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Synergetic urbanism: a theoretical exploration of a vertical farm as local heat source and flexible electricity user

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ABSTRACT

The urban energy transition requires innovative heating and cooling systems, as well as enhanced flexibility in electricity usage. This paper explores the theoretical potential for vertical farms to contribute to the energy transition by supplying residual heat to local district heat networks and flexible electricity usage. A stepped approach was used to design energy systems that achieve thermal energy balance through heat and cold exchange between a vertical farm and buildings within a specific Dutch neighbourhood. Furthermore, alternative lighting strategies for vertical farms were explored to reduce grid congestion and to respond to electricity price fluctuations, limiting the mismatch between electricity generation and demand. Compared to the baseline scenario, the energy system with an integrated vertical farm reduces overall energy use by 15 %, even when accounting for the farm's electricity use. By adopting intermittent lighting that is better aligned with electricity price fluctuations, the vertical farm obtained annual cost savings of 14 %. The integration of vertical farms into energy systems can, therefore, contribute to the urban energy transition by producing residual heat to balance thermal energy system and save money for growers by optimising LED operations to align with electricity price fluctuations, whilst producing fresh vegetables for the city.

1. Introduction

1.1. The urban energy transition

To limit the impacts of global warming, cities must achieve energy neutrality through the transition to renewable energy systems. One approach to realise energy-neutral cities is the 'New Stepped Strategy' introduced by Dobbelsteen (2008). At the urban scale, this strategy was elaborated as the 'Rotterdam Energy Approach and Planning' methodology (Tillie et al. 2009), and the 'Amsterdam Guide to Energetic Urbanism' (Dobbelsteen et al., 2011). The essence of the New Stepped Strategy lies in its structured steps: 0. Research the local circumstances; 1. Reduce energy demand; 2. Reuse residual energy flows; 3. Produce renewable energy. Research by Pulselli et al. (2021) and Caat et al. (2021) found great potentials in cities for energy savings (step 1), and residual heat usage by attuning, exchanging and storage of heat (step 2). In these studies, residual heat is exchanged between different urban functions based on geographic proximity. All buildings and urban areas generate residual heat and/or cold flows that could be employed, and making use of these could significantly reduce primary energy demands (Tillie et al., 2009). When in close proximity, these exchanges are often cost-efficient, resource-efficient, and logistically manageable (Lenhart et al., 2015).

Traditional energy systems relied on the centralised supply of electricity, natural gas, and/or high-temperature district heating. These centralised and high-temperature characteristics of these district heat networks (DHNs) have posed challenges in integrating low-temperature (LT) waste heat sources (Gjoka et al., 2023). Recent developments have shifted towards low-temperature and smaller scales at neighbourhood and district levels, thereby facilitating the potential to exchange energy

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Abbreviations: ATES, aquifer thermal energy storage; COP, coefficient of performance; C16/8, Lighting concept using 16 hours of continuous light followed by 8 hours of darkness; C24/0, Lighting concept using 24 hours of continuous lighting; DHN, district heat network; DHW, domestic hot water; EPEX, European Power Exchange; HE, heat exchanger; HP, heat pump; I3/1, Lighting concept using six cycles of 3 hours of light and 1 hour of darkness; I4/2, Lighting concept using four cycles of 4 hours of light and 2 hours of darkness; I8/4, Lighting concept using two cycles of 8 hours of light and 4 hours of darkness; LT, low temperature; PPFD, photosynthetic photon flux density; uLT, ultra-low temperature; VF, vertical farm.

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between the different buildings (Jansen et al., 2021a). These systems are called fifth-generation DHNs, which make use of decentralised heat and cold generation from multiple sources (Gjoka et al., 2023).

The use of lower temperatures in these DHN enables heat pumps, operating either in heating or cooling mode, to use the DHN as heat source or sink, and promote energy exchange in the network (Saini et al., 2023). Consequently, the exchange of warm return flows from cooling processes and the cold return flows from heating processes contribute significantly to covering thermal energy demands in the neighbourhood (Boesten et al., 2019; Saini et al., 2023). Ideally, the heat and cold demands are balanced throughout this neighbourhood to eliminate the need for additional heat or cold sources. However, in instances where equilibrium is not achieved, the ultra-low temperature of DHN allows for direct integration of renewable sources, such as solar heat and aquathermal energy (Boesten et al., 2019; Jansen et al., 2021b).

Despite these advantages of these low temperatures, they make the DHN unsuitable for direct heating, in contrast to the conventional high-temperature DHNs. Therefore, centralised or decentralised water source heat pumps must be included to deliver the required temperature levels for building heating (Jansen et al., 2021a).

The exchange of residual flows from heating and cooling processes is particularly interesting in urban environments, as cities accommodate diverse functions with different energy patterns. These functions demand varying quantities of heat, cold, and electricity at different times of the day, week, or year (Dobbelsteen et al., 2023). By attuning functions energetically, exchanging redundant waste heat or cold, and storing these diurnally, weekly or inter-seasonally, cities will achieve energy-neutrality more effectively than a sole focus on renewable energy production. Under high densities, after all, sufficient generation of renewable energy (e.g., from sun or wind) to fulfil our needs becomes more complicated (Jansen et al., 2021a).

1.2. The integration of Vertical Farms into urban energy systems

When considering synergetic urban energy systems, a novel function can be introduced that not only generates heat but also produces food: vertical farming (VF). These highly controlled indoor farms produce year-round crops with minimal land usage (Kalantari et al., 2017) using artificial LED lights (Delden et al., 2021). As a consequence of artificial lighting, VFs produce significant quantities of low-temperature heat. Recent studies by Martin et al. (2022) and Blom et al. (2023) presented the potential to capture and reuse this heat for building heating purposes. Martin et al. (2019) proposed to use this heat within DHNs to enhance the synergetic relationship between VFs and the built environment. This opportunity was also highlighted by Gentry (2019). The use of residual heat from VFs is mostly offers benefits within colder and temperate climates where buildings have significant heating demands (Blom et al., 2023). Graamans (2021) used residual heat produced by VFs to balance urban energy systems reliant on renewable energy. In this study, the VFs supplied heat to the DHNs and responded to fluctuations in renewable electricity production by adjusting the LEDs according to the availability of electricity in the grid, i.e., demand response operation by switching LEDs on and off.

Demand response operations can also offer a promising solution to high electricity costs, which is currently a limiting factor to scale up VFs and offers a big challenge to growers (Sørensen et al., 2016). On this basis, VFs can schedule their lighting periods according to the cheapest hours (Arabzadeh et al., 2023; Avgoustaki and Xydis 2021) and growers can determine the balance between operational costs and revenue by adjusting the growth parameters (Pimentel et al., 2023).

The transition to renewable electricity, and the electrification of transport and energy systems introduce new challenges, such as increased peak loads and bidirectional electricity flows (Voulis et al., 2018). Grid congestion occurs when the demand for electricity transportation in a certain area exceed the grid's capacity (Liander, 2019). As renewable energy sources are intermittent, this complicates the balance between renewable production and usage, leading to increased price fluctuations (Vandermeulen et al., 2018). System flexibility is crucial to counteract this effect (Arabzadeh et al., 2023). Flexibility, in this context, refers to the ability to accelerate or delay the injection or extraction of energy into or from an energy system, typically within time scales of less than a day (Vandermeulen et al., 2018). When operating the VF in a flexible manner, by increasing or decreasing LED luminance or switching the LEDs on or off, energy systems with integrated VFs can enhance overall energy system flexibility, limiting the mismatch between electricity production and demand (Arabzadeh et al., 2023).

1.3. Research aim

The energy transition requires the development of novel heating and cooling systems, as well as enhanced flexibility in electricity usage. Within the existing body of literature, VFs have been identified as a potential low-temperature heat source for urban environments, whilst allowing for flexible electricity usage. However, to date, the design and potential energy savings of the energy systems facilitating the exchange of residual heat and cold between VFs and urban functions remain unexplored. Additionally, the extent to which such systems can unlock flexibility within the electricity grid while sustaining food production levels remains unknown. Therefore, this research aims to investigate how the integration of VFs in cities can improve the daily and seasonal energy balances of heat and cold in a neighbourhood while enhancing flexibility for the electricity grid. To achieve this, a theoretical case study is employed, examining the integration of VFs into a neighbourhood in the Netherlands.

2. Methods

Fig. 1 represents the steps followed to design the optimal configuration of the DHN that integrates VFs into urban energy systems to balance heat and cold within a theoretical case study area. Concurrently, strategies are formulated to enhance the flexibility of electricity use in the VF. Step 1 to 5 and step 7 were adapted from the steps developed by Jansen et al. (2021b) to design optimal DHN configurations and estimate their energy efficiency. Step 6 was added to include for the integration with the electricity grid. The following sections describe each step of the methodology.

