Cake of groundnuts	Rem.
Groundnuts prepared	26,8
Peanut butter	24,3
Coconuts	1,7
Coconuts desiccated	6,9
Copra	6,0
Oil palm fruit	0,3
Palm kernels	7,3
Olives	1,3
Olives,preserved	1,1
Karite nuts	6,8
Sunflower seed	12,3
Rapeseed	19,6
Safflower	9,7
Sesame seed	17,7
Cake of sesame seed	Rem.
Mustard seed	24,9
Flour of mustard seed	26,4

Roots, tubers dried	Rem.
Average:	**1,3**
Pulses	
Beans, dry	22
Broad beans dry	23
Peas, dry	23
Chick-peas	20
Cow peas dry	23
Pigeon peas	21
Lentils	24
Bambara beans	18
Vetches	32
Lupins	40
Pulses nes	22
Flour of pulses	Rem.
Average:	**24**
Meat replacers > custom product assumed	
Soybeans	n.a.
Cake of soya beans	n.a.
Soya sauce	n.a.
Soya paste	n.a.
Soya curd	n.a.
Average:	**n.a.**
Vegetables and products	
Cabbages	1,0
Artichokes	1,1
Asparagus	1,6
Lettuce	1,1
Spinach	2,1
Cassava leaves	5,8
Tomatoes	0,8
Tomato juice	Rem.
Tomato juice concentrated	Rem.
Tomato paste	3,8
Tomatoes peeled	0,9
Cauliflower	0,8
Pumpkins, squash, gourds	0,9
Cucumbers, gherinks	0,5
Eggplants	0,9
Chillies, peppers,green	1,1
Onions,shallots, green	1,7
Onions, dry	1,1
Garlic	5,5
Leeks	0,7
Beans, green	3,0
Peas, green	2,1
Broad beans,green	2,3
String beans	1,6
Carrots	0,9
Okra	1,6

Poppy seed		18,0
Melonseed		18,2
Cottonseed		17,3
Linseed		18,0
Oilseeds nes		14,7
Flour/meal of oilseeds		Rem.
	Average:	**12,4**

Fruits and products

Bananas		0,7
Plantains		0,8
Oranges		0,7
Orange juice		Rem.
Orange juice concentrated		Rem.
Tangerines, mandarines, clementines		0,5
Tangerines juice		0,5
Lemons and limes		0,6
Lemon juice		Rem.
Lemon juice concentrated		Rem.
Grapefruit and pomelo		0,3
Grapefruit juice		Rem.
Grapefruit juice concentrated		Rem.
Citrus fruit nes		0,5
Citrus fruit nes juice		Rem.
Citrus fruit nes juice concentrated		Rem.
Apples		0,1
Apples juice		Rem.
Apples juice concentrated		Rem.
Pears		0,4
Quinces		0,2
Apricots		1,3
Sour cherry		0,9
Cherries		1,1
Peaches and nectarines		0,5
Plums		0,7
Plum juice		Rem.
Plum juice concentrated		Rem.
Stone fruit nes		0,9
Pome fruit nes		0,4
Carobs		1,6
Strawberries		0,6
Raspberries		0,9
Gooseberries		0,9
Currants		1,4
Blueberries		0,7
Cranberries		0,4
Berries nes		1,00
Grapes		0,5
Grape juice		0,6
Watermelons		0,3
Melons		0,4

Green corn		2,1
Sweet corn frozen		1,8
Sweet corn prepared		2,3
Mushrooms		2,0
Mushrooms canned		1,9
Mushrooms dried		9,6
Vegetables nes fresh		1,4
Vegetables nes dried		11,2
Vegetables nes canned		1,4
Vegetables nes juice		0,6
Vegetables dehydrated		Rem.
Vegetables prepared by vinegar		Rem.
Vegetables prepared nes		Rem.
Vegetables frozen		3,3
Vegetables provisionally preserved		Rem.
Vegetables prepared or pres,frozen		Rem.
Homogenized vegetables prepared		1,2
	Average:	**2,3**

Beef

Beef boneless		18,5
Beef dried salted smoked		34,3
Meat extracts		Rem.
Beef sausages		11,7
Beef preparations		25,0
Beef canned		25,0
Homogenized meat prepared		Rem.
Liver preparations		13,6
Offals of cattle		18,4
Buffalo meat		Rem.
Offals of buffalo		Rem.
	Average:	**20,9**

Mutton

Mutton and lamb		13,5
Offals of sheep		14,6
Goat meat		14,0
Offals of goats		14,6
	Average:	**14,2**

Pork

Pigmeat		11,0
Pork		13,4
Bacon—ham of pigs		13,1
Pig meat sausages		11,7
Pig meat preparations		16,1
Offals of pigs		18,3
	Average:	**13,9**

Poultry

Chicken meat		12,3
Chicken meat canned		21,8
Offal of chickens		18,0
Fat liver preparations		11,4

Figs	0,8
Mangoes	0,4
Mango juice	Rem.
Mango pulp	0,5
Avocados	1,5
Pineapples	0,2
Pineapples canned	0,4
Pineapples juice	Rem.
Pineapples juice concentrated	Rem.
Persimmons	0,6
Cashewapple	0,8
Kiwi	0,9
Papayas	0,4
Fruit tropical nes	0,5
Fruit nes fresh	0,5
Fruit nes juice	Rem.
Fruit nes prepared	Rem.
Flour of fruit	3,9
Fruit,nuts,fruit peel preserved by sugar	Rem.
Ruit cooked homogenized	Rem.
Dried fruits	Rem.
Apricots dried	3,7
Plums dried	2,3
Raisins	3,2
Figs dried	3,0
Dates	1,5
Fruit tropical nes dried	2,8
Fruit nes dried	2,8
Average:	**1,0**
Fish and fisheries products	
Freshwater diadromous fish fresh	10,9
Freshwater diadromous fish fillet	20,3
Freshwater diadromous fish cured	31,3
Freshwater diadromous fish canned	19,8
Freshwater diadrom, fish prepared nes	26,9
Demersal fish fresh	8,3
Demersal fish fillet	17,9
Demersal fish cured	37,9
Demersal fish canned	25,0
Demersal fish prepared nes	25,0
Pelagic fish fresh	12,6
Pelagic fish fillet	20,2
Pelagic fish cured	26,4
Pelagic fish canned	20,8
Pelagic fish prepared nes	44,2
Marine fish nes fresh	10,3
Marine fish nes fillet	19,0
Marine fish nes cured	32,1
Marine fish nes canned	22,9
Marine fish prepared nes	17,5

Duck meat	8,3
Offals liver ducks	18,7
Goose meat	12,9
Offals liver geese	16,4
Turkey meat	16,1
Offals liver turkeys	20,0
Poultry meat	17,1
Average:	**16**
Other meat products > not used	
Pigeons other birds	n.a.
Horsemeat	n.a.
Offals of horses	n.a.
Meat of asses	n.a.
Meat of mules	n.a.
Meat of camels	n.a.
Offals of camels	n.a.
Rabbit meat	n.a.
Meat of other rodents	n.a.
Meat of other camelids	n.a.
Offals of other camelids	n.a.
Game meat	n.a.
Meat nes	n.a.
Meat nes dried	n.a.
Meat prepared nes	n.a.
Offals nes	n.a.
Snails not sea	n.a.
Eggs	
Hen eggs	10,7
Eggs liquid hen	12,1
Eggs dry hen	Rem.
Egg albumine	10,1
Eggs excluding hen eggs	11,3
Average:	11.1
Milk and cheese dairy/milk	
Cow milk, whole fresh	3,3
Standardized milk	3,3
Cream, fresh	2,7
Whole cow milk evaporated	6,8
Whole cow milk condensed	7,9
Whole cow milk dry	Rem.
Skim milk of cows	3,4
Skim milk evaporated	7,6
Skim milk condensed	10
Skim milk dry	Rem.
Buttermilk curdled	3
Buttermilk dry	Rem.
Yoghurt	3,5
Yoghurt concentrated	4,7
Reconstituted milk	1,8
Whey fresh	0,8

Crustaceans fresh	9,3
Crustaceans frozen	18,4
Crustaceans cured	25,4
Crustaceans canned	19,8
Crustaceans prepared nes	19,5
Molluscs fresh	2,3
Molluscs frozen	10,5
Molluscs cured	49,4
Molluscs canned	14,9
Cephalopods fresh	13,5
Cephalopods frozen	15,1
Cephalopods cured	61,6
Cephalopods canned	20,8
Cephalopods prepared nes	20,8
Aquatic mammals meat	Rem.
Aquatic mammals prepared nes	Rem.
Aquatic animals nes fresh	4,0
Aquatic animals nes cured	5,5
Aquatic animals prepared nes	11,5
Aquatic plants	Rem.
Aquatic plants dried	Rem.
Aquatic plants prepared nes	Rem.
Average:	**20,9**

Whey condensed	0,9
Whey dry	Rem.
Casein	Rem.
Buffalo milk	3,8
Skim milk of buffalo	4,3
Sheep milk	5,9
Skim milk of sheep	6,1
Goat milk	3,6
Skim milk of goat	3,4
Camel milk	3,8
Average:	**4,3**

Cheese	
Cheese goat milk	16
Cheese whole cow milk	25
Cheese skim cow milk	46
Whey cheese	12,4
Processed cheese	Rem.
Cheese buffalo milk	Rem.
Cheese sheep milk	23,2
Average:	**25**

Appendix 4C: Data sources addressed - overview

Table A4.3. Overview of data sources for Global Warming Potential (GWP) and protein content of food groups. Data sources addressed for this study are accessible to the general public. Please note: this study uses the protein content dataset by the FAO for further assessment. An extensive breakdown and references of case study food consumption can be found in (N. ten Caat et al., 2022).

	GWP *unit>kg CO_2eq/kg_{food}*	**Protein Content** *$g/100\ g_{food}$*
AMS	(RIVM, 2020b) Published by the National Institute for Public Health and the Environment. GWP based on LCI studies, conducted by Blonk Consultants. Full dataset can be downloaded from website.	(RIVM, 2019) Online interactive platform called NEVO. Developed by the RIVM, a service department from the Ministry of Health, Welfare and Sports
BEL	(Scarborough et al., 2014) Open-access article published by Springer (Appendix, Table 4 in source article)	(British Nutrition Foundation, 2012) Aggregated dataset. Overview can be downloaded from website. Data is based on the work McCance and Widdowson's—The Composition of Foods (2015) [this work is not freely accessible]
DET	(Heller et al., 2018) Open-access article Published by IOP Publishing Ltd. Data is integrated to ' dataFIELD' (database of Food Impacts on the Environment for Linking to Diets). Download and more information can be found here (Heller, 2017).	(USDA, 2018) Data provided by the US Department of Agriculture—National Agricultural Library. Dataset can be downloaded online.
World	(Poore & Nemecek, 2018) Open-access research article published in Science. LCA-based GWP data based on a worldwide study.	(FAO, 2001) Extensive list of food items + nutritional content (protein, calories & fat), provided by the UN Food & Agriculture Organisation. Dataset can be retrieved online.

Appendices Chapter 5

Towards fossil free cities – Emission assessment of food and resources consumption with the FEWprint carbon accounting platform

Appendix 5A: Supermarket Energy Balance

Energy balance Equation (A1) is used to determine the cooling demand of the supermarket.

$$Q_{int}(t) + Q_{inf}(t) + Q_{vent}(t) + Q_{trans}(t) + Q_{cool}(t) = 0 \quad \text{[A1]}$$

In a supermarket building, the internal heat gains and the thermal energy exchange with the outside environment due to ventilation and infiltration (i.e., door openings), are strongly correlating with the opening hours. Outside of opening hours, the front and back door remain closed and the infiltration rate is set to zero. Heat gained from staff and customers working and walking in the supermarket varies through the course of the day and will show the highest loads during shopping peak hours. Lights are only switched on when people are present in the building. It is assumed that bake-off activities occur periodically throughout the day. The ventilation system is assumed to be CO_2 controlled and is therefore only active during opening hours, plus one additional hour after closing. Figure A5.1 shows the time slots used for the calculation of Q_{int}, Q_{inf} and Q_{vent}. For these calculations it is assumed that the supermarket is open 365 days a year, from 8 AM to 8 PM. Any holidays or deviant opening hours on Sundays are not taken into account. Finally, Q_{Cool} (W) describes the amount of excess energy that should be removed from the sales floor to maintain a steady indoor temperature. The supermarket does not have any transparent surfaces, thus heat gain by the sun can be neglected.

The internal heat gain (Q_{int}) that is coming from staff and customers present in the supermarket, heat gain from lighting, from equipment and heat coming from the bake-off section is calculated with Equation (A2):

$$Q_{int}(t) = ((q_{eq} \times f_{eq}) + (q_{light} \times f_{light}) + (q_{bake} \times f_{bake})) \times A_{floor} + (q_{per} \times f_{per} \times n_p) \quad \text{[A2]}$$

The internal heat gain by the customers and staff present on the sales floor is noted by q_{per} (W). In this study, a heat load of 130 W/person is assumed (ASHRAE, 2001). The number of customers (n_p) during a day is roughly estimated per hour (range = 10–75 persons) and can be found in Figure A5.1. Heat emitted by the ceiling lights and operational activities is noted by q_{light} and q_{eq} respectively and for this study, a heat load of 10 W/m^2 and 15 W/m^2 are applied, which is in accordance with the value Lidl adopts for their own energy calculations (personal communication, 2017). The bake-off section of the supermarket's bakery produces a lot of heat when the ovens are turned on and a value of 6000 W (i.e. ±8.5 W/m^2) is added to the equation when the ovens are active. The periodicity of the internal fluxes is controlled by f_{per}, f_{light}, f_{eq} and f_{bake} (active = 1, inactive = 0) and follows the timetable in Figure A5.1.

