DESIGN AND METABOLIC FLUX ANALYSIS OF WASTE-HEAT RECOVERY FROM DATACENTRES FOR CITY PROGRAMS

A research paper on the potential of heating indoor pools and other programs with waste heat from datacentres.

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ABSTRACT

This paper investigates the possibility of creating a synergy between future industries and urban programs, with the goal of restoring the relationship between the West-Port and Amsterdam, decreasing overall energy consumption and raising awareness of the spatial effect of our own energy consumption. The method used is a metabolic flux analysis with a focus on energy flows in the form of heat. The chosen programs for analysis are three datacentre models of various sizes and a 2500m² indoor swimming pool. The research showed that by recovering heat from a datacentre the size of Equinix AM3-4, 2200 indoor swimming pools with an area of 2500m² can be heated all year round. A liquid cooled datacentre with a PUE of 1,15 has the possibility to recover almost 60% of the total energy consumption. Furthermore, by placing the two programs in the same building volume, the heat recovery potential is increased. Based on the results, it is advocated to physically connect heat-consuming programs to heat-producing programs to maximize energy recovery.

KEYWORDS:

Metabolic flux analysis, Datacentre, Indoor swimming pool, Heat-recovery, Energy flows, Heating-network

I. INTRODUCTION

Population growth, urbanization and climate change put high pressure on city development. The transformation to a sustainable and circular city requires space for new industries. Electrolysers, 3D printers, urban farming storage, bio-energy plants all take up space, space that is very valuable for a growing city like Amsterdam. The West-Port of Amsterdam is an area which is currently undergoing this transformation, and offers the infrastructure (previously or still used by unsustainable industries) that could be used and adopted by a new generation of city-supporting industries. Connection to the heating network, transportation facilities, close proximity to city and surface water, underground pipelines to Schiphol, connections to power outlets, but also hundreds of silos that currently store petroleum.

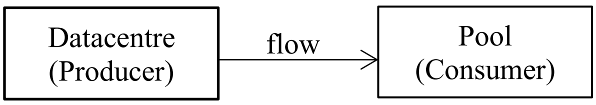
These industrial areas offer great possibilities for the development of for instance an energy hub. However, these areas are considered a burden for city developers, who would rather push the industry further away from the city (IJmuiden) and use this area for city expansion. Over the years, the character of industrial areas has grown further apart from the character and program of the city. The effect of this development on the one side is; the freedom for industries to grow and produce with limited obstructions, on the other; the city and port are now separated areas which rely on each other but have conflicting interests. Since the future cities are depending on a large sustainable energy supply, ideally there will still be some kind of machine-room area in close proximity to the city to support it without creating a mono-functional dead-city area.

To conclude; future cities depend on sustainable industrial areas (energy hub), for which the current industrial areas offer the best infrastructure and location. The question remains; how can the city and industry work together in symbiosis? Therefore, I will investigate; ‘’*How can connection between flows* *of [emerging port industries] and [public city functions] increase sustainability and restore the relationship between port and city?''*

The sub questions that will be investigated to answer the research question are;

1) *What flows will be part of the energy hub in the West-Port of Amsterdam in 2050?*
2) *Which of these flows offer the possibility to be integrated in a public program which reconnects the city with the port?*
3) *How can these flows be linked to each other and the area in order to achieve a more sustainable urban environment?*
4) *What will be the impact?*
5) *How can these flows be integrated into an architectural design within the West Port of Amsterdam?*

In order to answer the research question, this research had to be split in two parts. The preliminary research had to be performed in order to answer the first two sub questions and results in a selection of programs which are used to answer sub question three to five. The preliminary research will be summarized in chapter II Method. Multiple candidate-programs were found. However, this research paper only addresses the two chosen programs; a datacentre representing the industrial energy (heat) producer and a public indoor swimming pool representing the city program and consumer. The resulting research question is; ''*How can connection between flows of a datacentre and public swimming pool increase sustainability and restore the relationship between port and city?''*