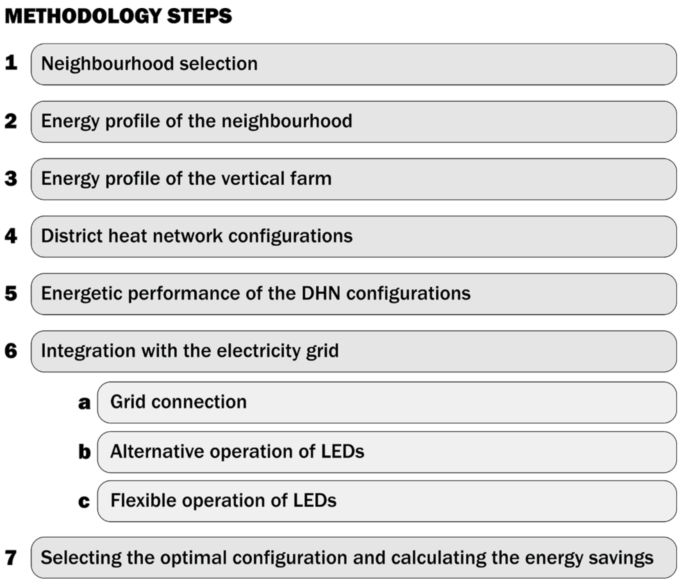

Fig. 1. Methodology steps of the research.

2.1. Step 1: Context and neighbourhood selection

As highlighted in the introduction, the use of residual VF heat for building heating purposes is particularly advantageous in cold and temperate climates. Therefore, this study focusses on the Westindische Buurt, a residential neighbourhood in Amsterdam, the Netherlands Situated in climatic zone Cfb according to the Köppen–Geiger classification, the Netherlands experiences a temperate climate characterised by evenly distributed precipitation throughout the year and moderate summers.

The neighbourhood consists of 3,632 multi-family houses of on average 93 m^2 gross floor area, and accommodates 1,245 company registrations (CBS, 2022). Non-residential functions include restaurants, cafes, retail, offices, and four large supermarkets. The majority of the buildings were constructed between 1920 and 1940, with 83 % of the residences possessing an energy label C or lower. This study focusses on the predicted energy use of the neighbourhood in 2025, and assumes minimal to no building renovations within this time frame. In the upcoming years, the municipality of Amsterdam is planning to introduce a DHN within the Westindische Buurt (Gemeente Amsterdam, 2023).

2.2. Step 2: Energy profile of the neighbourhood

To minimise the need for external heat or cold, the exchange of heat and cold between the different building functions within the neighbourhood should be maximised. To define to what extent the energy system can rely on this exchange, the thermal energy balance of the neighbourhood shall be defined initially. This thermal energy balance illustrates the monthly and annual heat and cold demands, with space heating and domestic hot water (DHW) collectively represented as positive values on the vertical axis and cooling demands as negative values.

A positive disbalance between heat and cold demands requires the connection of alternative heat sources to the energy system, such as residual heat from a VF. Seasonal energy storage should be considered to address seasonal mismatches between heat and cold demands. Moreover, heating and cooling demands were defined for the warmest and coldest day of the year: January 18th and July 24th, averaging 2.3 °C and 22.3 °C respectively (mean value over 24 h) between 2012 and 2022 (KNMI, 2023). Additionally, monthly electricity usage is defined for January 18th and July 24th.

Assuming no significant renovations by 2025, buildings will maintain their current energy performance, relying on natural gas for heating. Data on natural gas and electricity usage in the Westindische Buurt were collected from national statistics CBS (2021a;b) and Klimaatmonitor (2023) for the year 2022. Monthly and daily gas and electricity use profiles were generated using MMFBAS (2023), providing hourly gas and electricity use profiles for various user profiles. Cooling demands were estimated due to a lack of reliable data of electricity for cooling purposes. This study also includes for neighbourhood electric vehicle charging and user-related electricity. Appendix A provides further details on data collection and the conversion into monthly and hourly profiles for heating, cooling, and electricity usage.

2.3. Step 3: Energy profile of the vertical farm

This study builds upon the authors' previous work, which delved into the potential integration of VFs with the energy and resource systems of buildings (Blom et al., 2023). Further details regarding the VF, such as climate setpoints, and the cooling and dehumidification systems, can be found in this previous publication. In summary, the study focusses on a closed-box VF that produces butterhead lettuce with a Photosynthetic Photon Flux Density (PPFD) of 200 μmol m^{-2} s^{-1} and a 16-hour photoperiod. A closed-box VF is characterised by highly insulation and airtightness.

In this study, the VF conditions are maintained using one heat pump (HP1) and two air-to-water heat exchangers (HE1 and HE2) to cool and dehumidify the VF air (Fig. 2). HE1 cools the air below dew point temperature, while HE2 re-heats the air to the desired return temperature using the evaporator and condenser of HP1. Excess heat generated by the condenser is removed via HE3, and supplied to the DHN.

The LEDs used in this study have a molar efficacy of 3.5 μmol J^{-1} (Weidner et al., 2021), and approximately 90 % of their electricity usage results in both sensible and latent heat consistently throughout the year. Differing from the approach in Blom et al. (2023), this study accounts for heat production during both light and dark periods.

Throughout the 16-hour photoperiod, the exhaust air from the VF entering HE1 has a temperature of 26 °C and a 72 % relative humidity. The return air provided by HE2 is 24 °C with 76 % RH. During the dark period, the temperatures decrease by between 1-2 °C, and the relative humidity increases by 10 %, with no sensible heat production as the LEDs are turned off. The latent heat demand at 23 °C is estimated to be approximately 32.8 W m^{-2} (Graamans et al., 2021), assuming a constant air flow rate during both dark and light periods.

The total cultivation area of VF to obtain thermal energy balance within Westindische Buurt (step 2) will be determined in this study. The exact dimensions and the location of the VF remain unknown at this stage due to the wide range of approaches for food production in VFs, including number of growth layers, cultivation height, and level of automation. Consequently, it is presently impossible to define a typical VF layout (Blom et al., 2022). Therefore, electrical inputs and heat outputs are specified per m^2 of cultivation area, representing one m^2 of a growth layer in the VF.

2.4. Step 4: District heat network configurations

The energy system configurations considered in this study can be categorised as centralised and decentralised. Centralised systems use a central HP to obtain the desired temperature levels for heating and/or cooling, and distribution is done via DHNs and individual heat exchangers in each building. This eliminates the need for individual HPs in each building, which is beneficial for small apartments (Jansen et al., 2021b). In contrast, the decentralised configuration employs individual HPs in each building within the neighbourhood to adjust the temperatures of the DHN. DHN configurations can have 2, 3, or 4 pipes, with three-pipe DHNs being significantly more expensive and hydraulically complex (Jansen et al., 2021b). In this research, temperature levels are defined as cold when ranging from 5 °C to 15 °C, ultra-low-temperature (uLT) when between 15 °C and 30 °C, low-temperature (LT) when from 30 °C to 55 °C, mid-temperature when from 55 °C to 75 °C, and above 75 °C as high-temperature.

Aquifer thermal energy storage (ATES) will be implemented in all configurations to maximise the exchange of heat and cold among various building functions. The Netherlands exhibits a high potential for ATES systems (Bloemendal et al., 2018). The warm and cold aquifer temperatures for heat storage and cold storage were set at 24 °C and 7 °C, respectively. The ATES system is connected to a DHN using an 80 % efficient water-to-water heat exchanger, determining the DHN temperatures (Appendix B.1). The amount of thermal energy extracted and stored from the aquifers should be balanced annually to prevent exhaustion (Bloemendal et al., 2018).

2.5. Step 5: Energetic performance of the DHN configurations

The designed energy system configurations were assessed on six criteria:

(1) The cultivation area of the VF: the cultivation area required to meet the heat demands of the neighbourhood under both centralised and decentralised configurations. The cultivation area is affected by several factors:

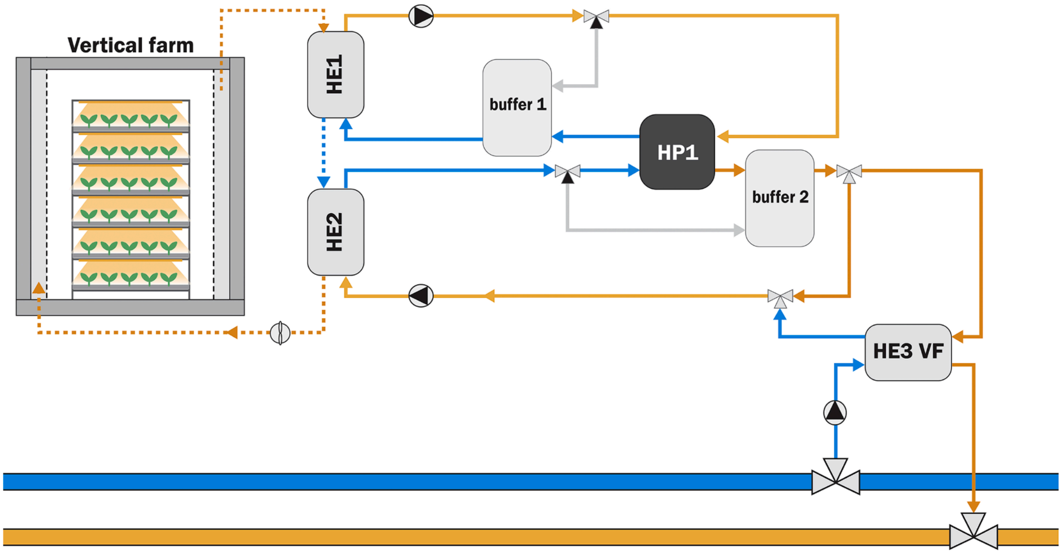

Fig. 2. The cooling and dehumidification system of the VF, using one heat pump (HP1) and three heat exchangers (HE1, HE2, HE3).

   a. The heating and cooling demands of the neighbourhood, which are the same for both configurations.
   b. Heat losses in the DHN. Modern DHNs experience heat losses ranging from 15 % to 20 % (Energy Transition Model, 2023), which were estimated at 15 % in this research.
   c. Heat from cooling processes. A share of the heating demands will be provided by the heat generated from cooling processes within the neighbourhood.
   d. Heat from compressors. The compressors of both the centralised and decentralised HPs will produce an additional quantity of heat beyond what is supplied to the HP. The heat produced by these HPs is the sum of the heat supplied via the DHN and the electrical input of the HP.