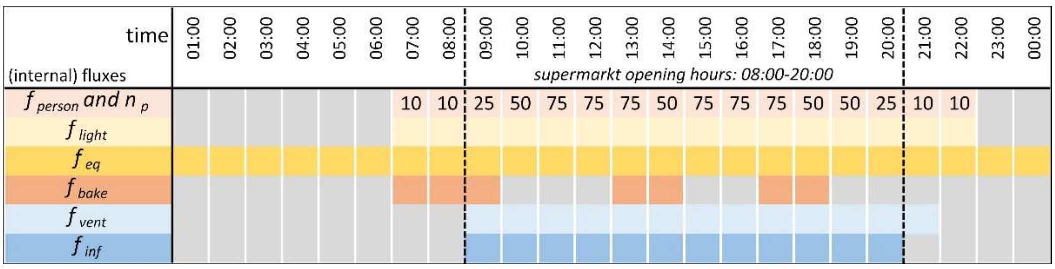


Figure A5.1. *Hourly timetable of time based thermal fluxes for the super-market building.*

Due to constant main door openings and multiple daily truck unloading at the back of the store, the heat loss by infiltration (Q_{inf}) of a supermarket building is significant; calculated with Equation (A3):

$$Q_{inf}(t) = V_{inf} \times \rho_{air} \times c_{air} \times (T_{in} - T_e(t)) \times f_{inf}(t) \quad \text{[A3]}$$

The uncontrolled air exchange (V_{inf}) between the indoor and the outdoor environment is in this study set to 0.443 m^3/s. The density of the air (ρ_{air}) is set to 1.21 kg/m^3 and the specific heat capacity (c_{air}) is set to 1005 J/kg.K. The indoor temperature (T_{in}) on the sales floor is maintained on 21 °C all year round, a temperature generally low enough to prevent undesirable condensation on the glass display covers. Additional infiltration due to cracks and holes in the facades and roof of the building are ignored. The ambient outside temperature is noted by T_e (°C).

Energy removed from the supermarket space due to mechanized air exchange with the outdoor environment for the purpose of ventilation (Q_{vent}) is determined with Equation (A4):

$$Q_{vent}(t) = V_{vent} \times \rho_{air} \times c_{air} \times (T_{in} - T_e(t)) \times f_{vent}(t) \quad \text{[A4]}$$

q_{vent} denotes ventilation rate, for which a value of 0.170 m^3/s is applied. Ventilation only occurs during specific hours, noted by f_{vent}.

Heat fluxes across the façades, roof and floor depend on the difference between the external air temperature and the indoor air temperature and is represented by Q_{trans} (W); calculated with Equation (A5):

$$Q_{trans}(t) = \sum(U_n \times A_n \times (T_{in} - T_e(t)) \quad \text{[A5]}$$

The heat transfer coefficients for the roof, walls and floor (U_n) are 0.17, 0.22 and 0.25 W/m^2K respectively. A_n represents the surface area of these facades (m^2). $T_e(t)$ is set to 15 °C when calculating the energy exchange across the floor of the supermarket.

Appendix 5B: Greenhouse Energy Balance

The energy balance of the greenhouse is contained in Equation (A6):

$$Q_{sun}(t) + Q_{inf} + Q_{int}(t) + Q_{em}(t) + Q_{trans}(t) + Q_{par}(t) + Q_{H/C}(t) = 0 \qquad \text{[A6]}$$

Equation (A6) is converted into Equation (A7) to isolate the Q_H or Q_C (see chapter 5.2.3.3.). Equation (A9) (infiltration losses) and Equation (A17) (transfer across façade) are integrated in Equation (A7):

$$+Q_H(t) = \left(q_{sun}(t) + \sum q_{int}(t) + q_{sen}(t) + q_{lat}(t) + q_{em}(t)\right) \times A_{floor} - (U_n \times A_n + q_{inf}(t)) \times (T_{in,}(t) - T_e(t)) \qquad \text{[XX]}$$

q_{sun} (W) represents the heat transfer by solar radiation and is denoted by Equation (A8). The total heat gain by solar radiation is calculated individually for each transparent façade.

$$q_{sun} = I_{sun} \times g_{glass} \times (1 - r_{PAR}) \times \frac{\sum(r_o \times A_{glass})}{A_{floor}} \qquad \text{[A7]}$$

The global horizontal solar radiation is noted by I_{sun} (W/m^2) and is retrieved from weather data (NEN5060). The material properties of the single glazing glass façade are standardized: the thermal transmittance (U-value) is set at 5.7 W/m^{2}K (Graamans et al., 2018) and the solar transmittance coefficient (g_{glass}) is set at 0.65 (Agrotechnology & Food Innovations BV, 2005). The central axis of the greenhouse has an angle of 66° relative to the North. Instead of using comprehensive trigonometric formulas, reduction coefficients (r_o) are applied to compensate for the non-optimal façade orientations in relation to the heat gain by global horizontal irradiance. Table A1. shows the r_o for all facades. Since the glass roof is slightly inclined towards the North-West, we assume a reduction coefficient of 0.9 instead of 1.0. Only wavelengths in the NIR & UV (Near Infra-Red & Ultra Violet) range are accounted for, since PAR light (Photosynthetic Active Radiation) is directly processed by the plants, which is noted by the factor r_{PAR} (0.475), which is discussed later in this section.

Even though the greenhouse is intended to be a closed system, there are structural imperfections and frequent door openings that cause exchange of air between the interior and exterior that affect the thermal balance of the greenhouse. This is calculated with Equation (A9):

$$q_{inf}(t) = (v_{wind}(t) \times i) * A_{floor} \times \rho_{air} \times c_{air} \times (T_{in}(t) - T_e(t)) \qquad \text{[A8]}$$

In standard greenhouses, air exchange v_{air} with the environment (m^3/m$^2_{GH}$/s) is assumed to increase linearly with the wind velocity v_{wind} (m/s), with a coefficient *i* of 0.00008 (Graamans et al., 2018). Energy exchange due to infiltration depends on the difference between the indoor and outdoor ambient air temperature T_e (°C).

The combined internal heat load is described by q_{int} (W/m^2) (Equation (A10)) and consists of q_{eq}, q_{per} and q_{light}.

$$q_{int}(\mathrm{t}) = W_{light} \times \frac{1}{c_{LED}} \times f_{light}(\mathrm{t}) + q_{eq} \times f_{eq}(\mathrm{t}) + n_p \times q_{per} \times f_{per}(t) \qquad \text{[A9]}$$

Heat gain coming from active mechanical equipment and operational activites is noted by a standard value of 15 W/m^2 (q_{eq}) and is applicable continuously. It is assumed that there are four people (n_p) performing heavy duty horticultural work inside the greenhouse from 7 AM till 6 PM, adding 180 W/person (q_{per}), or roughly 1 W/m^2. The thermal influx from the crop growing light system is determined by the efficiency of the installed lighting system (c_{LED}) combined with the installed power (W_{light}), in this study set at 52% and 54 W/m^2 (Graamans et al., 2017). The crop lights follow the selected photoperiod schedule; see section 5.3.4. Hourly incremental calculations allow to activate internal fluxes for set periods during the day, noted by f_{light}, f_{eq} and f_{per}, where f represents either 1 (active) or 0 (inactive).

The atmospheric long-wave irradiation, the nigh time release of accumulated thermal energy, can have an impact on the greenhouse's energy balance and is denoted by q_{em} (W/m^2). The thermal out flux is described by Stanghellini et al. (2018), who apply Equations (A11) and (A13):

$$q_{em}(t) = F_{sky} \times \varepsilon_{glass} \times \alpha_R(t) \times (T_{in}(t) - T_{sky}(t)) \quad \text{[A10]}$$

$$\alpha_R(t) = 4\sigma \times {T_{in}}^3(t) \quad \text{[A11]}$$

The released or gained thermal energy depends on the difference between the indoor temperature and the sky temperature (T_{sky}). The emissitivy (ε_{glass}) of the greenhouse facade (single pane glazing) is set at 0.97 when the night screens are up (i.e., open) and at 0.20 when the screens are down. For simplicity, the screens are assumed down from 20:00 in the evening until 06:00 next morning, for every day of the year, and there is only a fully closed or fully open setting. The sky view factor, F_{sky}, is set at 0.5, assuming an unobstructed hemispherical dome. The heat transfer coefficient of the greenhouse α_R (W/(m^2.K)) is based on the universal constant of proportion by Stefan-Bolzmann (σ = 5.67 × 10^{-8} W/m^{2}K^4). The sky temperature, T_{sky} (°C), can be calculated with Equation (A13):

$$T_{sky}(t) = \sqrt[4]{\frac{q_{sky}(t)}{\sigma}} \quad \text{[A12]}$$

Brunt (1932) found an empirical relationship for atmospheric back irradiation q_{sky} (W/m^2) as a function of the relative humidity of the air (*RH*), expressed as the water vapour pressure p (Pa) and the outside temperature T_e (K).

$$q_{sky}(t) = \sigma \times {T_e}^4(t) \times (a + b\sqrt{p(t)}) \quad \text{[A13]}$$

where $p(t) = RH(t) \times p_{max}(t)$ [A14]

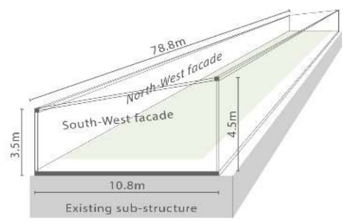
For the approximation of the saturated water vapour pressure P_{max} (Pa) we apply the updated Buck Equation (A16) (Buck, 1996). a + b are empirically found climate-specific constants and are for a sea climate, respectively 0.55 and 0.005.

$$P_{max}(t) = 0.61121 \times e^{\left(18.678 - \frac{T_e(t)}{234.5}\right) \times \left(\frac{T_e(t)}{257.14 - T_e(t)}\right)} \times 1000 \quad \text{[A15]}$$

Finally, q_{trans} (W/m^2) represents the heat transfer across the greenhouse glass surfaces and concrete floor based on the temperature differences between the interior and the exterior, see Equation (A17). Where the greenhouse is positioned above a heated residential complex, a T_e of 15 °C is applied all year round to calculate the energy exchange across the greenhouse floor. Structural properties U_n (W/m^2.K) and A_n (m^2) are noted in Table A1.

$$Q_{trans}(t) = U_{glass} \times A_{glass} \times (T_{in}(t) - T_e(t)) + U_{floor} \times A_{floor} \times (T_{in}(t) - 15) \quad \text{[A16]}$$

Table A5.1 Overview of structural properties rooftop greenhouse on the tenement building.

Facade	Material	Area (m^2)	U-Value (W/m^2.K)	Solar Transmittance	r_o	Greenhouse Main Geometry
Roof	single glazing	851	5.70	0.65	0.9	
North-East	single glazing	32	5.70	0.65	0.5	
North-West	single glazing	197	5.70	0.65	0.5	
South-East	single glazing	276	5.70	0.65	0.7	
South-West	single glazing	32	5.70	0.65	0.7	
Floor	concrete [1]	851	0.20	n.a.	n.a.	

[1] Material properties applied. Concrete: density (ρ_{con}) = 2500 kg/m^3, specific heat capacity (c_{con}): 840 J/kg.K. Effective thickness concrete slab: 0.08m. Air: density (ρ_{air}) = 1.21 kg/m^3, specific heat capacity (c_{air}): 1005 J/kg.K. Greenhouse volume = 3404 m^3.

The interior climate is greatly influenced by the crop response and vice versa. The crops reflect and absorb solar radiation and convert the absorbed energy to morphogenesis, as well as sensible and latent energy via transpiration. This process is governed by crop characteristics, crop and air temperature, air humidity, air movement and photosynthetic photon flux (Penman, 1947, 1948). There has been considerable research into predicting the (evapo)transpiration of greenhouse crops, for example in Boulard & Wang (2000), Seginer (2002) or in Stanghellini (1987). For this study, the calculations follow the method and assumptions as listed in Graamans et al. (Graamans et al., 2017). In this study the Penman-Monteith big leaf area model for crop transpiration is adapted to a predictive setting by formulating methods to determine the radiation absorption coefficient, as well as the aerodynamic and surface resistances.

Lighting can be measured in photometric units (lux), radiometric units (W/m^2) and quanta or Einstein units (µE/s^1/m^2) (Thimijan & Heins, 1983). Photometric units are commonly used within building design and thus account for the sensitivity of the human eye to different wavelengths. These units are therefore not relevant for crop applications or energy calculations and should not be used. Einstein units can be used for crop growth and radiometric units for energy.

Incident solar radiation is first split into three components: reflected radiation, radiation entering the greenhouse and radiation absorbed by the crops. Subsequently, radiation entering the greenhouse is split into three components, namely ultraviolet (UV, 300–400 nm), photosynthetic active radiation (PAR, 400–700 nm) and near infrared (NIR, 700–2500 nm). PAR is processed directly by the crop, UV and NIR influence only the interior climate (Stanghellini et al., 2018). This study assumes that the energy of solar radiation is distributed as 5.0% UV, 47.5% PAR and 47.5% NIR; therefore, the isolation coefficient r_{PAR} (0.475) is added to Equation (A18) to eliminate PAR.

In this study, only PAR is taken into account to have a physiological effect on crops. In order to calculate the crop response, it is necessary to determine the number of photons in the PAR range, and not just the energy they carry. The measuring unit of light for plant response is the photosynthetic photon flux density (PPFD) in µmol/m^{2}s, i.e., the number of photons in the PAR spectrum per square meter per second. The conversion factor from PPFD to PAR is approximately 4.5662. In this study a PPFD of 140 µmol/m^{2}s (PAR = ± 30.6 W/m^2) is considered as the optimal growing condition. The combined effective PAR radiation $\sum q_{PAR}$ on the crops can be determined with Equation (A18), considering both PAR$_{SUN}$ and PAR$_{LED}$:

$$\sum q_{PAR}(t) = \left(I_{sun}(\mathrm{t}) \times g_{glass} \times r_{PAR} \times \frac{\sum(r_o \times A_{glass})}{A_{floor}} + (W_{light}(t) \times r_{PAR})\right) \times (1 - r_{plant}) \times CAC \qquad \text{[A17]}$$

The artificial crop lighting switches on when PAR$_{SUN}$ reaches below 140 µmol/m^{2}s PPFD during the predefined photoperiod. This study sets W_{light} at 54 W/m^2, plant reflectivity r_{plant} is set at 5% and the cultivation area cover (CAC) at 90% (Graamans et al., 2017).

The energy balance Equation (A19) for a transpiring plant surface is comprised of sensible heat exchange (H, or q_{sen}) and latent heat exchange (λE, or q_{lat}) and together represent Q_{par} in Equation (A6).

$$\sum q_{par}(t) - H(t) - \lambda E(t) = 0 \qquad \text{[A18]}$$

The sensible and latent energy flux are predominantly affected by $\sum q_{PAR}(t)$, the greenhouse temperature $T_{in}(t)$ and the indoor relative humidity, which is assumed at a stable 85% throughout the year for a closed system. The proportion between E and λE is determined by a MATLAB model developed, validated and described by Graamans et al. (2017) Greenhouse cooling has a dehumidifying effect on the indoor air. However, dehumidification and its impact on the transpiration rate of the crops falls outside the scope of this study, which might lead to a higher extracted energy yield from the greenhouse than would be achievable in reality.

The net sensible thermal energy extracted from this greenhouse depends on the desirable indoor temperature range, which in its turn is based on the produced crop type, the life-stage of this crop (i.e., germination or plant raising) or desired morphogenetic activity. The morphogenetic activity is in the model codetermined by the set photoperiod or natural sunlight. Initially, the photoperiod is set to 16 h per day for maximum crop growth and the minimum greenhouse indoor air temperature is set to 9 °C during dark period ($T_{min,D}$) and 12 °C during photoperiod ($T_{min,P}$) (Graamans et al., 2018). The initial cooling set-point is set to 28 °C (T_{max}) but can be reduced accordingly to meet the energy demand from the system. When annual crop yields are paramount, as is generally the case in industrialized intensive greenhouse farming, parameters such as relative indoor humidity, temperature of the root zone, indoor CO_2 concentration are key aspects. However, they remain outside the scope of this energy-oriented study.

Appendices Chapter 6

Towards carbon free cities - Grasping the urban food production pentalemma during the design process by using the FEWprint platform

Appendix 6A: Kattenburg design workshop

Appendix 6A provides all the relevant (background) information and data used to run the workshop.

Design workshop: The design workshop was organised at the Faculty of Architecture and the Built Environment on 27/4/2022. The design team consisted of four architecture/building engineering students and two experts in the field of urban farming and urban design. Within one day, the team came up with a design proposal for the Marine Establishment and a transformation proposal for the Kattenburg neighbourhood in Amsterdam, based on the 11-stepped design approach (discussed chapter 3 and 4.1). In order to identify local challenges and get an idea of the atmosphere of the area, earlier stakeholder meetings were organised in 2019, which resulted in a *Kattenburg Vision* report (in Dutch) that formed the basis of the design spearheads. After the workshop, the author polished the produced material to make them suitable for publication.

Case study. The two urban neighbourhoods Kattenburg and the Marineterrein, respectively left and right of the main road on the map in figure A6.1, are located on an artificial river island in the city centre of Amsterdam and form the case study of this workshop. The island used to be a swamp near the river edge, until around 1650 the Admiralty warehouse building, now the Scheepvaart Museum, was built and the surrounding island was constructed for the VOC (Dutch East India Company) ship building in the 17th and early 18th century. Kattenburg was constructed simultaneously to provide housing for the workers in the adjacent Marine terrain. Throughout the centuries, the harbour continuously transformed to accommodate for the increasingly bigger ships that had to be constructed. This lasted until the early 20th century, when the ships started to outgrow the facilities of the docks and the ship building industry moved out of the area, after which the Dutch navy established a base, keeping its maritime function. The navy would settle on the island for another century, until in 2011 the decision was taken to leave Amsterdam. Within a few years, the existing naval building stock was repurposed to offices and educational functions as a temporary solution. On the Kattenburg side, the old housing of the dock workers was demolished in the seventies and the entire present Kattenburg was erected in just a couple of years. Nowadays, Kattenburg is a fully residential neighbourhood, housing ~1700 people of various backgrounds, including students. The Marine Establishment currently hosts mixed commercial-educational functions. In the coming decade, naval activities are further scaled down and the ownership is transferred to the municipality of Amsterdam, who is in charge of redeveloping the island.

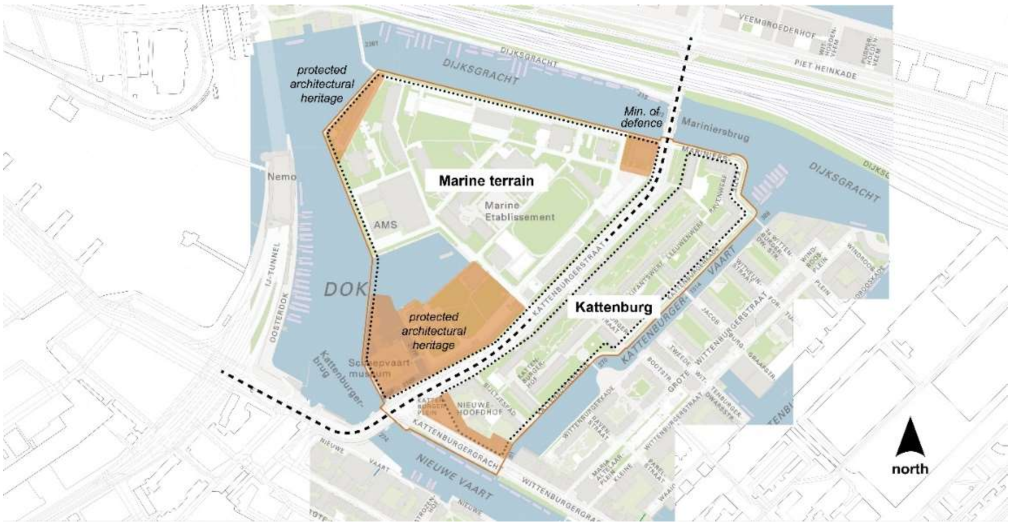


Figure A6.1*: Case study map: the former Marine Establishment (left of the main road) and the Kattenburg residential area (right). Areas marked in orange are excluded from design interventions in this workshop due to architectural heritage values, iconic visual values or they are reserved for future navy functions.*

Future of KB+MT. The design workshop assumed 2030 as the design year. At present, there is not yet a concretised plan and program set up for the future of the island. According to the most recent projections, the entire island should house an additional 1400 residents, 1800 students and provide space for 1800 workspaces. The island is currently being used as a living lab to test various urban experiments — a unique feature that continues to play a role in the future. One of the key local design challenges is to merge KB and MT into one strong neighbourhood and enhance social cohesion. This is currently challenged because of a busy traffic artery connecting Amsterdam with the ring road, closed architecture that is partly protected as architectural heritage and other socio-economic challenges like speculative investments, house splitting and an aging population. More information about the neighbourhood will be given during the workshop. An overview and brief description of the climate goals is provided in table A4.1.

Vulnerability of the liveability. During various stakeholder meetings, earlier design sessions of the island and desktop research, revealed various threats to the liveability of the neighbourhood. Continued discussions with the local stakeholders and residents, the following aspects were considered important to address during any design effort, split up in three themes:

- *Spatial quality*
- Traffic (noise nuisance, air pollution, split island)
- Spatial layout (split island, closed architecture, closed functions)
- *Sustainable future*
- Energy transition (costs, gas free Kattenburg before 2040)
- Motivation (protest against change, De Key housing association)
- *Socio-economical aspects*
- Openness (closed communities)
- Commitment (segregation, culture-based subgroups)
- Criminality (drugs, violence, burglary)
- Social cohesion (speculation investments, house splitting, childless)

Design spearheads. The results of the design workshop will not curtail the deep-rooted socio-economic challenges of the area. However, the (re)design of the urban public and private space can enhance social cohesion, for example by means of securing social control through the introduction of shared ownership and responsibility of elements in the public domain. Various design spearheads have been formulated and validated by the local stakeholders. During the design workshop, these themes were presented as guides for further exploration, discussion and translation into a ‘quick & messy’ urban design proposal, in which out-of-the-box and rather drastic interventions were encouraged.

The following design themes have been listed after the first stakeholder session:

- Unification of the Marine Terrain and Kattenburg (umbrella aim)
- Kattenburg island car-free
  The MT is a car free zone and will remain so in the future. Alternatives have to be provided for last-mile solutions for the commerce in the area. Includes finding a sustainable alternative for the main road
- Climate-adaptive Kattenburg
  Resistance against climate change, urban heat island effect, sea-level rise, extreme precipitation events or long droughts.
- self-sufficient Kattenburg.
  High-tech and low-tech solutions of food production, establishing energetic synergies with the existing environment, low-temperature and high-temperature heating
- carbon neutral Kattenburg
  By means of urban food production
- Circular Kattenburg (food, nutrients)
- Collective initiatives (bottom-up resident initiatives in Kattenburg)

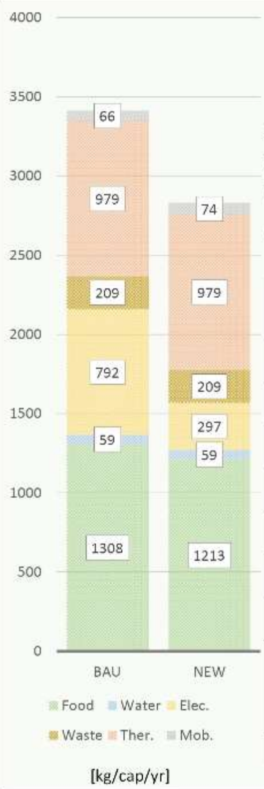
Assessment of the present and the future scenario. Table A6.2 below shows the two changes taken into account when assessing the present and future scenario. We decided to exclude any changes in consumption or carbon intensity of goods, services or resources to maintain comparability between the scenarios and make sure that any changes in the carbon balance can only be attributed to the implemented UFP system. Apart from the demographic changes, the only exception to this, is the carbon footprint of grid mix electricity as this plays a considerable role in the carbon assessment of farming systems and is expected to drop significantly in the period leading up to 2030.

Table A6.1.

BAU and NEW scenario

Country / city / neighbourhood: The Netherlands, Amsterdam, Kattenburg and the Marine Establishment		
Carbon footprint assessment / nature of energy: Grid mix - Standard national (secondary research data) / fossil		
Item	**2020**	**2030**
Carbon footprint grid mix electricity	0,460 kg/kWh$_e$	0,180 kg/kWh$_e$. In 2017, the PBL projected in the National Energy Monitor of the Netherlands that the carbon emission intensity of grid mix electricity is projected to reduce to ±180 gram per kWh, based on the expected short- and long term changes to the energy provision in NL. (ECN, 2017)
Population / households / household size	1721 / 987 / 1,74	3121 (+1400)

Figure A6.2 below shows the FEWprint of the KBMT island in 2020 and 2030, before the addition of an urban food system but with the demographic and electricity carbon footprint included. In other words, the figure below shows the business-as-usual situation in 2030, showing a considerable increase in total emissions due to the projected population increase, but a lower per capita footprint.



FEWprint

Food, Energy & Water carbon footprint

The Netherlands ,	Amsterdam	Population, BAU:
Kattenburg + MT		1800
UFP assessment approach	*Community Assessment*	Population, NEW:
Future scenario used:	**2030**	3200

BAU		Sectoral carbon emissions community [ton/year]:		**NEW**
2354	<	**Food**	>	**3880**
1426	<	**Energy , Electrical**	>	**950**
1762	<	**Energy, Thermal**	>	**3133**
118	<	**Mobility**	>	**236**
105	<	**Water**	>	**187**
376	<	**Waste**	>	**668**
		UFP system (not added to total)		
6141		Total carbon emissions		**9055**
-				+2914 47%
3412		Per capita emissions [kg/yr]		2830

***Figure A6.2**. FEWprint of KBMT.*

Consumption data. Table A6.2 gives an overview of the 2020 average per capita consumption data in Kattenburg, Amsterdam. All data and information are retrieved from publicly accessible data sources. All data is entered in the FEWprint platform in order to establish a baseline carbon profile.

Table A6.2. Overview of the resource demand/use for Kattenburg and other relevant data to complete a carbon assessment with the FEWprint platform.

Sector	Component	Product/Activity/Note (source)	demand	Unit
Food	Subdivided into 18 categories	Vegetables: 131,0; Fruits: 107,0; Pulses & Legumes: 5,0; Grains: 146,9; Rice: no data; Starchy Roots: 72,0; Beef: 12,2 (+13,4); Pork: 13,0 (+13,4); Mutton: no data; Poultry: 16,4 (+13,4); Fish & Sea Food: 16; Cheese: 32,6; Dairy/Milk: 310,6; Eggs: 13,0; Wheat (pasta): 47,1; Nuts & Seeds: 5,7; Meat replacers: 1,5; Dairy replacers: 8,4. Total: 922,4 g/cap/day. Data obtained from the National Institute for Public Health and the Environment in the Netherlands (RIVM, 2020a). Data reports on average consumption in the Netherlands, age 1-79, expressed in daily per capita food intake (gram). Heavy-processed food products are excluded from the assessment**. * Dataset reports the categories *meat products* (21,1g) and *processed meat for warm dish* (26g). These food items are equally spread over beef, pork and poultry, i.e. +13,4g. ** excluded categories are *Oils & Fats, Sugar & Candy, (non-dairy) non-alcoholic drinks, Alcoholic drinks, Sauces & Seasonings, Stock, Savoury snacks*.	~337	kg/cap/yr
Energy	Electrical	grid mix electricity (Liander, 2021)	1650	kWh_e/cap/yr
	Thermal	natural gas, centrally provided (Liander, 2021)	849	m^3/cap/yr
	Mobility	Car ownership (source)	361	#/1000hh
		Distance driven per year (2016 data): 11.700 km/car/yr (CBS, 2017). Based on the car ownership data, there were 356 cars registered in Kattenburg in 2020. By combining the data we get an approximation of ~2420 personal kilometers per year.	2422	km/cap/yr
		petrol (80%), assumed efficiency: 1:15[1]	44,0	L/cap/yr
		diesel (15%), assumed efficiency: 1:18[1]	6.9	L/cap/yr
		electric (5%), assumed efficiency: 1:15[1]	2.8	kWh/cap/yr
Water	Domestic use	centralised production (107L/cap/day, water source: external surface water) (Waternet, 2016)	40	m^3/cap/yr
	Wastewater prod.	centralised treatment (107L/cap/day, water treatment: external, conventional sewage treatment.)	40	m^3/cap/yr
	Rainwater management	Annual rainfall specific to region (2019 precipitation)	±871	mm/m2/yr
		Surface area: permeable / non-permeable	8.0/3.0	ha
		Pre-treatment of rainwater before disposal?	No	-
Waste	Processing	total domestic waste produced (2019 data) (CBS, 2018)	377	kg/cap/yr
		Waste-to-Recycle (this value is based on a separation fraction provided by the municipality) (CBS, 2018)	17,5	%
		Non-recyclable waste processing: Waste-to-energy / Waste-to-Landfill / Waste-to-Compost. All non-recycled waste is sent to the central waste incineration plants (cogeneration power station).	100/0/ 0	%

Carbon footprint data. Table A6.3 provides an overview of the applied carbon footprint indicators. The indicators describe the carbon footprint of resource provision and infrastructure at the Dutch national level.