      The preference for a smaller cultivation area arises from the challenge to spatially integrate sufficient vertical farm cultivation area to meet the heating demands of the Westindische Buurt.

(2) The ability to balance the ATES aquifers annually to prevent exhaustion (Section 2.4).
(3) The quantity of thermal energy stored within these aquifers.
(4) The total annual electricity use of the configuration, including electricity use of the neighbourhood (user-related electricity and electric vehicle charging), the VF (LEDs, HP, fans, and pumps), and the energy systems themselves. The latter includes the energy used to produce mid-temperature heat for space heating and DHW using centralised or decentralised HPs (1), to produce space and product cooling (2), and to pump energy through the DHN (3) and ATES system (4). The calculation methods for these four components are described in Appendix C. The electricity used to distribute heat or cold within the buildings is excluded.
(5) Spatial requirements for energy systems within buildings. Buffer tanks for DHW storage in residences are not required when using mid-temperature DHNs, but are needed for buildings connected to (u)LT DHNs. For each apartment, these buffer tanks have an approximate volume of 0.14 m^3 alongside individual HPs of 0.25 m^3 (Meerkerk, 2022).
(6) Future readiness, using the following considerations.
   a. (u)LT DHNs are better suited to connect other sustainable heat sources. The number of (u)LT heat sources in the built environment are also more readily available than mid-temperature heat sources (Meerkerk, 2022).
   b. (u)LT DHNs are capable of direct delivery of passive or high-efficient cooling, whilst cooling demand will increase in the future due to climate change.
   c. (u)LT DHNs allow for future building renovations that lower heating temperature requirements. When using individual HP systems, these temperature levels can be attuned to the individual requirements without affecting the other households.

2.6. *Step 6: integration with the electricity grid*

Step 6 addresses the integration of VFs with the electricity grid, while maintaining the thermal energy balance. Two aspects are essential to enhance the electricity balance between supply and demand in the grid, to meet its transportation capacity, and to reduce costs for growers: minimising grid connections, and optimising production usage according to the hourly day-ahead electricity prices (Avgoustaki and Xydis, 2021).

Given that LEDs represent approximately 80 % of the VF's electricity use (Section 2.3), we focus on exploring alternative lighting concepts to minimise grid connections and to adapt to price fluctuations. The following sections explore the average hourly electricity prices in the Netherlands (Section 2.6.1), alternative operation concepts for LEDs (Section 2.6.2), and flexibility concepts for LEDs (Section 2.6.3).

2.6.1. *Average hourly electricity price profile*

Since 2015, the Dutch electricity prices have been determined one day-ahead at the European Power Exchange (EPEX) market, i.e., the day-ahead market. These prices are established based on expected demands and supplies. Large electricity consumers (above 100 MWh) pay for their electricity consumption in accordance with these EPEX prices. The electricity prices drop significantly at times of high inflexible generation that meet low electricity demands.

Fig. 3 presents the average hourly day-ahead electricity price in the Netherlands for 2022 in euro per MWh. The graph indicates peak prices at 06:00 and 17:00. Due to the high penetration of solar energy during the day and low demands at night, the electricity prices are the lowest around noon and mid night.

2.6.2. *Alternative operation of LEDs*

In general, lettuce cultivation involves continuous light with a 16-hour photoperiod and a PPFD of 200 μmol m^{-2} s^{-1} (Blom et al., 2023), resulting in a daily light integral of 11.52 mol m^{-2} d^{-1}. The photoperiod typically aligns with working hours, operating between

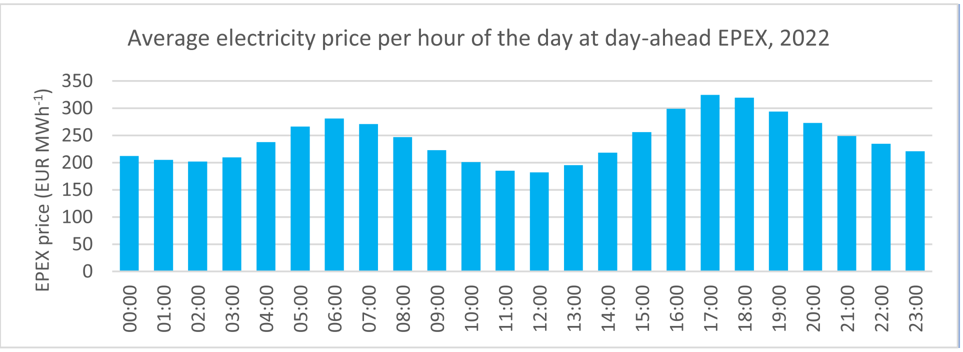

Fig. 3. Average electricity price per hour of the day for 2022 at day-ahead pricing by EPEX, the Netherlands (ENTSOE, 2023).

06:00 and 22:00 (Pimentel et al., 2023). This lighting schedule is referred to as the ‘baseline scenario’ in this study. Five alternative lighting concepts (Fig. 4) were considered to minimise grid connection and respond to the electricity price profile defined in Fig. 3. C-strategies refer to one continuous and uninterrupted photoperiod each day, while I-strategies involve multiple intermittent photoperiods. Each of these attempts aims to reduce lighting costs while sustaining plant yields (Arabzadeh et al., 2023).

Firstly, the operational hours of the baseline lighting strategy were adjusted, a concept referred to as ‘C16/8’. Secondly, considering lettuce’s tolerance for constant 24-hours lighting (Velez-Ramirez et al., 2011), a strategy involving continuous 24-h light (C24/0) was considered. In this approach, a PPFD of 133 µmol m^{-2} s^{-1} was used to maintain the daily light integral at 11.52 mol^{-2} d^{-1}.

Besides continuous lighting, intermittent light periods can be provided to lettuce crops. Chen and Yang (2018) conducted experiments comparing lettuce growth under a continuous 16-h photoperiod to intermittent lighting concepts while maintaining the daily light integral. Their findings indicate that lettuce fresh weights could increase by 111 % to 118 % when adopting intermittent lighting, compared to the C16/8 concept, without increasing overall energy consumption. The intermittent light concepts had a total photoperiod of 16-h and a PPFD of 200 µmol m^{-2} s^{-1}. These concepts included two cycles of 8 h of light and 4 h of darkness (I8/4), four cycles of 4 h of light and 2 h of dark ness (I4/2), and six cycles of 3 h of light and 1 h of darkness (I3/1). The increased yield when using I8/4 over C16/8 was also observed by Kondrateva et al. (2021), and Chen and Yang (2018) noted improved taste in terms of crispness and sweetness.

2.6.3. Flexible operation of LEDs

The actual day-ahead electricity prices will differ from that of the average day as depicted in Fig. 3. To avoid high electricity costs, adapting the VF’s electricity consumption from its regular routine is essential (Arabzadeh et al., 2023). Consequently, we explored the potential to adjust LED schemes to real-time price fluctuations by varying light intensity. This concept involves exposing crops to bright light during periods with low electricity prices and dimming the light during peak price hours (Pimentel et al., 2023).

This approach is based on the idea that the PPFD received by the plants does not need to be uniform throughout the day, as long as the number of photons remain constant during the photoperiod. The experiment conducted by Bhuiyan and van Iersel (2021) indicated that PPFD fluctuations between 400 and 0 µmol s^{-1} m^{-2}, and 360 and 40 µmol s^{-1} m^{-2}, result in lettuce crops with fewer and smaller leaves compared to treatments with smaller variations. They concluded that lettuce tolerates fluctuating PPFDs as long as the differences are not too extreme. Building on this study, Pimentel et al. (2023) selected a PPFD that varied between 80 and 320 µmol s^{-1} m^{-2} stating that the growth conditions and lettuce yields were unaffected as long as the daily light integral remained constant throughout the photoperiod. Although, the effects of fluctuating light intensities on lettuce yields require study, PPFD variations in the range of 320 to 80 µmol s^{-1} m^{-2} were selected, ensuring a consistent daily light integral within each photoperiod. The cost savings resulting from these PPFD variations will be determined for January 18th and July 24th, 2022, using the hourly electricity prices (ENTSOE, 2023).