Table A6.3. Overview of the carbon footprint (CF) indicators for Kattenburg

Sector	Component	Product/Activity/Note (source)	CF	Unit	(source) / Note
Food	Subdivided into 18 categories	Vegetables	1,820	kg_{CO2}/kg_{food}	(N. ten Caat et al., 2022), based on LCI assessment by (RIVM, 2020b)
		Fruits	1,530	kg_{CO2}/kg_{food}	
		Pulses & Legumes	2,530	kg_{CO2}/kg_{food}	
		Cereals & Grains	1,320	kg_{CO2}/kg_{food}	
		Rice	1,710	kg_{CO2}/kg_{food}	
		Starchy Roots	0,920	kg_{CO2}/kg_{food}	
		Beef	30,82	kg_{CO2}/kg_{food}	
		Pork	13.73	kg_{CO2}/kg_{food}	
		Mutton	n.d.	kg_{CO2}/kg_{food}	
		Chicken	16,60	kg_{CO2}/kg_{food}	
		Fish & Seafood	8,610	kg_{CO2}/kg_{food}	
		Cheese	32,60	kg_{CO2}/kg_{food}	
		Dairy (except cheese)	2,310	kg_{CO2}/kg_{food}	
		Eggs	4,320	kg_{CO2}/kg_{food}	
		Wheat (pasta)	1,520	kg_{CO2}/kg_{food}	
		Nuts & Seeds	4,160	kg_{CO2}/kg_{food}	
		Meat replacers	n.d.	kg_{CO2}/kg_{food}	
		Dairy replacers	0,760	kg_{CO2}/kg_{food}	
Energy	Electrical	grid mix electricity	0,480	kg_{CO2}/kWh_f	(CE Delft, 2020)
	Thermal	natural gas, centrally provided (Liander, 2021)	1,780	kg_{CO2}/m^3	(RVO, 2020)
Mobility	Personal mobility, car fuel	petrol (80% of fleet), assumed efficiency: 1:15	2,784	kg_{CO2}/L	(Milieucentraal, 2020)
		diesel (15% of fleet), assumed efficiency: 1:18	3,262	kg_{CO2}/L	(Milieucentraal, 2020)
		electric (5% of fleet), assumed efficiency: 1:15	0,480	kg_{CO2}/L	As *energy-electrical*
Water	Potable water production	centralised. Water source: external surface water	0,360	kg_{CO2}/m^3	(STOWA, 2008)
	Water treatment	centralised. Treatment: external, conventional sewage treatment	1,140	kg_{CO2}/m^3	(STOWA, 2008)
Waste	Processing of domestically produced waste	Incineration. Footprint indicator based on the data by the Dutch Emissions Authority. Short-cycle carbon, i.e. the carbon stored in biomass, is eliminated from the equation with a biomass fraction. Fraction = 0,634, based on 0,965 (footprint household waste) x 0,657 (bio fraction)	0,634	kg_{CO2}/kg	(NEa, 2021)
		Landfilling.	0,000	kg_{CO2}/kg	No landfilling applies
		Composting	0,000	kg_{CO2}/kg	Short cycle carbon emissions
		Recycled fraction	0,000	kg_{CO2}/kg	No emissions apply.

The following climate goals are applicable to the case study and serve merely as background information for the workshop. This table is not complete.

Table A6.4. National/Local climate goals applicable to the case study

Scale	Target/ambition	Party	Year	Source
(trans) National	-49% CO_2 emissions (relative to 1990 levels)	Dutch government in accordance with the Paris 2015 agreement, converted into the Dutch Klimaat Akkoord	2030	(UNFCCC, 2015a)
	-95% CO_2 emissions (relative to 1990 levels)		2050	
Municipal	80% of domestic electricity demand comes from wind and solar power.	Amsterdam municipality	2030	(Gemeente Amsterdam, 2019b)
	-55% CO_2 emissions (relative to 1990 levels)		2030	
			2050	
	Reduce the use of virgin materials with 50%		2030	
	Half of all suitable rooftop surface used for PV		2030	
	Full disconnection for the national gas supply		2040	
	-95% CO_2 emissions (relative to 1990 levels)		2050	
	All suitable rooftops used for PV panels		2050	
	Promote short/local food chains		-	
	Healthy food for Amsterdam residents		-	
	Climate neutral (not further specified)		2050	
	Recycle organic waste flows for high value applications		-	
	Amsterdam is climate adaptive		2050	
Local (resident initiative)	Expand existing PV array, from 357 panels (2019) to the maximum of 800 panels on 3 outof 8 rooftops.	Neighbourhood	<2030	Project called 'Zon op Kattenburg' (Dutch).

Appendix 6B: FEWprint default scaffolding data

The FEWprint is fitted with a library of default *scaffolding* data required to perform various calculations surrounding food production.

The food groups and products listed in table A6.5 are provided in the FEWprint as default items. The diet of a community — as well as the subsequent carbon impact assessment — is based on a composition of the items in the food group column. Food groups are disaggregated into sub-groups or individual products to offer more design freedom when composing a food production system. Table A6.6 gives an overview of the default scaffolding data of the *plant-based* products. Table A6.7 gives an overview of the default scaffolding data of the *animal-based* products.

Table A6.5. Overview of default food group and food products provided on the FEWprint platform. Carbon footprints are based on the study by Poore & Nemecek (Poore & Nemecek, 2018). Checkmarks note the availability of scaffolding data for that product.

•	Food group	CO_2 eq	Food products/sub-groups	OF	GH	PFAL
1	Vegetables	0.40	Leafy Greens	✓	✓	✓
			Tomatoes	✓	✓	✓
			Bell Peppers	✓	✓	✓
			Cucumbers	✓	✓	✓
			Carrots	✓	✓	
			Zucchini	✓	✓	✓
			Broccoli	✓	✓	
			Onion	✓		
			Spinach	✓	✓	
			Cabbage	✓	✓	
			Cauliflower	✓	✓	
2	Fruits	0.40	Apples	✓		
			Pears	✓		
			Grapes	✓	✓	
			Strawberries	✓	✓	✓
			Oranges	✓		
			Berries	✓		
			Melon	✓		
3	Pulses & Legumes	0.90	Lentils	✓		
			Peas (green)	✓		
			Green beans	✓		
			Brown (dry) beans	✓		
			Lupines	✓		
4	Grains	1.40	Wheat, Oats	✓		
5	Rice	4.00	Rice, Basmati Rice	✓		
6	Starchy Roots	0.60	Potatoes, Sweet potato	✓		
7	Beef	60.00	Cows (meat herd), Cows (dairy herd)	✓		
8	Pork	7.00	Free-range pork, Barn pork	✓		
9	Mutton	24.00	Sheep, Goat, Lamb	✓		
10	Poultry	6.00	Free-range chicken, Barn chicken, Turkey	✓		
11	Fish / Sea food	3.00	Shrimp (small), shrimp (large), Tilapia, Carp	✓		
12	Cheese	*21.00*	*Not considered for urban food production*	-		
13	Dairy / Milk	3.00	Cow milk, goat milk	✓		
14	Eggs	4.50	Free range chicken, barn chicken, battery chicken	✓		
15	Wheat (Pasta)	0.40	Durum Wheat, Other Wheat	✓		
16	Nuts & Seeds	0.30	Ground nuts, Walnuts	✓		
17	Meat replacers	2.00	Soybeans, Seitan (wheat based)	✓		
18	Dairy replacers	0.90	Soybeans, Almond (milk)	✓		

[spacer]

Table A6.6. Food product default options in the food groups vegetables, fruits and pulses & legumes are more extensive and can be selected from a dropdown list. Notes on data: data is either Dutch or EU. Range is considerable. Yield implies fresh weight.

		Food products		Open field Farming				Greenhouse farming					PFAL plant factories					
		Food groups (n)	Food products (n)	Agri. Yield	Emb. Elec.	Emb. Ther.	Irrig. water	Agri. Yield	Emb. Elec.	Emb. Ther.	Irrig. water	Resid. biom.	Layers[8]	Agri. Yield[9]	Emb. Elec.[9]	Emb. Ther.[9]	Water use[9]	Resid. biom.
•				*kg/yr*	*kWh/yr*	*MJ/yr*	*L/yr*	*kg/yr*	*kWh/yr*	*MJ/yr*	*L/yr*	kg/kg	*n°*	*kg/yr*	*kWh/yr*	*MJ/yr*	*L*	*kg/kg*
1	1	Vegetables	Leafy Greens	-	-	-	486[3]	2,92[4]	72[5]	282[6]	±850[7]	0,30	8	24,00	3040	0	71,0	0,30
	2		Tomatoes	-	-	-	782[3]	50,84[4]	72	1148[6]	850	0,30	2	100,00	760	0	100,0	0,30
	3		Bell Peppers	-	-	-	743[3]	28,00[4]	72	1154[6]	850	0,20	2	50,00	760	0	50,0	0,20
	4		Cucum. (& Gherk.)	5,62[2]	-	-	478[3]	69,00[4]	72	1132[6]	850	0,20	2	130,00	760	0	130,0	0,20
	5		Carrots (& turnips)	4,41[2]	-	-	563[3]	-	-	-	-	-	4	40,00	1520	0	40,0	0,20
	6		Zucchini	*As 1.4*	-	-	*As 1.4*	8,04[1]	72	951[6]	650	0,40	-	-	-	-	-	-
	7		Broccoli	1,74[2]	-	-	585[3]	2,15[1]	72	880[5]	650	0,30	4	9,00	1520	0	9,0	0,30
	8		Onion (yellow)	3,51[2]	-	-	810[3]	6,00[1]	72	880[5]	650	0,10	-	-	-	-	-	-
	9		Spinach	1,62[2]	-	-	360[3]	14,00[1]	72	880[5]	650	0,10	4	60,00	1520	0	60,0	0,10
	10		Cabbage (& other)	3,17[2]	-	-	585[3]	5,00[1]	72	880[5]	650	0,20	4	20,00	1520	0	20,0	0,20
	11		Cauliflower	*As 1.7*	-	-	585[3]	5,00[1]	72	880[5]	650	0,50	-	-	-	-	-	-
2	1	Fruits	Appels	1,92[2]	-	-	630[3]	-	-	-	-	-	-	-	-	-	-	-
	2		Pears	2,10[2]	-	-	630[3]	-	-	-	-	-	-	-	-	-	-	-
	3		Grapes	0,73[2]	-	-	378[3]	4,00[1]	72	880[5]	±850	0,10	-	-	-	-	-	-
	4		Strawberries	1,22[2]	-	-	*As 3.3*	10,37[4]	72	631[6]	±850	0,10	4	40,00	1520	0	40,0	0,10
	5		Oranges	2,20[2]	-	-	1080[3]	-	-	-	-	-	-	-	-	-	-	-
	6		Berries	0,56[2]	-	-	*As 3.3*	-	-	-	-	-	-	-	-	-	-	-
	7		Melons (& other)	2,53[2]	-	-	630[3]	12,00[1]	72	880[5]	±850	0,10	-	-	-	-	-	-
3	1	Legumes & pulses	Lentils (Linze)	0,10[2]	-	-	792[3]	1,00[1]	72	880[5]	±850	0,10	4	4,00	1520	0	4,0	0,10
	2		Peas, green.	0,54[2]	-	-	470[3]	3,00[1]	72	880[5]	650	0,10	3	9,00	1140	0	9,0	0,10
	3		Green Beans	1,03[2]	-	-	411[3]	5,00[1]	72	880[5]	850	0,10	4	20,00	1520	0	20,0	0,10
	4		Brown (dry) beans	0,29[2]	-	-	510[3]	5,00[1]	72	880[5]	±850	0,10	4	20,00	1520	0	20,0	0,10
	5		Lupines	0,17[2]	-	-	*As 3.1*	1,00[1]	72	880[5]	±850	0,10	4	4,00	1520	0	4,0	0,10

[1)] Estimation.

[2)] European Union average 2017 data, retrieved from FAO database (FAO, 2020b).

[3)] Own calculations, based on figures and recommendation from FAO manual on irrigation water management (FAO, 1986, table 2&3).

[4)] Based on data retrieved from EuroStat database: Yield [x1000 ton] / Area [x1000 ha] (agriculture > crops > crop production> crop production […] humidity), 2017 data for the Netherlands - vegetables *under glass or high accessible cover.* Top down data (EuroStat, 2018).

[5)] Average values for the entire Dutch horticultural sector, based on national total energy demand and acreage. Electricity = 0.26 GJ_e/m^2, or ±72 kWh_e/m^2. Thermal energy = 0.88 GJ_T/m^2 (Van der Velden & Smit, 2019, fig. 2.6, p.26).

[6)] Present day values for conventional greenhouse farming in the Netherlands, based on average set point temperature (Stanghellini et al., 2016, p.14-table 2).

[7)] Determining the water demand of crops and greenhouses is complex. Models are available, but application would go beyond the required accuracy of this study. Provided reference values Dutch context and describe water uptake by plants, not farm process water. Source does not mention all crops used this study - here the normal class is applied (±850) (WUR, 2012, p.32-table 17).

[8)] Estimation of maximum number of production layers per floor height.

[9)] Estimations on yield and embodied resources are based on total number of production layers and various assumptions, see section F2 for more information.

Table A6.6. Productivity and embodied resource data for plant-based food products, specified per production method: open field farming, greenhouse horticulture or plant factories (i.e. stacked farming). Food products tabulated here are offered as a default options in the FEWprint platform. Data represents either general reference data or is specific to one farming context. The user can always amend the default data if necessary or add context specific data.

Food products				**Open field Farming [m²]**					**Greenhouse Horticulture [m²]**	**Plant factories (stacked farming) [m²]**
•		Food groups (n)	Food products (n)	**Agri. Yield**	**Emb. Electricity**	**Emb. Thermal**	**Emb. Water**	**Residual biomass**		
				kg/yr	*kWh/yr*	*MJ/yr*	*L/yr*	kg/kg		
4	1	Grains	Wheat	0,59[2]	-	-	668[6]	-	Staple foods (group 4-6 and 16-18) are not considered for greenhouse horticultural farming or plant factories (PFAL).	
	2		Oats	0,31[2]	-	-	*As 4.1*	-		
5	1	Rice	White Rice	0,43[3]	-	-	792[6]	-		
	2		Basmati	0,30[1,4]	-	-	792[6]	-		
6	1	Starchy roots	Potatoes	3,55[2]	-	-	619[6]	-		
	2		Sweet potato	2,69[2]	-	-	*As 6.1*	-		
15	1	Pasta (Durum)	Durum Wheat	0,23[5]	-	-	*As 4.1*	-		
	2		Other	0,20[1]	-	-	*As 4.1*	-		
16	1	Nuts & Seeds	Ground nuts (+ shell)	0,28[2]	-	-	729[6]	-		
	2		Walnuts (+ shell)	0,24[2]	-	-	*As 16.1*	-		
17	1	Meat replacers	Soybeans (soy cake)	0,62[7]	-	-	708[6]	-		
	2		Seitan (wheat based)	1,18[7]	-	-	*As 4.1*	-		
18	1	Dairy replacers	Soybeans (Soy milk)	3,50[7]	-	-	708[6]	-		
	2		Almond (+ shell) (milk)	1,00[7]	-	-	*As 16.1*	-		

[1] Estimation.

[2] European Union average, 2017 data (countries that do not produce on a considerable scale do not provide data and are not included in data set (FAO, 2020b).

[3] South-East Asia 2017 data used (Rice, paddy) (FAO, 2020b).

[4] Online research reveals average Basmati rice yields ranging from ±2.25-4.25 ton/ha, depending on the species. Nowadays, also yields of ±6 ton/ha are reported. This study assumes a centred 3,00 ton/ha.

[5] Based on average of 5 durum wheat types grown by conventional means in the Mediterranean (Fagnano et al., 2012).

[6] Own calculations, based on figures and recommendation from FAO manual on irrigation water management. Rice irrigation based on humid climate and >25°C mean temperature (FAO, 1986, table 2&3).

[7] Meat - and dairy replacements are processed food groups. In this study, we include soy cake, seiten cake, soy milk and almond milk as default food products. These four products consist mainly of water, soy/wheat/almond and negligible supplementary ingredients, for example thickeners, conservers or spices. Therefore, the agricultural productivity data has been converted into final product yield. The following conversions apply:

(1) Soy cake. Soybeans agricultural yield: 0.28 kg/m^2. Assumed soy content in soy cake: 45% (range ± 36-50%), or 450 grams per kg of final product. Conversion gives a final product yield of 0,62 kg soy cake per m^2.

(2) Seitan cake (wheat based). Wheat agricultural yield: 0.59 kg/m2. Assumed soy content in seitan cake: 50%, or 500 grams per kg of final product. Conversion of data gives a final product yield of 1,18 kg seitan cake per m^2.

(3) Soymilk Soy beans agricultural yield: 0.28 kg/m^2. Assumed soy content in soy milk 8% (range 6-8%), or 80 grams per kg of final product. Conversion of data gives a final product yield of 3,50 L Soy milk per m^2.

(4) Almond milk Almond nuts agricultural yield: 0.05 kg/m^2. Assumed almond content in almond milk 5%, or 5 grams per kg of final product. Conversion of data gives a final product yield of 1,0 L Almond milk per m^2.

Table A6.7. Farming data, productivity and embodied resource data for animal sourced food products. Vales expressed per animal. Food products tabulated here are offered as a default options in the FEWprint platform.

Food group + products				**Space demand**		**Embodied resources**			**Animal specs. & productivity**			
•		**Food groups (n)**	**Food products (n)**	**Farm**	**Field**	**Elec.**	**Therm.**	**Water**	**Carc. weight**	**manure prod.**	**FLC**	**Productivity**
				m²	*m²*	*kWh/yr*	*MJ/yr*	*L/yr*	*kg*	*kg/yr*	*days*	*kg/day*
7	1	Beef	Cows, meat herd (organic farming)	8,50[2]	1700[3]	100[1,4]	500[1,4]	5510[10]	345,8[12]	5000[16]	730[1]	n.a.
	2		Cows, dairy herd (organic farming)	8,50[2]	1700[3]	100[1,4]	*As 7.1*	*As 7.1*	307,8[13]	5000[16]	*As 7.1*	n.a.
	3		Cows, meat herd (<u>common</u> farming)	4,00[1]	n.a.	150[1,4]	*As 7.1*	*As 7.1*	*As 7.1*	7300[16]	*As 7.1*	n.a.
8	1	Pork	Pigs (organic farming)	1,30[2]	1,00[2]	24,5[5]	29,9[5]	1600[10]	62,0[11]	1000[16]	180[5]	n.a.
	2		Barn Pigs (<u>common</u> farming)	0,90[2]	n.a.	*As 8.1*	*As 8.1*	*As 8.1*	*As 8.1*	*As 8.1*	161[5]	n.a.
9	1	Mutton	Sheep (Ewes & Rams)	1,50[2]	600[1]	25,0[1]	20,0[1]	1230[10]	27,0[14]	2540[16]	420[1]	n.a.
	2		Goat	1,50[2]	400[1]	20,0[1]	30,0[1]	1910[10]	12,0[1]	1300[16]	270[1]	n.a.
	3		Lamb	0,85[2]	200[1]	30,0[1]	50,0[1]	1000[1]	19,7[15]	650[16]	180[1]	n.a.
10	1	Poultry	Free-range chicken (organic farming)	0,10[2]	2,0[2]	1,81[6]	7,8[6]	120[10]	2,0[1]	10[16]	81[2]	n.a.
	2		Barn chicken (<u>common</u> farming)	0,06[2]	n.a.	2,64[6]	11,2[6]	*As 10.1*	*As 10.1*	17,5[16]	± 56[2]	n.a.
	3		Turkey (organic farming)	0,40[2]	10,0[2]	3,00[1]	15,00[1]	170[10]	5,0[1]	45[16]	140[2]	n.a.
13	1	Dairy & Milk	Dairy, Cow (organic farming)	6,00[2]	1700[3]	365[7]	25.550[9]	22290[10]	n.a.	16.000[16]	n.a.	25,00[17]
	2		Dairy, Goat (organic farming)	1,50[2]	400[1]	100[1]	10.000[1]	1910[10]	n.a.	1300[16]	n.a.	2,700[17]
	3		Dairy, Cow (<u>common</u> farming)	6,00[2]	n.a.	*As 13.1*	*As 13.1*	*As 13.1*	n.a.	25.000[16]	n.a.	*As 13.1*
14	1	Eggs	Free-range chicken (organic farming)	0,15[2]	2,0[2]	3,00[8]	*As 10.1*	90[10]	n.a.	9,0[16]	n.a.	0,053[18]
	2		Barn Chicken (<u>common</u> farming)	0,11[2]	n.a.	4,00[1]	*As 10.1*	*As 14.1*	n.a.	17,5[16]	n.a.	*As 14.1*
	3		Battery Chicken (intensive bio-industry)	0,10[2]	n.a.	4,75[8]	*As 10.1*	*As 14.1*	n.a.	*As 14.2*	n.a.	*As 14.1*

[1)] Estimation.

[2)] Based on Dutch organic farming standards (Better Life certificate - 3 stars), controlled by SKAL (SKAL, 2021).

[3)] Organic farming norms requires at least 120 days/year and 6 hrs/day of outdoor grazing for dairy cows and recommends no more than 6 dairy cows per ha of grass land, this gives 1700m2/dairy cow. Same values for meat cows are applied.

[4)] Estimated values. Notes: organic farming assumed less than common farming because more time spent outdoors. Energy demand values considerably lower than dairy cattle due to absence of energy demanding milking systems and machine cleaning.

[5] Source specifies per 100 kg life weight, default values are converted to 125 kg life weight, i.e. assume slaughter weight pigs (Dalgaard, Halberg, & Hermansen, 2007, p.14 - table 2).

[6] Electricity demand poultry. Source provides on farm average energy input of various aggregated LCA studies: 0.73 MJe/kg FU and 0.86 MJt/kg FU (Skunca, Tomasevic, Nastasijevic, Tomovic, & Djekic, 2018, p.18-table 2). Electricity demand is converted into kWh/animal by accounting for carcass weight and multiple production cycles per year: (0.73 / 3.6 * Carcass weight * (365/FLC)) = 1.81 kWh/ animal/year. Same conversion applies for thermal energy demand. Barn chicken requite more energy due to increased production cycles.

[7] Based on literature review of global data. Source specifies mean value conventional grazing dairy farming (conv-g): 39.89 Wh/kg milk (Shine, Upton, Safeedpari, & D. Murphy, 2020, p.6-table 4). Expressed per animal gives 0.040 * 25 L/day * 365 = 365 kWh/animal/year (assuming average milk production of 25 L/cow/day).

[8] Source provides reference value ranges for 1) (enriched) cage rearing system: 43-50 kWh/m2; and 2) free range rearing system: 15-25 kWh/m2 (Costantino, Fabrizio, Biglia, Cornale, & Battaglini, 2016, p.191-table 9). Converting the average value of these ranges into kWh/animal gives respectively 3,00 and 4,75 kWh/chicken. No energy for space mentioned in sources, hence thermal energy assumed as 10.1. Note: total energy demand depends on chicken density.

[9] Source provides mean value from literature review: 2.8 MJ/kg ECM (energy corrected milk) for conventional grazing dairy farm (Shine et al., 2020, p.3-table 1). Converting to energy demand per animal gives 2.8 x 25 * 265 = 25.550 MJe/cow/yr.

[10] Water use livestock. Based on data for Belgian context, 2005 situation. Pig water demand is based on adult animal (20-110 kg). Lamb not mentioned separately.(D'hooghe, Wustenberghs, & Lauwers, 2007).

[11] Average edible meat yield (52%) from pig carcass. Based on 119 kg life weight, this gives 62 kg/animal. Data provided by CSR report VION food group (Vion, 2017, p.19).

[12] Carcass weight prima cattle (prime cattle include calves, steers, heifers and young bulls) - 2020 United Kingdom data (Shahbandeh, 2021c). [13] Carcass weight slaughter cows (dairy cows), 2020 United Kingdom data (Shahbandeh, 2021b).

[14] Carcass weight ewes and rams - 2020 United Kingdom data (Shahbandeh, 2021a).

[15] Carcass weight sheep (lamb) - 2020 United Kingdom data (Shahbandeh, 2021d).

[16] Data from Dutch national statistics bureau (CBS, 2016, p.8). Notes: this study assumes solid manure is recovered from the field for sheep, lamb, goat and pigs (not for poultry & cows). Lamb is assumed 50% of adult ewe. Free range poultry assumed 50% of barn poultry. Beef herd common farming is average of <1year old male cattle (4500 kg/yr) + >1-2-year old male cattle (10.000 kg/yr), gives 7300 kg/animal/yr. Organic meat cows is assumed 5000 kg/yr due to field losses.

[17] Dairy yield cow/goat. Value depends on factors like animal breed, feed intake, age/health of animal or farming method. Yields from literature show therefore a large range. Specified yield are common average figures from professional farms in the Netherlands.

[18] Assume 300 eggs/animal/year and average egg weight = 65 grams, gives 53 gram/animal/day.

Appendix 6C: Animal feed data

The table below gives an overview of the common animal feed crops used in the livestock sector and present default consumption data use in the platform. Keep in mind that there is no broadly applicable average standard and animal feed management is unique between nations, regions and even farms.

Table A6.8. Overview of animal feed staple crops and the (approximation of) animal diets. Often, the livestock diet contains residue from the food industry, which should be considered as an imported product across food system boundaries. Imported feed should be replaced by local alternatives. However, smaller fractions of supplementary/complement food items can remain for some animals. Further explanation of animal feed intake data can be found below the table.

Animal feed				**Animal diet [gram/animal/day]**							
•	Products	Yield *[ton/ha/yr]*	***Irrigation [L/ha/yr]***	**Meat cows[4]**	**Dairy cows[4]**	**Pigs[5]**	**Poultry (broiler)[6]**	**Poultry (eggs)[6]**	**Sheep[7,1]**	**Goat[8]**	**Lamb[7,1]**
1	Grass (fresh weight)	6,50[1]	6680[3]		29.850	0	0		200	300	100
2	Hay (dry matter)	3,50[1]	6680[3]		0	0	0		0	600	0
3	Soybean (meal)	2,78[2]	7079[3]		950	0	20		200	200	0
4	Maize (+corn)	7,89[2]	7574[3]		15.200	0	40		450	200	300
5	Sugar Beets (pulp)	81,55[2]	9653[3]		450	0	0		75	200	50
6	Oats (grain/meal)	3,11[2]	6500[1]		0	0			75	400	50
7	Wheat (grain/meal)	5,86[2]	6683[3]	*As dairy cows*	450	340	0	*As broiler chickens*	150	0	100
8	Barley (grain/meal)	4,89[2]	6683[3]		0	310	0		0	0	0
9	Rape Seed	3,25[2]	6500[1]		700	0	0		0	0	0
10	Lupine	1,65[2]	6500[1]		0	290	0		0	0	0
11	Rye	3,50[1]	6500[1]		0	0	0		0	0	0
12	Sorghum	5,37[2]	6188[3]		0	0	20		0	0	0
13	Water	n.a.	n.a.		0	550	0		0	0	0
14	Other [9]	n.a.	n.a.		1000	170	5		50	0	0
15	Grass intake outdoor grazing	n.a.	n.a.	11.400[10]	11.400[10]	n.a.	n.a.	n.a.	300[1]	300[1]	200[1]
Total				60.000	60.000	1640	85	85	1500	2000[1]	800

[1)] Estimation.

[2)] European Union averages, 2017 data from FAOSTAT databased (FAO, 2020b).

[3)] Indicative values for a semi-arid region. Values based on FAO manual methods (FAO, 1986).