2.7. Step 7: Selecting the optimal configuration and calculating the energy savings

The evaluation of the two configurations will be based on the six criteria defined in step 5. In addition, the performance of the configurations for integrating the VF within the electricity grid will be assessed according to two specific criteria. First, the required grid connection for the VF related to the peak loads. Second, the annual electricity cost savings by selecting an alternative LED operation in comparison the baseline, and/or the daily cost savings by PPFD fluctuations using day-ahead electricity prices. Finally, the energy savings achieved by the

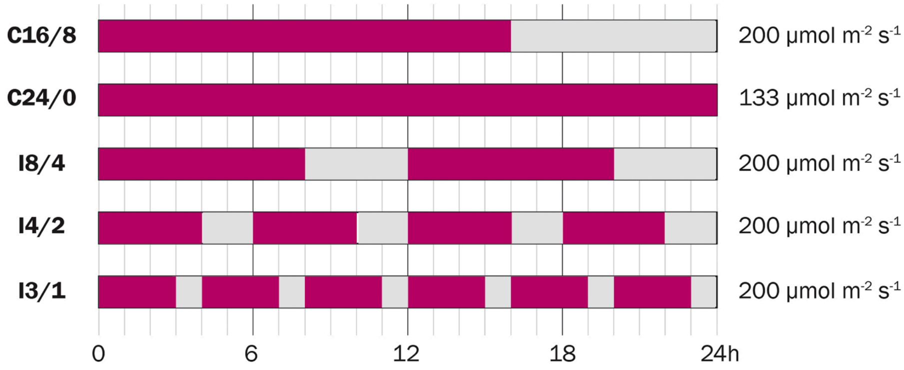

Fig. 4. Lighting concepts considered for VF integration.

selected configuration will be calculated in comparison to those of the current energy system.

3. Results

3.1. Step 1 to 3: Energy profiles of the neighbourhood and vertical farm

The total baseline energy use of the Westindische Buurt was 44,388 MWh y^{-1}, of which 76 % was natural gas used for DHW and space heating. The remaining 24 % was used for user-related energy, electric vehicle charging and cooling. The heating and DHW demands were 30,212 MWh$_{th}$ y^{-1}, and the cooling demands were 4,038 MWh$_{th}$ y^{-1}. Appendix D.1 presents more details on the daily heat, cold and electricity profiles of the Westindische Buurt. The thermal energy balance is presented in Fig. 5. The heat and cold demands indicated a significant disbalance of 26,129 MWh annually when exchanging heat and cold between the different building functions.

The VF used 434 kWh y^{-1} of electricity per m^2 cultivation area and produced 462 kWh m^{-2} y^{-1} of LT residual heat (Appendix D.2).

3.2. Step 4 and 5: District heat network configurations and energetic performance

3.2.1. Centralised: 4-pipe DHN with central heat pump

The centralised configuration (Fig. 6) makes use of a central HP (HP2) that upgrades the LT heat produced during the cooling of the VF (via HE3), buildings (via HE6) and supermarkets (via HP3) to mid-temperature heat. This mid-temperature heat is used for space heating and DHW applications (via HE5). The centralised HP2 is connected to a 4-pipe DHN, including cold, ultra-low, low, and mid-temperature levels. An ATES system is integrated via HE4 to address timing issues between heat and cold production and demand.

The energy system operates in ‘winter mode’ when the total heat produced (by HE3, HE6, and HP3) is insufficient to meet the heat demands and losses in the DHN. Therefore, additional heat is extracted from the warm aquifer during winter mode. Simultaneously, centralised HP2 generates more excess cold than used (by HE3, HE6, and HP3), which is then stored in the cold aquifer. Conversely, in ‘summer mode’ (Appendix D.3.1), when heat production exceeds heat demands, the surplus heat is stored in the warm aquifer. The cold produced by centralised HP2 is supplemented with cold extracted from the cold aquifer.

The total electricity use of the configuration amounted 44,738 MWh y^{-1} (Fig. 7). This total comprised 11,091 MWh for user-related electricity and electric vehicle charging, 18,385 MWh for the VF, and 15,262 MWh for the energy system. The central HP2 accounted for 31 % of the total electricity use, primarily due to its relatively low coefficient of performance (COP) ranging between 2.4 and 3.0.

To achieve thermal energy balance within the neighbourhood, the VF required a cultivation area of 42,385 m^2. The annual heat and cold balances are detailed in Appendix D.3.1 (Fig. D.4 and D.5). The compressor of the central HP2, the VF, and the cooling processes within the supermarkets and buildings fulfilled respectively 37 %, 52 % and 12 % of the heating demands. Due to the 4-pipe system, heat losses within the DHN were relatively high, contributing an additional 7,661 MWh to the building’s heat demand of 30,212 MWh. During winter, 7,701 MWh of heat was extracted from the ATES warm aquifer, while the same quantity of heat was stored again in the summer. This process was reversed for the cold aquifer.

3.2.2. Decentralised: 2-pipes DHN with decentralised heat pumps

The decentralised configuration (Fig. 8) uses a 2-pipe DHN with individual HPs to generate mid-temperature heat (HP4) from LT waste heat derived from cooling the VF (via HE3), supermarkets (via HP3), and the buildings (via HP4 in cooling mode). The DHN consist of one uLT and one cold pipe. Similar to the centralised system, an ATES system is integrated to overcome timing issues between heat and cold production and demand.

During winter mode, the amount of heat produced (by HE3, HP3, and HP4) is insufficient to meet the heat demands (HP4 and losses DHN). Consequently, heat is extracted from the warm aquifer. The surplus of cold produced by HP4 is stored in the cold aquifer during this mode. In summer mode (Appendix D.3.2), heat production exceeds the demands and is stored within the warm aquifer. The cold generated by decentralised HP4 is supplemented by cold extracted from the cold aquifer to meet cooling requirements.

The decentralised configuration used 39,702 MWh annually (Fig. 9). Again, 11,091 MWh was allocated to user-related electricity and electric vehicle charging. To achieve thermal energy balance in the neighbourhood, a VF with a cultivation area of 38,547 m^2 was required, consuming 16,720 MWh y^{-1}. The energy systems used 11,891 MWh y^{-1}.

The individual HPs for building heating exhibited COPs ranging between 2.6 and 3.8 throughout the year, contributing to 27 % of the configuration’s electricity use. These decentralised HPs generated 32 % of the total annual heat demands of 30,212 MWh y^{-1}. The cooling processes of the VF and neighbourhood provided the remaining 54 % and 14 % of the annual heat demands, respectively. Losses within the 2-pipe DHN represented 15 % of these heat demands.

To balance the DHN seasonally, 7,390 MWh was extracted from the ATES hot source in winter, with the same quantity being stored in summer. The cold source operated inversely. The heat and cold balances are presented in Appendix D.3.2 (Figs. D.7 and D.8).

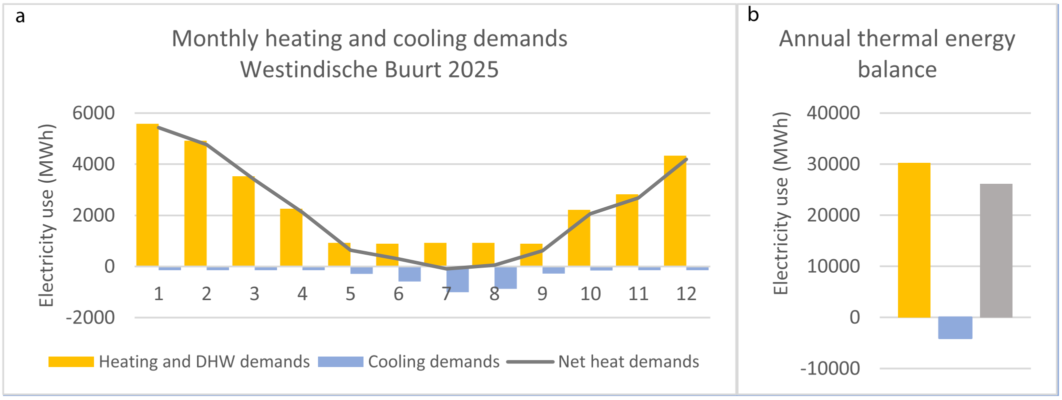

Fig. 5. a (left): Monthly heating and cooling demands of the Westindische Buurt in 2023.
Fig. 5b (right): Annual thermal energy balance of the Westindische Buurt in 2023.