[4)] *Meat cows & dairy cows.* Feed intake according to Dutch dairy farming diet (NZO, 2016). Cow's diet consists of 55 kg roughage and 5 kg concentrate. Source specifies '*by-products from food industry*' as standard feed component (20% of concentrate, or 1 kg). This has been removed in this study and is evenly substituted by feed that can be produced locally.

[5)] *Pigs*. Total daily feed intake and diet composition represent Dutch organic farming pigs (wet feed method). In organic farming conditions, piglets stay 42 days with the sow and consume 30kg feed. Fattening pigs live another 138 days before slaughter (at 180 days) and consume 265 kg of feed (Rougoor et al., 2015). This leads to an average feed consumption over the full life span of the pig of 1.64 kg/day (piglet: 0.71 kg/day; fattening pig: 1.92 kg/day). Imported feed elements specified in the source's diet (whey, potato peels and brewery waste) have been removed and are evenly substituted by feed items that can be produced locally.

[6)] *Broiler chickens, laying hens, turkey*. Total daily feed intake is based on organic farming standards for broiler chickens: final life weight = 2400g, feed conversion rate = 2,65 and full life cycle = 75 days results in ±85 grams/animal/day (Van Horne, 2020). Composition of chicken diet varies per farm, animal type and farming context. However, recurring staple crops used for chickens are: maize, soybean (meal), wheat, sorghum and feed supplements; specified composition is an estimation.

[7)] *Sheep & lamb.* Concrete diets of sheep and lamb within a productive farming system are difficult to find. In online sources, recurring feed crops are grass, maize, oats, wheat and beet pulp. The daily feed intake and dietary composition remains an estimation.

[8)] *Goat (meat & dairy).* Diet composition based on LCA study conducted in European-Mediterranean setting (Spain) for dairy goats. Diet: Alfalfa Hay (30%), oat hay (20%), oat grain (20%), soybean meal (10%), maize grain (10%) and sugar beet pulp (10%) (Pardo et al., 2015). *Oat hay* is in this study substituted with standard grass. This study assumes a daily feed consumption of 2000 grams per animal.

[9)] *Other*. Complementary / supplementary food, rich in minerals and important for quality of animal products (dairy/eggs). Not further specified in this study.

[10] Grass intake outdoor grazing. To avoid double counting, grass intake during outdoor grazing is calculated separately and integrated in daily diet. Assumed grazing density outdoor grazing = max. 6 animals / ha with a minimum grazing period of 6hrs/day, 120 days/year. This leads to an average grass intake of 5.2 kg DM/cow/day (Van den Pol-van Daddelaar et al., 2015, p.55, table b1). Assume a dry matter (DM) content of 15% for fresh grass and accounting for roughly 2/3 of the year spent indoors, the daily fresh weight grass uptake of cows can be estimated around 11.400 kg/day. Same value applies to meat herd.

Appendix 6D: Carbon footprint food groups - stage breakdown

Table A6.9 gives an overview of each station's contribution to the global warming potential (GWP) of food groups. Some of the food groups provided by the source are combined in this overview into one indicator. The fractions are used in the FEWprint to account for the emissions that occur at food chain station that remain unaffected by it production location, which are by default *transport, packaging and retail.* Since this method is a rough approximation and does not reflect reality or contextual parameters, the user can amend the values accordingly when required.

Table A6.9. The overview below displays the default values applied in the FEWprint platform surrounding the share [%] of a food station in the GWP of a food group. Values are retrieved from research by Poore and Nemecek (2018). *n* represent the number of aggregated food group from the dataset to arrive at an average value used in the FEWprint, see the footnotes.

•	**Food group**	**Land use change**	**Animal Feed**	**On Farm**	**Food proc.**	**Transport**	**Packaging**	**Retail**	***n***
1	Vegetables[v8.0]	18%	0%	53%	5%	20%	5%	0%	*6*[1]
2	Fruits	0%	0%	59%	3%	28%	9%	0%	*5*[2]
3	Pulses & Legumes	0%	0%	75%	0%	8%	17%	0%	*2*[3]
4	Grains	3%	0%	73%	7%	7%	7%	3%	*2*[4]
5	Rice	0%	0%	90%	3%	3%	3%	3%	*1*
6	Starchy Roots	0%	0%	67%	0%	33%	0%	0%	*1*[5]
7	Beef	21%	5%	68%	3%	1%	1%	0%	*2*[6]
8	Pork	21%	40%	24%	4%	4%	4%	3%	*1*
9	Mutton	2%	10%	80%	4%	2%	1%	1%	*1*[7]
10	Poultry	41%	30%	11%	7%	5%	3%	3%	*1*
11	Fish/Sea food	4%	20%	0%	0%	2%	2%	1%	*2*[8]
12	Cheese	21%	11%	62%	3%	0%	1%	1%	*1*
13	Dairy / Milk	18%	7%	54%	4%	4%	4%	11%	*1*[9]
14	Eggs	16%	49%	29%	0%	2%	4%	0%	*1*
15	Wheat (Pasta)	3%	0%	73%	7%	7%	7%	3%	*2*[10]
16	Nuts & Seeds	-65%	0%	135%	15%	8%	8%	0%	*2*[11]
17	Meat repl.	33%	0%	17%	27%	7%	7%	10%	*1*[12]
18	Dairy repl.	20%	0%	10%	20%	10%	10%	30%	*1*[13]

1) Maize (meal), tomatoes, Onions & Leeks, Root vegetables, Brassicas, Other vegetables.

2) Citrus fruit, Bananas, Apples, Berries & Grapes, Other fruit.

3) Peas, Other pulses,

4) Wheat & Rye (bread), Oatmeal.

5) Potatoes.

6) Beef (beef herd), Beef (dairy herd).

7) Lamb & Mutton.

8) Fish (farmed), Shrimps (farmed).

9) Milk.

10) As food group 4.

11) Nuts, Ground nuts.

12) Tofu.

13) Soymilk

Appendix 6E: FEWprint UFP Design Component - framework

The Method & Materials section of this work provides a general description of the pentalemma behind urban food production system design and evaluation. In the FEWprint platform, this macro-framework is constructed from a network of interlinkages, sub-components, data sets, user input, data entry points and equations, shown in figure A6.3

Table A6.10 give an overview of the workflow steps taken by the user to produce an evaluated UFP design. Some aspect of the UFP design component (in green) are explained in this appendix. Further step-by-step information on how to operate the FEWprint is provided in detail within the FEWprint itself.

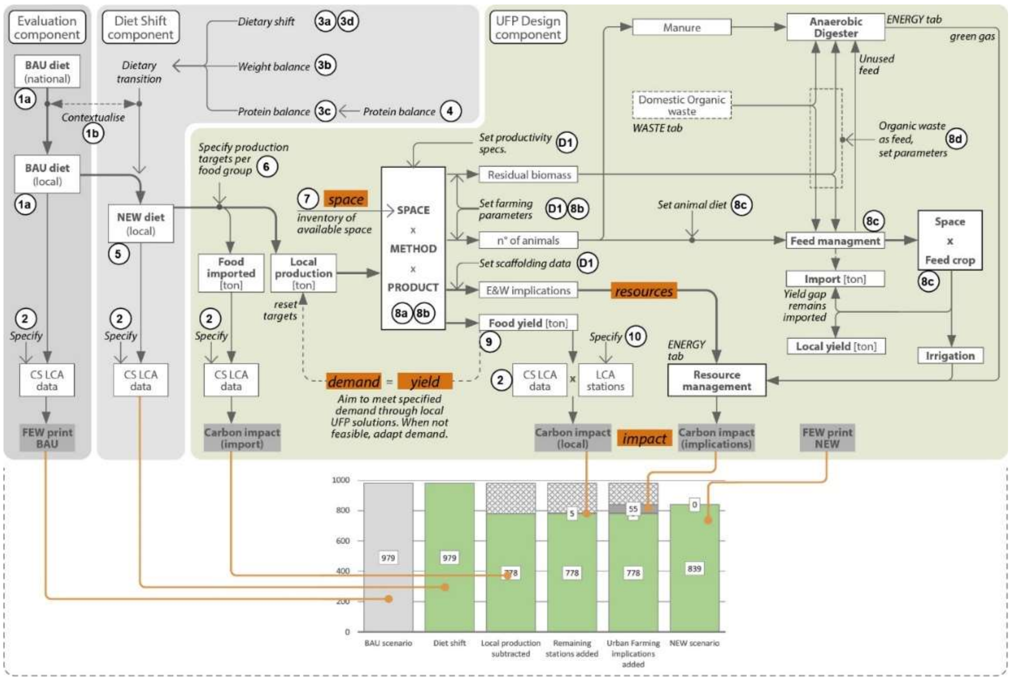


Figure A6.3: Functional diagram of the food tab within the platform. The numbers correspond with the various steps on the platform and with table E1 below. Numbers in the graph are exemplary.

Table A6.10. Overview of the user steps on the FEWprint platform + short description. Links refer to further information in this article or previously published work.

Step	Title	User Action?	More information
Step 1a	Start - Set current diet *Enter/select the present diet of the community*	Yes	(Caat et al., 2022a)
Step 1b	From national diet to neighbourhood diet *Contextualisation of the national diet into local diet*	Yes	
Step 2	Environmental impact food consumption *Select default or enter carbon footprint data of food resources*	Yes	(Caat et al., 2022b)
Step 3	Community dietary changes	No	
Step 3a	Specify dietary transition *Specify dietary shift or recompose present diet*	Yes	
Step 3b	Substituting animal sourced food: weight balance *Choose substituting food groups during diet shift (NEW diet)*	Yes	
Step 3c	Substituting animal sourced food: maintaining a protein balance *Amend resulting diet to secure equal protein intake (PROT diet)*	Yes	
Step 3d	(part of 3c) Substituting animal sourced food: maintaining a protein balance *Add final changes to the diet when necessary*	Optional	
Step 4	Substitutional food components: Protein content food groups *Select default or enter protein content of the food groups*	Optional	
Step 5	NEW diet - Overview	No	
Step 6	Assessment method and food production targets *Select one of the two design & evaluation approaches*	Yes	Chapter 6.2 (*demand*)
Step 7	Inventory of available space (sub-surfaces) *Insert available space (three types)*	Yes	Chapter 6.2 ((*space*)
Step 8	Compose urban farming system: available space + production method	No	Chapter 6.2 ((*yield*)
Step 8a	Plant based food groups *Choose and scale the farming elements - plant products.*	Yes	Chapter 6.2.3
Step 8b	Animal based food groups *Choose and scale the farming elements - animal products.*	Yes	Chapter 6.2.3
Step 8c	Livestock feed *Reconfigure animal feed intake and allocate space*	Yes	Appendix 6C
Step 8d:	Local bio-waste as animal feed *Use organic waste-based animal feed to substitute standard feed*	Yes	Chapter 2
Step 9:	Food consumption and production - Overview	No	n.a.
Step 10	Accounting for remaining food stations *Specify the fraction of the carbon impact of local food that remains*	Yes	
Data I	URBAN FARMING: Embodied resources (scaffolding data) *Insert custom data when necessary.*	Optional	Appendix 6B
Data II	URBAN FARMING: Additional resource demand & bio waste production *Insert custom data when necessary.*	Optional	Appendix 6E
Overview	UFP System design | overview	No	

E1. Impact

The *new* scenario entails the situation where food producing elements are added to the context. The baseline, or business-as-usual (BAU) carbon footprint of a community is estimated by determining the carbon emissions associated with electricity use (elec.), thermal energy demand (heat), fuel use for personal mobility (mob), domestic waste processing (waste), water production and (rainwater) treatment (water) and food consumption (food). This scope, method and framework are discussed in Caat et al. (2022). See equation E1:

$$C(total)_{BAU} = C(food)_{BAU} + C(elec.)_{BAU} + C(heat)_{BAU} + C(water)_{BAU} + C(waste)_{BAU} + C(mob.)_{BAU} \quad \text{[E1]}$$

When local food production is implemented, the new emissions are calculated with equation E2:

$$C(Food)_{new} = C(Food)_{BAU} - C(UFP)_{yield} + C(UFP)_{FEW} + C(UFP)_{proc} \quad \text{[E2]}$$

Where $C(food)_{BAU}$ [ton/yr] notes the total food sector carbon impact in the baseline situation, $C(UFP)_{yield}$ constitutes the virtual emissions of the agricultural output, calculated with the same carbon footprint indicators [Kg CO_2eq/kg_{food}] as the baseline scenario, $C(UFP)_{FEW}$ denote the added carbon footprint consequential to the production and management of resources required to run farming elements and finally $C(UFP)_{proc}$ describes the carbon emissions of food processing of the locally produced food goods. The total food sector emissions for the baseline scenario are calculated with E3:

$$C(food)_{BAU} = \sum(PCC(n)_{prot} * N_{tot} * \frac{365}{1000} * ef(n)) \quad \text{[E3]}$$

And the virtual emissions of the yield are calculated with E4:

$$C(UFP)_{yield} = \sum(PCC_{prot} * demand(n) * N_{tot} * \frac{365}{1000} * ef(n) \quad \text{[E4]}$$

N_{tot} denotes the number of individuals in the community. *demand (n)* is the onsite production target for food group *n*, set by the user. PCC_{prot} describes the daily food intake of one person, after dietary changes and re-establishing protein intake equilibrium (see Caat et al., 2022). When no dietary transition is simulated, but only local food production implementations are explored, PCC_{prot} in equation E4 is substituted with PCC_{ctx} (ctx = context). Finally, $ef(n)$ constitutes the carbon footprint indicator of food group (n).

$C(UFP)_{E\&W}$ represent the additional emission coming from energy (E, electrical and thermal energy) and water (W) management. The additional demand for thermal energy, electricity and water is a direct result of design decisions regarding the composition of the food producing elements, the scale of the different elements (discussed in section E2) and the assumed resource exchange loops (discussed in section E3). $C(UFP)_{E\&W}$ is calculated with E5:

$$C(UFP)_{E\&W} = C(T) + C(E) + C(W) \quad \text{[E5]}$$

Where $C(T)$ represents the carbon emissions consequential to added thermal energy (T) use, $C(E)$ represent the added emissions due to extra electricity (E) demand and $C(W)$ notes the emissions coming from water (W) provision and treatment for the farming system. The three factors are calculated with equation E6-E8 below:

$$C(T) = \sum(A(n) * t(n)_{PM} * ef(n)) \quad \text{[E6]}$$

$$C(E) = \sum(A(n) * e(n)_{PM} * ef(n)) \quad \text{[E7]}$$

$$C(W) = \sum(A(n) * w(n)_{PM}) * e(n_{prod}) * ef(n)) + \sum(a(n) * W(n)_{PM}) * e(n_{trt}) * ef(n)) \quad \text{[E8]}$$

The amount of space allocated to the production of a specific product *n* is noted with *a* [m^2] and is the parametric factor changed by the user to design the system. The invested thermal, electrical and water resources associated with the production of food are noted by $t(n)_{PM}$, $e(n)_{PM}$ and $w(n)_{PM}$, respectively expressed in [kWh_e/m^2], [MJ_t/m^2] and [L/m^2]. An overview of this scaffolding data is provided in table B1, B2, B3 and C1. In alignment with the working sequence of the platform, the total UFP energy and water demand by the system is first calculated based on default or inserted custom data, following by a process of resource management that allows further (sustainable) configuration of the system.

Accounting for food station emissions.

Emissions associated with the consumption of food can be subdivided into seven food chain stations: (1) Land use change, (2) Animal feed, (3) On farm, (4) Food processing (5) Transportation, (6) Packaging and (7) Retail. This categorisation and allocation is methodologically repeated for each food group when the LCA method is used to evaluate the environmental impact of a food product.

Land use/land use change (LULUC) is the aboveground changes in biomass from deforestation, and below-ground changes in soil carbon sequestration. *On Farm* accounts for methane emissions from cows, methane from rice fields, emissions from fertilizers, manure storage and management and farm machinery. *Food processing* are the emissions from energy use in the process of converting raw agricultural products into final food items for human consumption. *Transportation* are the emissions from energy use in the transport of food items nationally and internationally. *Packaging* are the emissions from the production of packaging materials, material transport and end-of-life disposal. *Retail* describes the emissions related to the energy use in refrigeration and other retail processes and finally *Animal Feed* note the on-farm emissions from crop production and its processing into feed for livestock.

In a local food system, such as the ones designed with the support of the platform, some of these food stations no longer apply while others still remain. It is likely that *LULUC, on farm* (in case of plant products) and transportation do no longer apply, or do to a lesser extent, while stations like *processing*, *animal feed*, *packaging* and *retail* will remain applicable even when food is produced locally. Emissions occurring at the remaining stations are accounted for with $C(UFP)_{proc}$, where *proc* stand for processing emissions and is described with equation E9.

$$C(UFP)_{proc} = \sum(demand(n) * ef(n) * \sum FS \qquad \text{[E9]}$$

$\sum Station_n$ represents the sum of all food stations that should be accounted for when calculating the remaining carbon impact of the food production chain. As default, the stations *processing, transportation, packaging, retail and animal feed* are included, but can be switched off by the user in the platform. The stations *land use change* and *on farm* have been turned off by default as the former does no longer apply in a local system and the latter is now accounted for with equation E5.

E2. Design of an UFP system - crops

As mentioned in section 2.3.4, the user combines a desired crop with one of the three default production methods and enters a surface area. The three production methods (PM) are: *field farming (FF), greenhouse horticulture (artificial lighting) (GH(AL))* and *plant factories artificial lighting (PFAL)*. The productivity of the farm is directly related to the space allocated to a specific product and is calculated with equation E10:

$$Yield\ (n) = A(n) * y(n)_{PM} \qquad [E10]$$

The amount of space reserved for a specific crop *n* is described with *A(n)* [m^2] and the theoretical productivity [kg/m^2/yr] is noted by *y(n)* (yield) of production method *pm*, where *pm* can be open field farming (y_{FF}), greenhouse farming (y_{GH}) or plant factory (i.e. stacked farming, y_{PF}). Default values for the various farming productivities are specified per food product and production method in table B1, B2 and B3.

PFAL performance - an estimation.

At the moment of writing this article, clear and public data on the performance of PFAL system for all the considered crops was not available. The PFAL sector is a developing, highly competitive industry and performance data is sensitive. Even though some figures describing PFAL farming can be retrieved from different online sources and an estimation can be formed, it is not possible to systematically acquire and verify the required data across all the crops considered in the platform. As such, estimations apply.

Agricultural output. Assuming PFALs (Plant Factory Artificial Lighting) provide the optimal growing conditions for crops, the agricultural output of a PFAL system depends mainly on the number of stacked layers present. To estimate the output, this study applied the productivity of high-performance greenhouse systems and multiplied this figure by the number of stacked layers assumed possible within the height of one floor, figure A6. Shortened crop production cycles due to highly optimised lighting schemes have been disregarded in this estimation.

Electricity use. The square meter electricity demand of a PFAL is mainly determined by the installed lighting power, which on its turn depends on various structural parameters (e.g. number of stacked production layers), growing climate settings (e.g. duration of daily photoperiod, desired PPFD [µmol/s/m^2] and the spectrum range of the produced light) and technical properties (e.g. lamp type). The installed power can be estimated by choosing a LED type and combining this with customary growing conditions for PFALs. The Philips Greenpower LED production module is used for stacked PFAL production (type: DeepRed/Blue 150, 61.5 µmol/s, 40W per array (153cm) i.e. 26 Watt/m (Philips, 2013). This study assumes two arrays per square meter and a photoperiod of 16 hours/day throughout the full year. To account for dehumidification and cooling (AC based), a top-up coefficient of 1.25 is included (Kozai, 2016). PFAL dehumidification depends on the total plant's transpiration rate within the system and cooling depends mainly on the total installed lighting power. As both factors increase with the number of growing beds, this coefficient applies to all layers. All aforementioned parameters combined leads to an estimated electricity demand of ±380 kWh/yr*production layer (0.052kW x 16hrs x 365days x 1.25).

Thermal energy use. Modern closed PFAL systems require cooling throughout the year due to the internal heat loads of the growing light system and energy demand for heating is therefore set to zero. Cooling requirement of a PFAL structure is included in the top-up coefficient of the electricity demand estimation.

Water demand. In a perfect closed farming system, water is recovered from the dehumidification and/or air conditioning system and reused in the nutrient delivery system. As such, the only water leaving the system is stored in the biomass of the crop and some minor spillage. Since farming process water input is difficult to estimate, this study assumes the water demand equals the agricultural output of the farm.

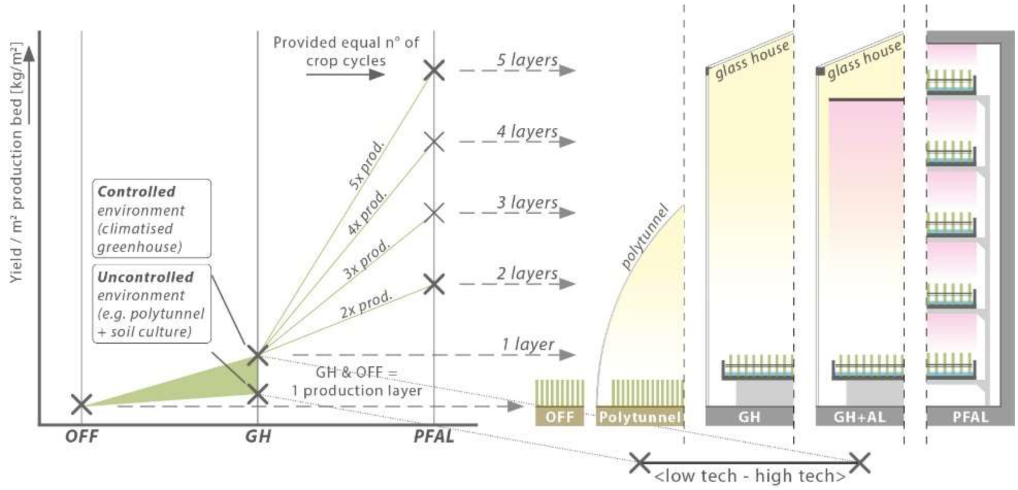


__Figure A6.4__: Productivity range of field farming, greenhouse horticulture and PFAL farming methods. PFAL yield is based on the best performing GH methods, multiplied by the number of growing beds stacked on top of each other.

E3. Design of an UFP system - animal products

Beef, Pork, Mutton, Poultry

Similar to the production of crops, animal product yield is also coupled with the amount of space allocated to rear the animals. The amount of assigned space determines the number of animals that can be kept at any moment in time on this space, including the space required for animal housing and outdoor rearing or grazing.

The production of beef, pork, mutton and chicken (fish not included!) can be estimated with equation E11:

$$Yield_{(n)} = \frac{A_{(n)}}{a_{farm}+a_{field}} * \frac{365}{d} * \frac{Cw}{1000} \qquad [E11]$$

Where *A(n)* represents the total amount of space allocated by the designer to a specific farming animal (n) and $a_{farm} + a_{field}$ describe respectively the indoor housing and outdoor rearing/grazing space requirement of that animal. $Cw(n)$ notes the carcass weight [kg] of the animal and *d* notes the full life cycle of the animal [days], i.e. the period from birth to slaughter. All farming/livestock parameters can be adjusted by the designer. Default values can be found in appendix 3B.

Fish & Shrimp

Fish or shrimp farming is a comprehensive breeding practice that comes in various forms for different climate and/or cultural contexts. Similar to crop farming, fish production methods range from low-tech methods to optimised high-tech breeding ponds and various options in between. The platform offers a simplified calculation to estimate the annual yield of a fish farm, based on the space allocated to the fishponds. The estimation method is based on the biology of the fish species and takes into account the space demand (a.k.a. the *Stocking Rate*, or n° fish/m^3) of the fish at various stages of its life. The stages are based on increasing animal weight and as the fish grows, the stocking rate will be decreasing. The fish yield [kg/yr] is estimated with equation E12:

$$Yield(fish) = A(fish) * D_{tank} * SR_{fin} * c_{fin} * Cw * (\frac{365}{d}) \qquad [E12]$$

Where $A(fish)$ denotes the space assigned by the designer to a fish/shrimp species [m^2]. D_{pond} denotes the depth of the tank [m]. The carcass or edible weight of the fish is denoted by *Cw* [kg] and the full life cycle of the fish is expressed with *d*. [days]. SR_{fin} is the Stocking Rate of the fish/shrimp in the final farming stage and is expressed in n° animals/m^3. c_{fin} is a coefficient to isolate the amount of space that is used during the final growing stage of the species from the total space used by the fish farming system.

Initially, the stocking rate density is very high in the days after hatching and when the animals are in their larva/fry life stage (see figure 14 for Tilapia). As the fish grow larger, the stocking density decreases as an individual animal require more space, i.e. larger tanks are needed to keep the same number of fish. Since the final life stage of fish usually entails the longest period of fish farming, most of the space on the fish farm is reserved to accommodate the final life stage of the fish. This c_{fin} factor used to isolate the space demand is a rough estimation. It is possible to determine this coefficient with a comprehensive calculation that combines stocking rates and stage durations into one coefficient (as was done for Tilapia, fig. A7), however this is only possible when this fish breeding data is available. Table E2 provides the default fish & sea food farming values used in the platform.

Table A6.8. Default farming parameters used in FEWprint to estimate fish farming yield. The practise of fish farming is contextual and farming parameters can depend on many factors. The values below apply for intensive farming practises.

food product		**SR_{fin}**	**FLC**	**c_{fin}**	**weight**		**embodied resources**		
Fish	Food products	n°/m³	days	(0-1.0)	Final weight gram	Carcass weight gram	Elec. kWh	Thr. MJ	Wtr L/kg
11.1	Shrimp, large (p.monodon)	20	180	0,90	50	40[1]	5,0[1]	20[1]	10[1]
11.2	Shrimp, small (p.monodon)	60	105	0,90	20	16[1]	5,0[1]	20[1]	10[1]
11.3	Tilapia[4]	100	270	0,65[2]	450	325[1]	5,2[3]	41[4]	238[5]
11.4	Carp (common)	3	365	0,65[1]	2.0K[1]	1.5K[1]	As 11.3	As 11.3	As 11.3

[1)] Estimation.

[2)] Extracted from detailed stocking density table provided in (Rakocy, 2005, table 1.). Also see figure 14 below.

[3)] Based on conventional RAS (Recirculating Aquaculture System) production in Europe (Martins et al., 2010, table 3).

[4)] Based on estimated modelled values for global aquaculture. Farming class applied: CILP: Cold climate, Intensive, Low natural trophic level species, Pond.

[5)] Based on a theoretical intensive Tilapia farm (Martins et al., 2010, table 4).

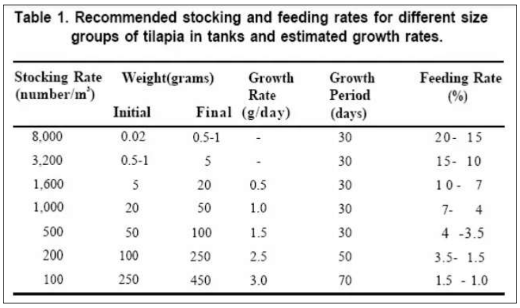


Table 1. Recommended stocking and feeding rates for different size groups of tilapia in tanks and estimated growth rates.

Stocking Rate (number/m³)	Weight(grams) Initial	Final	Growth Rate (g/day)	Growth Period (days)	Feeding Rate (%)
8,000	0.02	0.5-1	-	30	20- 15
3,200	0.5-1	5	-	30	15- 10
1,600	5	20	0.5	30	10- 7
1,000	20	50	1.0	30	7- 4
500	50	100	1.5	30	4 -3.5
200	100	250	2.5	50	3.5- 1.5
100	250	450	3.0	70	1.5 - 1.0

***Figure A6.5**. SR Tilapia fish farming (example)*

Dairy & Eggs

The production, or Yield [ton/yr] of dairy and eggs can be estimated with equation E13 and E14 and is based on the number of productive animals and the daily per-animal average productivity. The number of animals is based on the allocated space (A_n) and space requirements that are mentioned in appendix B, table B2. The platform offers both cow milk ($y_{cow} = 25L/day$) and goat milk ($y_{goat} = 2{,}7L/day$) as default options. The productivity of chicken is set to 53 g/day (based on 300 eggs/animal/year and average egg weight = 65 grams).

$$Yield_{(dairy)} = \frac{A_{(dairy\ cow/goat)}}{a_{farm}+a_{field}} * y_{cow/goat} * \frac{365}{1000} \quad [E13]$$

$$Yield_{(eggs)} = \frac{A_{(chicken)}}{a_{farm}+a_{field}} * y_{egg} * \frac{365}{1000000} \quad [E14]$$

E4. Animal feed management

The platform offers a sub-component (step 8c) to manage the space demand for animal feed provision. The annual livestock feed demand depends on the number of animals required to meet the food production targets. The platform offers a standard default diet composition for cows (meat & dairy), pigs, poultry (meat & eggs), sheep, goat and lamb. The diets consist of a selection out of 14 possible animal feed components. An overview of the livestock feed components can be found in Appendix 6C, table C1. Animals that graze (cows, sheep, goat & lamb) also take up part of their diet from outdoor grazing, which is added as a feed component to the diet.