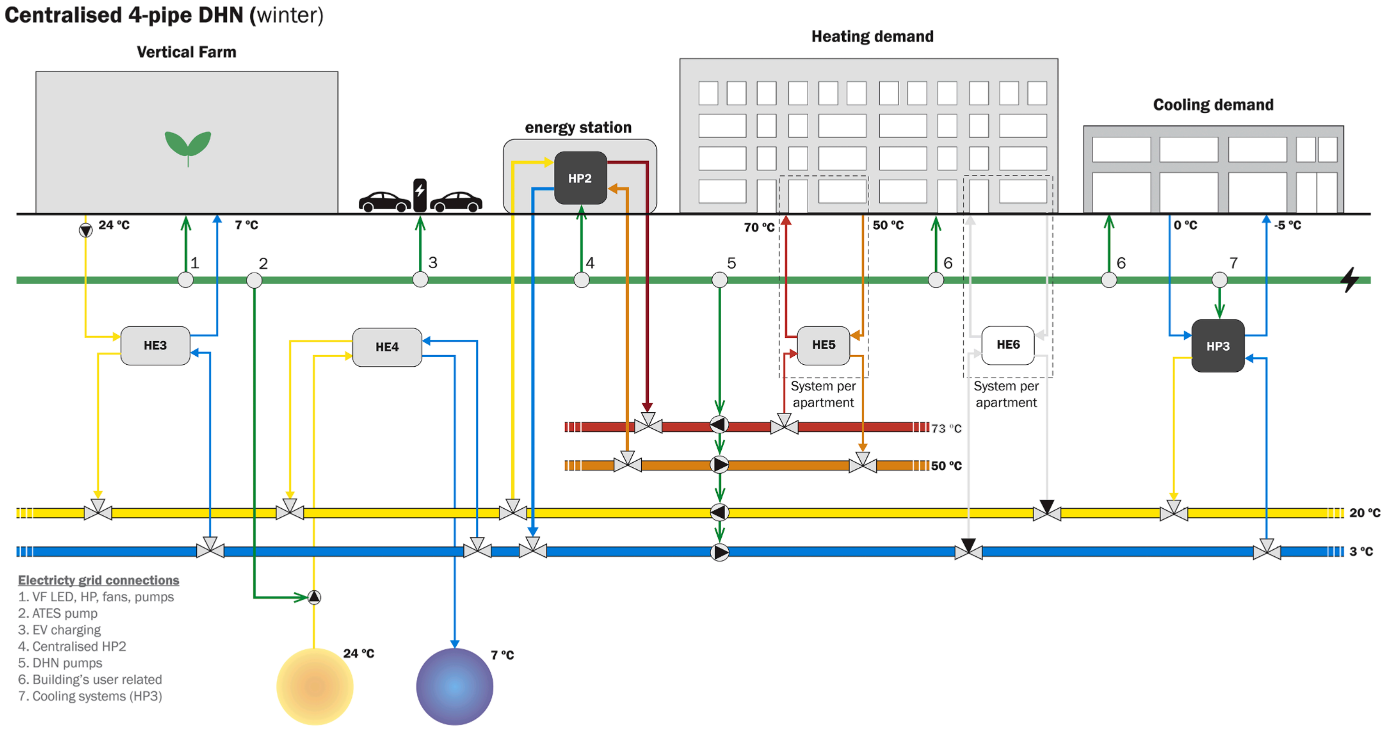

Fig. 6. Centralised energy system configuration with 4-pipe DHN in winter mode.

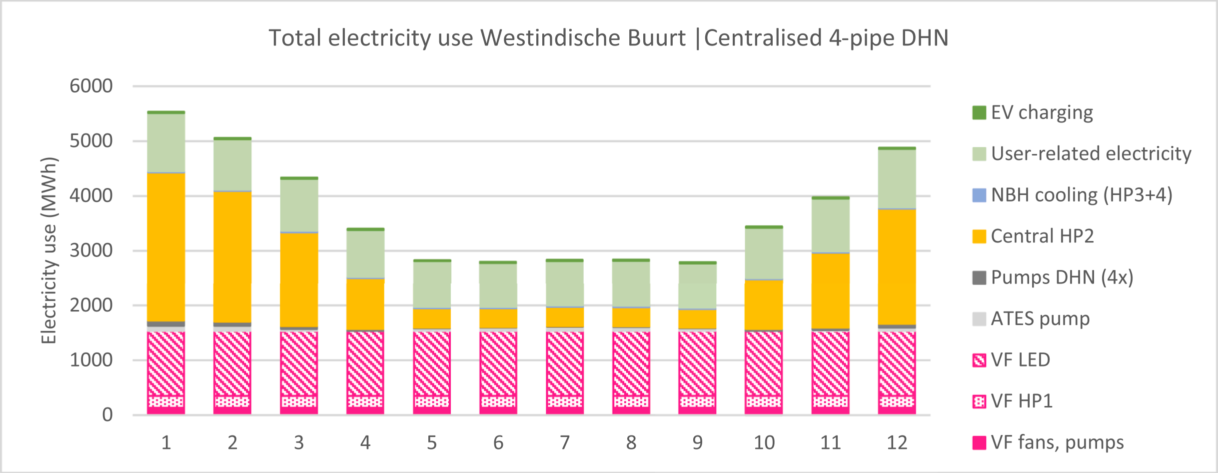

Fig. 7. Annual electricity use of the Westindische Buurt with integrated VF using the centralised 4-pipe DHN configuration.

3.3. *Step 6: Integration with the electricity grid*

3.3.1. *Grid connection*

Given that 80 % of the VF's electricity use was attributed to LEDs, their optimisation offers the highest potential to reduce peak loads and subsequent grid connection in both the centralised and decentralised systems. The LEDs generated a peak load of 57.1 W m^{-2} when using the baseline profile or alternative strategies C16/8, I8/4, I4/2, and I3/1. A reduction of 33 % was achieved by using 24-h continuous light (C24/0), or by segmenting the VF in three modules with non-overlapping dark periods. The latter approach was applied to concepts C16/8, I8/4, and I4/2, referred to as '3x'. Fig. 10 illustrates the segmented VF concept for C16/8(3x).

3.3.2. *Alternative operation of LEDs*

The annual electricity costs of the baseline scenario, operating the VF lights from 06:00 to 22:00, was 83.8 EUR per m^2 of cultivation area in 2022. Each of the five lighting concepts (Fig. 4) were optimised for reduced electricity costs based on the hourly electricity prices in 2022 (ENTSOE, 2023). Table 1 presents the peak loads and annual costs per m^2 cultivation area for each lighting concept.

In comparison to the baseline scenario (C16/8 06:00-22:00), alternatives C16/8, C24/0, I8/4, and I4/2 reduced the electricty costs by 11 %, 4 %, 14 %, and 5 % respectively when using the operational hours as presented in Fig. 11. Alternatives C16/8(3x), I8/4(3x), and I4/2(3x) demonstrated similar performance to C24/0. Profile I3/1 increased the electricity costs by 7 %. Operating the LED lights from 04.00 to 08.00 and from 16.00 to 20.00 (I8/4) resulted in the lowest annual electricity costs of 73.3 EUR m^{-2} for 2022.

3.3.3. *Flexible operation of the LEDs*

Hourly variations of light intensities between 80 and 320 μmol m^{-2}

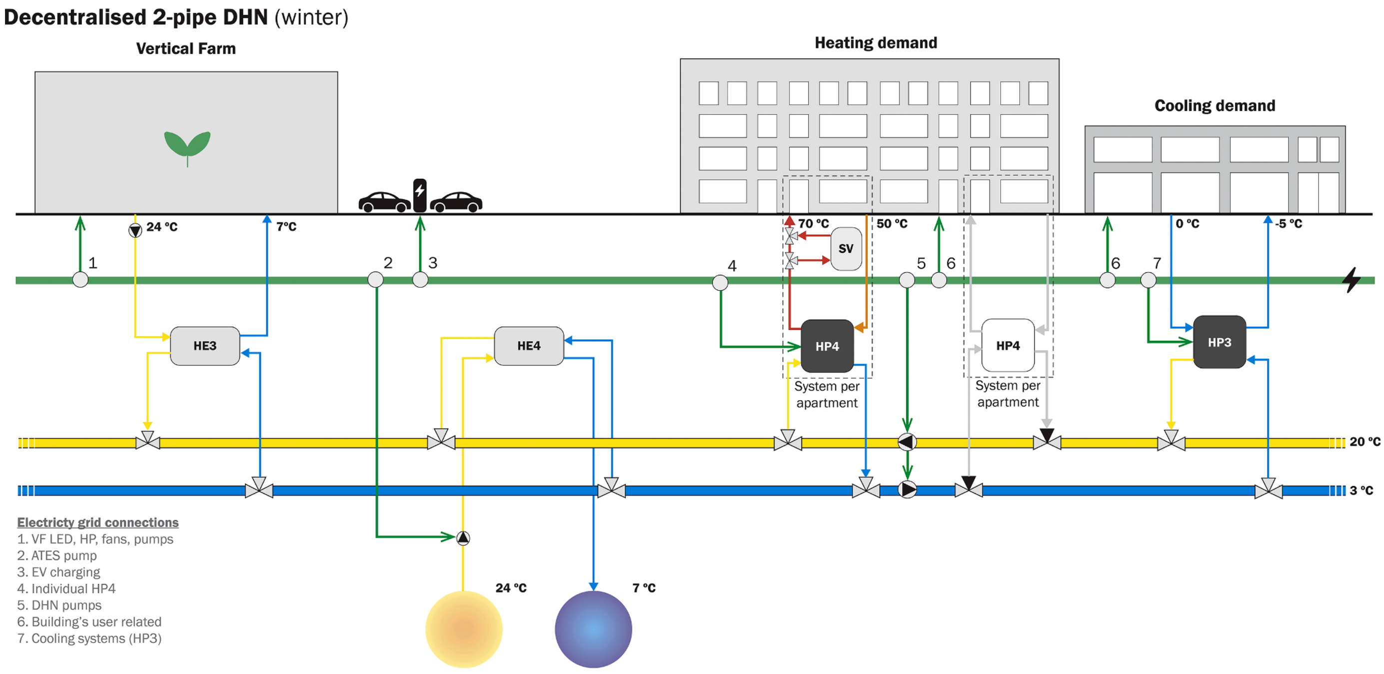

Fig. 8. Decentralised energy system configuration with 2-pipe DHN in winter mode.