As mentioned, the feed demand is based on the number of individual animals within the farming system. The platform advises on the minimal amount of cropland required for each feed component to produce sufficient animal feed for all the animals that consume that feed component. It is the task of the user to either reconfigure the animal diet to reduce the space requirements, for example by switching to crops with a higher yield or using organic waste as animal feed or reducing the daily feed intake overall of an animal. The demand of a feed component (n) should be satisfied with local yield, i.e. $Demand(n)_{feed} = Yield(n)_{local}$, and is calculated with equation E15 & E16.

$$n°_{livestock\,(n)} * D(n)_{feed} * \frac{365}{1000000} = A(n)_{feed} * y(n)_{feed} \qquad [E15]$$

$$n°_{livestock(n)} = \frac{A(n)}{a_{farm}+a_{field}} \qquad [E16]$$

The total number of livestock is based on the total space ($A(n)$) assigned to an animal group (also see equation E15). The demand of feed component $D(n)_{feed}$ [gr/animal/day] is based on default values listed in table C1 or on values adjusted by the user. It is up to the user to meet the demand of all feed components (n) with local production by assigning sufficient field farming space ($A(n)_{feed}$) to a feed component. The yield is subsequently based on the productivity of a crop, $y(n)_{feed}$. The animal feed management process is schematically displayed in figure A8 below.

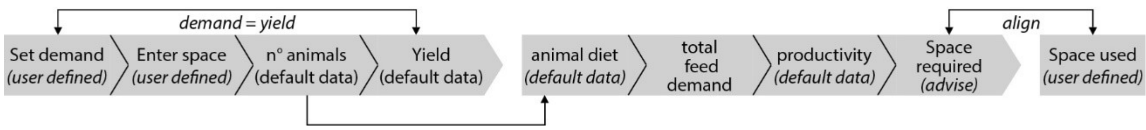


Figure A6.6*. Animal feed management*

The production of animal feed crops is considered only for the *field farming* method. This discards thermal and electrical energy from the embodied resources but water for irrigation remains, of which the environmental impact is calculated with equation E17.

$$C(W)_{feed} = \sum((A(n)_{feed} * w(n)_{feed}) * e(n_{prov}) * ef(n)) \qquad [E17]$$

Where $A(n)_{feed}$ notes the user-assigned space for the production of animal feed component (*n)* in ha. Values for average irrigation values, $w(n)_{feed}$, can be found in table A6.8. The electricity demand associated with the user-selected water provision method (prov) is noted with $e(n_{prov})$ and the corresponding carbon footprint is noted with $c(n_{prov})$.

E5. Organic waste management

Within the UFP system, two organic flows are considered for internal circulation and reuse and are therefore quantified: residual inedible organic matter from crop farming and manure from livestock. In addition, part of the community's domestic waste is of organic nature. The organic part of domestic waste and the inedible fraction of crops can (partly) be used for conversion into animal feed. The remaining organic material can be converted into biogas in an *anaerobic digester* module. The platform contains a subcomponent that streamlines the assessment of animal feed production from organic matter (step 8d) and a subcomponent that informs about biogas production from the remaining organic material.

Local feed

Local biomass flows are converted into animal feed or green gas, primarily depending on the quality of the organic flow. In the FEWprint platform, the inedible crop residue (mainly leaves, stems and roots) from greenhouse horticulture and plant factory production (F_{UFP}) and the organic fraction from domestic or household waste (F_{DW}) are considered for conversion into animal feed ($D(waste)_{feed}$) [ton/yr]. Crop residue material involved in open field farming is assumed to be left on the field between seasons in order to maintain better soil fertility and will not be processed into livestock feed. The annual animal feed produced from organic waste is estimated with equation E18-E20:

$$D(\,waste)_{feed} = F_{DW} + F_{UFP} \quad \text{[E18]}$$

Where

$$F_{UFP} = \sum(Yield(n)_{PM} * W(n)_{PM} * r_1 * r_2) \quad \text{[E19]}$$

$$F_{DW} = W_{bio} * r_1 * r_2 * N_{tot} \quad \text{[E20]}$$

F_{UFP} [ton/yr] is the total amount of residual material that becomes available during crop farming and F_{DW} represent the total annual organic fraction of domestic waste produced in the community [ton/yr]. $Yield(n)_{PM}$ represents the food yield of a product (*n)* by means of a production method *PM,* which is either greenhouse horticulture or plant factories [ton/yr]. $W(n)_{PM}$ represents the residual biomass after harvesting, expressed as a coefficient of the final yield [ton_{waste}/ton_{yield}]. W_{bio} denotes the domestic organic biomass production in the community [ton/cap/yr]. Not all biomass can be used for further processing into animal feed and this suitable fraction is isolated with r_1. Material losses occur during the screening, sterilisation and conversion processes of suitable biomass into animal feed, which is accounted for by r_2. The amount of people in a community is denoted with N_{tot}. Table A20 gives an overview of the default values for r_1 and r_2 for all considered organic flows. In the FEWprint, the annual flows F_{UFP} *and* F_{DW} [ton/yr] are normalised into daily flows [gram/day] to better align with the daily food intake of animals and provide a more sensible design process/experience.

Table A6.9. Overview of waste processing parameters

Organic flow	*Waste to Animal fed* Term[1]	Suitability coefficient[2], r_1	Processing losses[3], r_2	*Anaerobic Digestion* Term[1]	Solids fraction[4] $S(n)$ [%]	Biogas content[5] ($v(n)$)[m^3/1000kg$_{TS}$]
Organic domestic waste	F_{DW}	0.43	0.39	$AD(DW)$	33%	618
Residual material crop farming	F_{UFP}	0.90	0.05	$AD(UFP)$	50%	265
Manure from livestock farming	*n.a.*	n.a.	n.a.	$AD(M)_{in}$	50%	325
Unused animal feed	*n.a.*	n.a.	n.a.	$AD(F)_{in}$	90%	618

1) Term in equations

2) Suitability coefficient: fraction of the organic waste flow that is suitable for further processing into animal feed. Remaining waste is sued in the anaerobic digester.

3) Processing losses: the loss of organic material due to waste dehydration, screening and processing.

4) Total solids: fraction of solid material in organic waste mix. Non-solid material is generally water.

5) Biogas content: the amount of biogas that can potentially be extracted from 1000kg of total solids of a waste flow.

Anaerobic Digester

The user decides for which animals' bio-waste-based fodder is used and to which extent this feed source constitutes the daily recommended feed intake of that animal. During this allocation process, it is up to the user not the exceed the daily availability of bio-waste-based fodder

The total annual green gas production (V_{gas}) of the Anaerobic Digestion (AD) system can be estimated with equation E21 and E22. Four flows of organic mass can be directed to the AD system: domestic organic waste (DW), crop farming residual material (UFP), manure from livestock (M) and unused animal feed (F).

$$V_{gas} = (\sum AD(n)_{in} * TS(n) * v(n)) * r_{con} \quad \text{[E21]}$$

$$AD(tot)_{input} = AD(F)_{in} + AD(UFP)_{in} + AD(DW)_{in} + AD(M)_{in} \quad \text{[E22]}$$

V_{gas} is the produced green gas with local organic material [m^3/year]. Volumetric losses occur when biogas is converted into green gas due to the near-complete removal of carbon dioxide gasses in the biogas mixture. This process of biogas cleaning is necessary to obtain a similar caloric value of green gas compared to its fossil counterpart (methane gas). These losses are accounted for by r_{con}, which is set to 0.60 as a default value.

F5. Rainwater capture and reuse

The platform contains a subcomponent that can be used to estimate the captured rainwater potential. It can be used to estimate the amount of captured rainwater if surfaces would be designed or used for that specific purpose. Captured rainwater can be used for domestic purposes or for UFP. The '*local - RAINWATER*' option is provided when designing the new system. The total greenhouse rooftop surface is extracted from the urban farming component on the food tab, as this can effectively serve as a rainwater collection surface. The captured rainwater is calculated with equation E23:

$$R_{cap} = \sum(A(n) * P * RoC(n) * C(n)) \quad [F23]$$

R_{cap} denotes the total rainwater captured [m^3/yr] by combining all surfaces *A* [m^2] that are used for this purpose. *P* notes the annual precipitation [m^3/m2*yr]. Ro*C* denotes the Run-Off Coefficient (ROC) and accounts for the first amounts of precipitation that is unsuitable for capture and storage due to a higher concentration of pollution (for example: dirt, dust, leafs, sand). The RoC factor also accounts for less intense or very short periods of precipitation, in which rainwater never flows off the surfaces due to its cohesive properties and therefore evaporates instead of being captured. The height of the fraction depends on the material of the surface. An overview, provided by the Texan A&M (Texas A&M, n.d.), of different values are listed on the platform falls generally in the range of 0.05 for lawns up to 0.95 for metal surfaces

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Curriculum Vitae

Pieter Nick ten Caat

Master of Science in Architecture, Urbanism and Building Sciences

Education

2018-2023 PhD Candidate, dept. of Architectural Engineering & Technology, Climate Design & Sustainability lab, Delft University of Technology

2015-2018 MSc Architecture, Urbanism and Building Sciences, Building Technology track.

2015 Bridging program Faculty of Architecture to grant access to the Master Education of Delft University of Technology

2010 - 2014 Bachelor of Building Engineering (currently Built Environment), Hanzehogeschool Groningen, The Netherlands

Professional Experience

10.2022- present CAAT consult | Carbon Accounting & Analysis for Transformation.

06.2021 - present Urban Input Output design collective. www.urban-io.org

09.2013-01.2014 Internship building construction planner. Volker Wessels - Visser & Smit Bouw, Groningen, The Netherlands

02.2012-07.2012 Internship Architectural draftsman. Artés Architecten, Groningen, The Netherlands

Academic Experience - Education

2018-2022 Tutoring various MSc. Student graduation projects. Faculty of Architecture and the Built Environment, Faculty of Civil Engineering and Geosciences and Advanced metropolitan Solutions (Amsterdam).

2022 EXTREME design studio, student tutoring, TU Delft

2021 Lecturer Food Innovation Design, TU Delft

2020,2021 SWAT studio, lecturer, TU Delft

Academic Presentations (part)

2022 The Moveable Nexus: Design-led urban food, water and energy management innovation in new boundary conditions of change [SUGI project closing session]. SUGI. (22/03/2022, SUGI, online)

2020 Towards fossil free cities: A supermarket, greenhouse & dwelling integrated energy system as an alternative to district heating: Amsterdam case study [online conference]. The 4th South-East European Conference on Sustainable Development of Energy, Wester and Environmental Systems (SDEWES) (28/6-2/7, SDEWES, Sarajevo)

2019 *De Water-Energie-Voedsel Nexus in de stad.* VerDus/Platform 31 meeting. (10-10-2019, VerDus, Den Haag)

2019 *The Ecological Footprint of the conference* [Closing presentation]. International LDE-Heritage Conference 2019 Heritage and the Sustainable Development Goals. (26-28 November 2019, TU Delft, The Netherlands)

2019 Synergetic solutions for food, water and energy [Conference presentation]. MNEX DOHA - Doha Living Lab Food Water Energy Nexus (25-26 Feb, Qatar University, Doha)

List of (peer reviewed) publications

2020

ten Caat, N.; Graamans, L.; Tenpierik, M.; van den Dobbelsteen, A. Towards Fossil Free Cities—A Supermarket, Greenhouse & Dwelling Integrated Energy System as an Alternative to District Heating: Amsterdam Case Study. *Energies* 2021, *14*, 347. https://doi.org/10.3390/en14020347

ten Caat, N; Tenpierik, M.J. Een kas-zonnecollector als alternatief voor stadsverwarming. *Bouwfysica - Vakblad voor de Nederlands Vlaamse Bouwfysica vereniging [trade journal] 2020,31-2.*

2021

ten Caat, N., Tillie, N., Tenpierik, M. (2021). Pig Farming vs. Solar Farming: Exploring Novel Opportunities for the Energy Transition. In: Roggema, R. (eds) TransFEWmation: Towards Design-led Food-Energy-Water Systems for Future Urbanization . Contemporary Urban Design Thinking. Springer, Cham. https://doi.org/10.1007/978-3-030-61977-0_12

2022

ten Caat, N.; Tenpierik, M.; van den Dobbelsteen, A. Towards a More Sustainable Urban Food System—Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform. Sustainability 2022, 14, 1797. https://doi.org/10.3390/su14031797

Pieter Nick ten Caat, Martin J. Tenpierik, Tithi Sanyal, Nico M.J.D. Tillie, Andy A.J.F. van den Dobbelsteen, Geoffrey Thün, Sean Cullen, Shun Nakayama, Theodora Karanisa, Stewart Monti. Towards fossil free cities – Emission assessment of food and resources consumption with the FEWprint carbon accounting platform, Cleaner Environmental Systems, Volume 4, 2022, 100074, ISSN 2666-7894, https://doi.org/10.1016/j.cesys.2022.100074.

under review

Caat. P.N. ten, Tenpierik, M.J., Tillie, N.M.J.D., Dobbelsteen, A.A.J.F. van den (2022) Towards carbon free cities - Grasping the urban food production pentalemma by using the FEWprint design platform [working title], submitted to XXXX

2023

Urban Food Production

Exploring the potential of urban agriculture for the decarbonisation of cities

Pieter Nick ten Caat

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