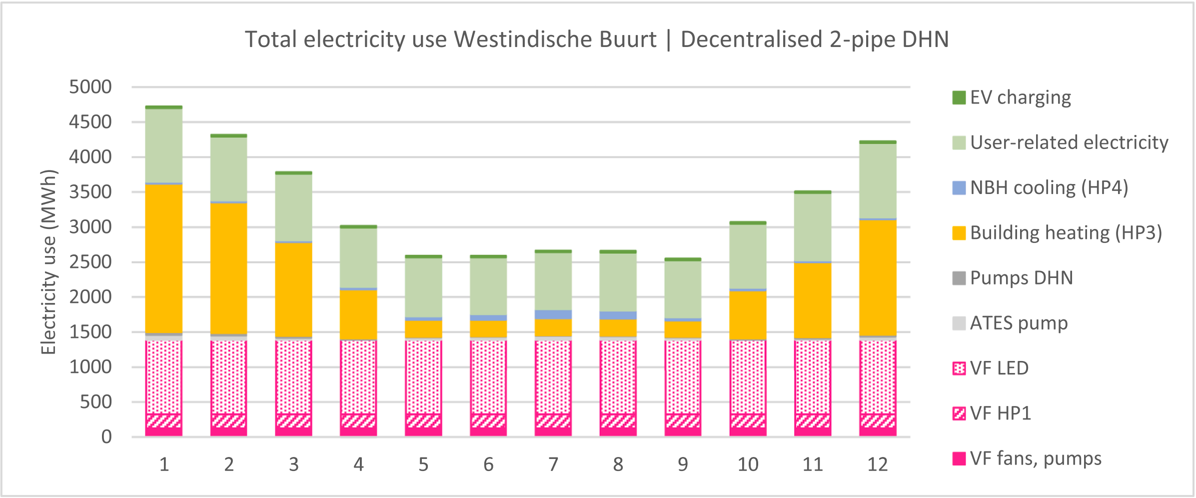

Fig. 9. Annual electricity use of the Westindische Buurt with integrated VF using the decentralised 2-pipes DHN configuration.

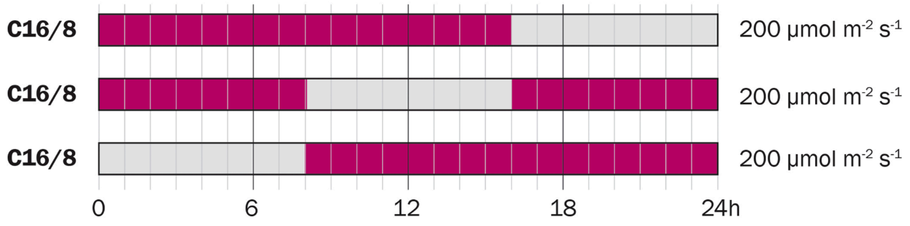

Fig. 10. Lighting concept C16/8(3x) consisting of three segmented VF modules with non-overlapping dark periods.

Table 1
Peak loads and operation costs (for 2022) per lighting concept when in fixed operation per m^2 cultivation area of the VF.

		Base-line	C16/8	C24/0	I8/4	I4/2	I3/1	C16/8 (3x)	I8/4 (3x)	I4/2 (3x)
Peak loads	W m^{-2}	57.1	57.1	38.1	57.1	57.1	57.1	38.1	38.1	38.1
Annual costs	EUR m^{-2} y^{-1}	83.8	75.6	80.7	73.3	79.5	90.6	80.7	80.7	80.7

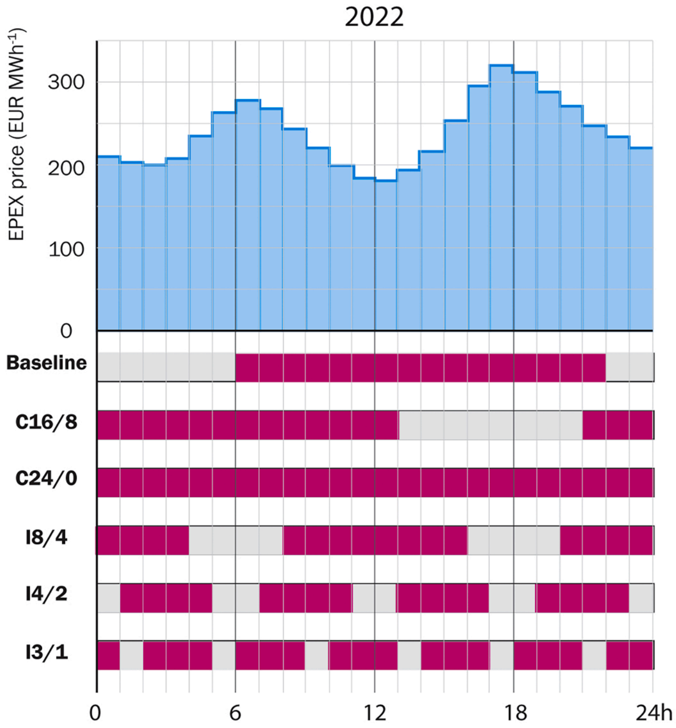

Fig. 11. The baseline profile, and the optimised operation periods of the five alternative lighting concepts in pink. The average hourly electricity prices in 2022 are presented in blue (ENTSOE, 2023).

s^{-1} were applied to alternatives I8/4 and C16/8(3x). The moles of incident light within each photoperiod remained the constant as in the non-flexible concept: 5.76 mol m^{-2} for each 8-h photoperiod in I8/4, and 11.52 mol m^{-2} for the 16-h photoperiod in C16/8(3x).

On January 18th, 2022, flexible operation of both I8/4 and C16/8 (3x) reduced cost by 11 % compared to the baseline. On July 24th, 2022, I8/4's flexible operation resulted in 3 % lower costs than for C16/8(3x), and reduced the electricity cost by 15 % in comparison to the baseline. Comparing flexible operation with standard operation in I8/4, cost savings were 4 % for the winter day, and 16 % for the summer day. Fig. 12a,b presents the hourly day-ahead electricity prices on the left axis (ENSTOE, 2023), and the PPFD for both standard and flexible operation of I8/4 on the right axis. The daily costs per m^2 cultivation area are presented in Table 2.

3.3.4. *Effects on thermal balance*

When employign the baseline LED operation (C16/8, 06:00–22:00), the ATES system effectively managed seasonal timing issues between heat and cold production and usage. Aquifer exhaustion was avoided as the heat and cold extracted and stored in the aquifers remained balanced throughout the year (see thermal balances in Appendix D.3).

In the alternative lighting strategy I8/4, whether in standard or in flexible operation, the total light energy provided to the crops remained constant throughout each photoperiod, ensuring consistent heat production. Hourly fluctuations in heat production were effectively covered by ATES system. For example, when the PPFD is reduced to 80 µmol s^{-1} m^{-2} for 4 h, heat production decreased. However, with daily light integral remaining constant, the subsequent 4 h use a PPFD of 320 µmol s^{-1} m^{-2}, compensating for heat production. In winter, this translates into a 4-hour increased heat extraction from the warm aquifer, followed by a 4-hour decrease. In summer, there is a 4-hour reduction in heat storage, which is compensated in the next 4 h. Consequently, flexible LED operation does not affect the annual thermal energy balance of the system.

3.4. *Step 7: Selecting optimal energy systems configuration and determine savings*

The optimal energy system configuration for integrating VFs within the urban DHNs and the electricity grid was selected based on eight criteria: VF cultivation area to achieve thermal energy balance (1), aquifer balancing capability (2), quantity of energy stored (3), annual energy use (4), spatial requirements within buildings for HPs, buffers, and HEs (5), future readiness (6), grid connection (7), and cost savings by LED operations (8).

As highlighted in Section 3.2, the decentralised configuration excelled in criteria 1, 3, and 4. Both configurations effectively managed to balance the aquifers year-round and obtained equal percentage cost-savings through alternative LED operations. The centralised system required less apartment space since no individual HPs and buffer tanks were needed. Concerning future readiness, both configurations allowed for the integration of (u)LT heat sources and passive or highly efficient cooling via the (u)LT DHN. However, the decentralised configuration offered greater flexibility in adjusting heating temperature during

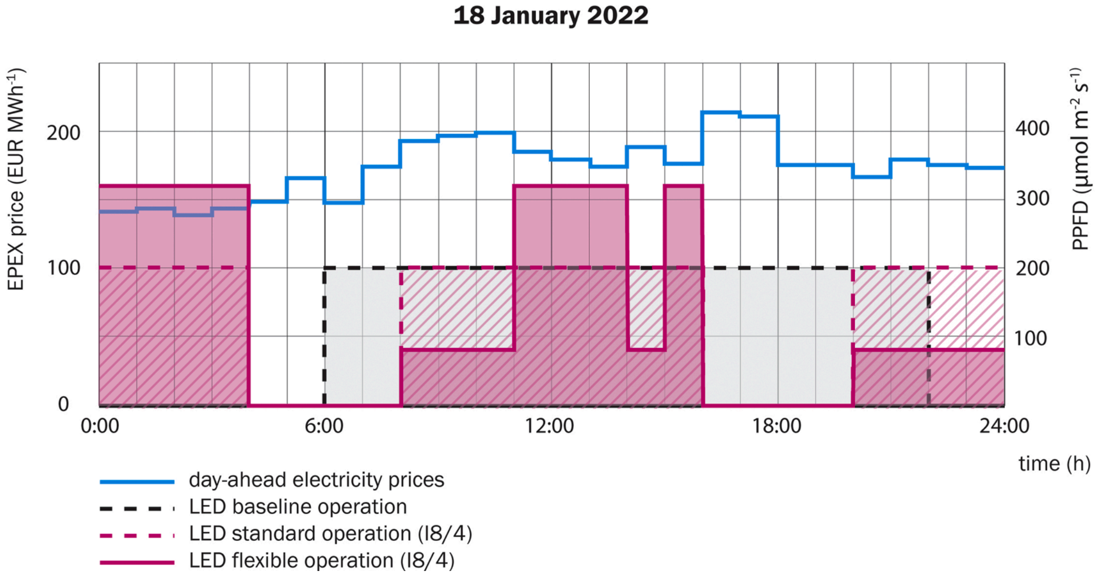

Fig. 12a. LED operation I8/4 standard versus flexible operation on January 18th, 2022.

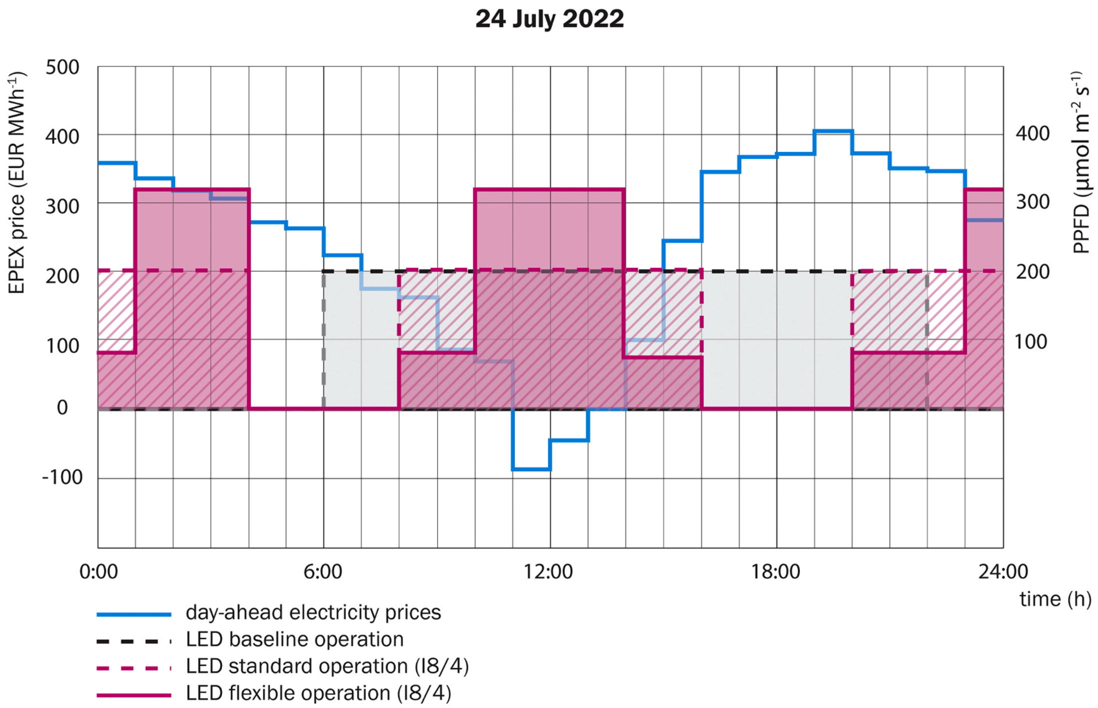

Fig. 12b. LED operation I8/4 standard versus flexible operation on July 24th, 2022.

Table 2
Cost flexible operation of the LEDs per m^2 cultivation area of the VF for two specific days in 2022.

		Baseline	I8/4	C16/8 (3x)	I8/4 (3x)
January 18th, 2022	EUR m^{-2} d^{-1}	0.173	0.154	0.163	0.154
July 24th, 2022	EUR m^{-2} d^{-1}	0.179	0.153	0.157	0.176

scattered building renovations.

The decentralised energy configuration was selected as the most optimal energy system for integrating VFs in the Westindische Buurt, reducing the energy use for heat, DHW, and cooling by 65 % compared to the current system based on natural gas. Even when accounting for VF electricity use, the energy savings reached 15 %, while simultaneously producing 3037 kg fresh weight lettuce annually (Blom et al., 2023). These findings are summarised in Table 3.

4. Discussion

The following section discusses the results in more detail and in relation to other studies, identifies research limitations, and makes suggestions for further research. Section 4.1 focusses on the integration of VFs within the neighbourhood to create thermal energy balance, and Section 4.2 on the integration of VFs with the electricity grid.

4.1. *Integration of VF with district heating*

4.1.1. *Centralised vs decentralised configuration*

Compared to the centralised configuration, the decentralised configuration use 11 % less energy, required a 9 % smaller cultivation area to obtain thermal energy balance, minimised aquifer thermal energy storage by 4 %, and enabled future-ready temperature control for the buildings. However, spatial integration, particular for apartments and small non-residential units, may be challenging due to the need for individual HPs and buffer tanks, and could lead to the choice of collective systems.

Table 3
Results per assessment criteria.

Assessment criteria	Unit	Centralised 4-pipe DHN + centralised HP	Decentralised 2-pipe DHN + decentralised HP
1. VF cultivation area	m^2	42,385	38,547
2. Annual aquifer balance	[-]	*yes*	*yes*
3. Q_{stored} hot/cold aquifers	MWh	7,701	7,390
$Q_{extracted}$ hot/cold aquifers	MWh	7,701	7,390
4. Annual energy use	MWh	44,738	39,702
	MWh	15,262	11,891
a. Energy systems configuration			
	MWh	18,385	16,720
b. Vertical farm			
	MWh	11,091	11,091
c. Neighbourhood			
5. Spatial requirements in building	[-]	+	-
6. Future readiness	[-]	-	+
7. Grid connection LED I8/4	kW	2422	2203
8. Annual savings by LED I8/4	%	14	14

These results align with Jansen et al. (2021b), concluding that the energy system is more efficient when the energy station (HP) is closer to the end-users, as temperatures can be matched precisely with the demands and distribution losses are minimised. The heat losses within each 2-pipes DHN were assumed to be 15 % (Section 2.5). In the 4-pipes DHN, 20 % of the total heat produced was lost, compared to 9 % in the 2-pipes configuration (Appendix D.3). The increased heat losses in the centralised system contributed to a larger cultivation area requirement to maintain thermal balance.

Both configurations reached annual equilibrium within the ATES aquifers. The Netherlands generally has a high potential for ATES systems (Bloemendal et al., 2018). Factors such as aquifer sizing, spatial well distancing, energy losses, and temperature variations during storage were not considered in this study. Approximately 23-24 kWh of thermal energy should be stored annually per square meter land of the Westindische Buurt. In a case study in Amstelveen, the Netherlands, an annual storage capacity of 40 kWh m^{-2} was planned (Bloemendal et al., 2018). Although more research is needed to determine the storage capacity in the Westindische Buurt, this comparison suggest it is feasible.

4.1.2. *Vertical farm size*

Significant cultivation areas of 42,385 m^2 and 38,547 m^2 were necessary to achieve thermal energy balance within the Westindische Buurt when utilising the centralised and decentralised configurations, respectively. This study did not address the spatial integration of these large VFs in the Westindische Buurt, as numerous factors influence the floor areas needed by VFs. These factors make it impossible to define a typical VF layout (Blom et al., 2022), e.g., growth method and the number and height of growth layers. Nevertheless, integrating such substantial cultivation areas poses a significant challenge. Even with multi-layer stacking, incorporating VFs in existing neighbourhoods will be difficult. Possible (combinations of) solutions include situating VFs on the outskirts of the city, spreading multiple small-scale VFs throughout the neighbourhood (e.g., building-integrated farms, Blom et al., 2023), utilising alternative (u)LT heat sources (e.g., PV-thermal, and heat extraction from water or ground sources), and building renovations to reduce heat demands. Further research is required to understand the spatial integration of VF in urban settings.

4.1.3. *Energy efficiency*

In the Westindische Buurt, gas boilers currently provide space heating and DHW, and air conditioning units are used for space cooling. Integrating VFs into this neighbourhood with the decentralised configuration resulted in a total energy saving of 15 % for heating, DHW, and cooling compared to the baseline system. This calculation includes energy used by the energy systems (individual HPs for heating and cooling, DHN pumps, and ATES pumps), and the VF (LED, HP, fans, and pumps). When excluding the energy use of the VF, savings increased to 64 % compared to the current system. The VF significantly affects the energy system efficiency, but also produces 3037 kg of lettuce annually. To fully assess the potential benefits of integrated VFs in urban energy systems, a carbon footprint assessment is needed. This assessment should compare the carbon footprint of a city with integrated VFs for heat and vegetable production with that of a baseline city relying on natural gas for heating and importing food.

Datacentre heat is an alternative LT residual heat source that is commonly studied. Similar to VFs, datacentres consistently generate heat throughout year (Li et al., 2021). Approximately 90 % (Oltmanns et al., 2020) to 97 % (Lu et al., 2011) of the electrical input of IT equipment in datacentres is converted into heat, compared to around 90 % of the electrical inputs of LEDs in VFs (Blom et al., 2023). The electrical input of IT equipment in datacentres accounts for 52 % (Nadjahi et al., 2018) to 75 % (Lu et al., 2011) of the total electricity use, while LEDs in the VF consume about 80 % of the electricity inputs (Blom et al., 2023). This suggests that VFs and datacentres exhibit similar efficiency in terms of residual heat production. However, there are distinctions; datacentres produce heat at 45 °C (Oltmanns et al. 2020) in contrast to the approximately 25 °C produced by VFs (Blom et al., 2023). Conversely, VFs offer the potential to adapt their operation based on the availability in the electricity grid, while datacentres necessiate non-flexible operation to ensure a secure and reliable environment for IT equipment (Nadjahi et al., 2018).

4.1.4. *Geographical location*

This study focussed on a case study in the Netherlands, characterised by a temperate climate and a high potential for ATES systems. The temperate climate results in relatively high heating demands, making it suitable for VFs to supply their residual heat. The integration of VFs and urban thermal energy systems will, however, offer little value for locations primarily characterised by cooling demands (Graamans, 2021; Blom et al., 2023). Furthermore, countries with ample heat demand but limited potential for ATES systems will require significantly larger cultivation areas. This is because the heat produced by the VF during the summer cannot be stored for usage in the winter, and is dissipated into the outdoor environment.

4.2. *Integration of VF with the electricity grid*

4.2.1. *Alternative lighting concepts*

This study presents a significant potential to reduce operational costs associated with artificial lighting in VFs. This potential lies within the adaptation of the lighting recipe to align with the annual average hourly electricity prices and, additionally, adjusting this profile to the day-ahead price fluctuations. These price fluctuations are a direct reflection of the availability of electricity in the grid. The alternative lighting concepts, therefore, enhance the system's flexibility, limiting the mismatch between electricity production and demand.

Five alternative lighting concepts were considered (Fig. 3), all of which existing studies have demonstrated no adverse effects on lettuce yields (Velez-Ramirez et al., 2011; Chen and Yang, 2018; Kondrateva et al., 2021). In this study, the intermittent light concept including two cycles of 8 h of light d 4 h of darkness (I8/4) achieved the highest annual cost savings of 14 % compared to the baseline concept with 16 h of continuous light when using Dutch hourly day-ahead electricity prices for 2022.

Avgoustaki and Xydis (2021) conducted a similar comparison between 16-hours of continuous light and an intermittent lighting concept for lettuce production. The intermittent concept involved three four-hours photoperiods during the cheapest electricity hours, within the remaining 12 h 10 min of light was provided during each hour of darkness. By employing this intermittent concept, annual costs were reduced by 16 % to 26 %. Although this VF was located in Denmark, its suggests that additional cost-savings might be obtained when considering more granular lighting concepts.

Additionally, this study explored potential cost savings by varying light intensities between 80 and 320 μmol s^{-1} m^{-2} while maintaining a constant daily light integral within each photoperiod. Operating I8/4 in this manner reduced the electricity costs by 11 % on January 18th, 2022, and 15 % on July 24th, 2022, compared to I8/4 with a constant PPFD of 200 μmol s^{-1} m^{-2}. The chosen light intensity range was based on preliminary findings of Bhuiyan and van Iersel (2021), suggesting that such variations would not adversely affect lettuce crop yields as long as the daily light integral remains constant within the photoperiod.

Pimentel et al. (2023) conducted a similar study on costs savings through light intensity fluctuations within the presented range for lettuce production in Hungary, using a baseline scenario identical to that of our study. Pimentel et al. (2023) obtained annual cost savings of 16 %, exceeding the daily savings obtained in this study. This difference may be explained by the focus on Hungary, which has another electricity price profile due its different electricity mix and climate conditions. However, Pimentel et al. (2023) concluded that further research is necessary to understand crop performance under changing photoperiods and alternating light intensities.

Further research is thus needed to explore alternative lighting concepts and the effects of varying light intensities on crop yields, aiming to determine the optimal balance between crop yields and annual electricity costs. These experiments should include various crop types, considering that each crop has specific light intensity and photoperiod requirements, allowing for a broader range of light intensity fluctuations. For instance, Arabzadeh et al. (2023) found that plants with shorter photoperiods achieve higher electricity cost savings due to their increased flexibility in avoiding peak prices. Furthermore, each crop has unique requirements for PPFD, photoperiod, temperature, and relative humidity, which affects the quantity of residual heat produced by the VF.

4.2.2. Additional flexibility

To address structural capacity issues in the electricity grid through flexible consumption, a range of users and suppliers should participate (Steman et al., 2021). Load shifting according to the day-ahead hourly electricity prices should thus extend beyond the VF. In winter, the HPs producing mid-temperature heat represent a significant share of the total electricity use. For instance, on January 18th, these HPs represented between 39 % and 89 % of the hourly peak loads in the centralised configuration, and between 35 % and 87 % in the decentralised configuration. Flexible operation of these HPs, in addition to the VF, in response to the day-head electricity prices would enhance grid stability even further and results in cost savings for energy consumption.

One way this can be achieved is by using thermal inertia of buildings for short-term flexibility, under the condition that the indoor comfort is maintained (Vandermeulen et al., 2018). This can be achieved by temporarily overheating and underheating buildings, with room temperature variations limited to ±0.5 °C (Kensby et al.,2015) and ±2 °C (Dreau and Heiselberg, 2016). In this way, short-term distributed storage divided over all buildings connected to the DHN is created (Romanchenko et al., 2018). Hong et al. (2023) shifted HP usage for heating of existing houses in the UK by one to two hours without causing discomfort. Employing these strategies allows for the adjustment of HP operation times, enhancing flexibility during periods of grid congestion or low renewable energy production (Hong et al., 2023; Bos et al., 2022). The use of thermal inertia presents a significant potential to gain flexibility and is cost effective, however, it requires collaboration with the end-users (Kensby et al., 2015; Dreau and Heiselberg, 2016). Future research should quantify the additional flexibility potential and cost savings associated with the use of thermal inertia in both DHN configurations.

In 2025, 10 percent of the vehicles in the Westindische Buurt are projected to be electric (Refa et al., 2019). The city of Amsterdam set the ambitious goal of complete electrification of all vehicles in Amsterdam by 2030. Consequently, the total annual electricity use of the Westindische Buurt will increase with 6 % in the decentralised scenario. This growth could lead to severe peak loads if not attuned with the capacity of the electricity grids. To address this challenge, electric vehicles could be used as batteries to store excess electricity during periods of low prices and subsequently release this stored energy during times of scarcity, providing additional flexibility to the grid.

5. Conclusion

This study demostrates that VFs can establish year-round thermal energy balance within the district heat networks of neighbourhoods, whilst concurrently offering flexibility to the electricity grid through adaptive LED operation. Two configurations were designed for the Westindische buurt in the Netherlands that enabled the exchange of residual heat and cold between the buildings and the VF: a 4-pipes DHN with a centralised HP, and a 2-pipes DHN with decentralised HPs. Both configurations included ATES to address timing issues between heat and cold supplies and demands. The decentralised configuration proved to be most effective in terms of VF size, energy storage requirements, and overall energy usage. Furthermore, it enabled individual temperature control to allow for future building renovations. However, spatial integration of individual HPs and required buffer tanks may pose challenges at building level.

In comparison to the baseline systems using natural gas systems for heating and DHW, and air-conditioning for cooling, the decentralised configuration achieved a 15 % reduction in energy consumption when including for VF energy usage. A substantial cultivation area of 38,547 m^2 was needed to produce sufficient heat for thermal energy balance. The integration of such area within existing neighbourhood might pose a significant challenge. The cultivation area could be reduced through the inclusion of alternative LT heat sources, e.g., PV-thermal and surface water heat, and through building renovations. The spatial integration of VFs, whether placed on the outskirts of the city or scattered small-scale farms within the city, requires further study.

Due to the substantial cultivation area of the VF, a significant electricity load is added to the neighbourhood. When excluding the VF's energy usage and considering only the energy systems of the decentralised configuration, the total savings increased to 64 % compared to the baseline system. This suggests that VFs produce heat inefficiently, however, the ratio between electricity input and LT heat production is comparable to that of datacentres. Additionally, VFs can provide flexibility to the electricity grid, minimising additional loads by attuning its lighting schedules in response to the day-ahead electricity price fluctuations. Implementing intermittent lighting in two cycles of 8 h of light, followed by 4 h of darkness, reduced the electricity cost for lighting by 14 % in 2022. Further savings could be achieved by varying light intensities between 80 and 320 μmol s^{-1} m^{-2} while maintaining a consistent daily light integral. Although further research is needed to explore the impacts of alternative lighting concepts and the impacts of varying light intensities on the crop yields, the findings indicate the potential of adaptive LED operation to reduce operational costs for VFs. This is of significant importance given the high electricity prices that limit VF scalability (Sørensen et al., 2016). In near future, flexible operation of LEDs will become even more important as the growing share of renewables in the grid will increase electricity cost fluctuations.

In conclusion, the integration of VFs into energy systems can balance DHNs with residual heat from the farm. Although this requires a substantial VF cultivation area, resulting in significant electricity loads, the use of dynamic LED operation in response to day-ahead electricity pricing can minimise these peaks and enhance stability in the electricity grid. Through these contributions, VFs can play a valuable role within the ongoing energy transition, while simultaneously providing fresh vegetables for the city.

CRediT authorship contribution statement

T. (Tess) Blom: Conceptualization, Data curation, Methodology, Resources, Visualization, Writing – original draft. **A. (Andrew) Jenkins:** Conceptualization, Supervision, Writing – review & editing. **A.A.J.F. (Andy) van den Dobbelsteen:** Conceptualization, Supervision, Writing – review & editing.

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.

Data availability

The datasets presented in this study can be found at: https://doi.org/10.4121/8b67deea-aa93-4284-adda-464cc285f45b.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.105267.

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