Our current lifestyle depends on the internet more than it has ever before and it causes the data centre sector to be one of the biggest and fastest growing industrial sectors (Allepuz, Martorell, Oró, & Salom, 2017) (Andersen, Clarke, Luo, Maroto-Valer, & Rajendra, 2019) (Bai & Ni, 2016) (Ruijs, 2019). The current COVID-19 pandemic has increased the activity of datacentres even more (Manganelli, Martirano, Ramakrishna, & Soldati, 2021). According to Andersen, Clarke, Luo, Maroto-Valer and Rajendra (2019) this sector accounts for 3% of the global electricity use and is responsible for 4% of total greenhouse gas emissions. Concerning is not only the energy consumption, but also the spatial demand of datacentres. The soon to be built Facebook datacentre in Zeewolde uses 166 hectares of land (Nu.nl, 2021). Therefore, there is reason to investigate possible ways to make datacentres more sustainable and raise awareness for the effect our lifestyle has on the environment.

II. METHOD

2.1. Preliminary research

First, large-scale qualitative research has been performed to find out what flows are available in the current context of the West-Port of Amsterdam, which flows have been there in the past and which will be there in the future. Literature studies on governmental and company websites and reports and technical reports form the basis of this research.

After identifying the current and future programs, they were compared based on:

1) Sustainable impact
2) Safety for the (urban) environment
3) Possibilities for connection to a public function
4) Possibility to generate energy for the city of Amsterdam.

The resulting tables can be found in appendix 8.1.

Multiple programs met the requirements, but a selection has been made of programs that use similar flows (heat and water) to increase potential for connections between systems. The resulting industrial programs were; datacentres, hydrogen electrolysis and storage and the aqua battery. Both datacentres and hydrogen electrolysis are part of the vision reports for the West-Port. The aqua battery is a relatively new invention, which uses brackish water and therefore connects directly to the context of the brackish Noordzeekanaal.

In order to connect the city and port, a public program was chosen which could be placed in the West-port and connected to one of the industrial programs. A public indoor swimming pool was chosen, because it has a public recreational function and uses both water and heat. Subsequently, the datacentre seemed the most suitable function to be connected, because the datacentre is a big heat producer and the pool has a large heat demand.

2.2. Research assignment

To answer the third sub question; '' *How can these flows be linked to each other and the area in order to achieve a more sustainable overall result?*'', flow diagrams of the individual programs can show the potential.

First a schematic diagram based on common knowledge and the previously gained information from the preliminary research is drawn. Secondly, the diagrams are adapted according to the gathered information from the interviews with experts. These diagrams were separated in water and energy flows. Further knowledge on the flows within the chosen programs is derived from a selection of reports; the research performed by Allepuz, Martorell, Óro and Salom (2017) investigated the possibilities for heat recovery between a datacentre and pool, and has thus been very relevant for this research paper. Also, the graduation project of Nora Mees; ''*Gas free Swimming Pools; A Review of Interventions and their Impact*'' (2019) is used as a guideline for the metabolic flux analysis of the indoor swimming pool. In her research she constructed a metabolic flux analysis for a pool model, based on various references, after which she added various sustainable interventions to it. For the datacentre, Equinix AM3-4 is used as a model as well as the datacentre which will be built in Zeewolde (Gemeente Zeewolde, sd). Both datacentres produce waste-heat recovery to heat a different program.

By comparing the inputs and outputs of the datacentre and pool MFA's, possibilities for connection between the flows are found. Furthermore, processes are slightly adjusted to make connection possible and reduce loss of heat within the system boundaries. A new MFA is drawn in which the two system boundaries are connected (appendix 8.3, Figure 6).

Quantitative research consists of calculating the flows, for which excel is used. These calculations are necessary to answer sub question 3; '*'What could be the impact?*''. Three datacentre models are used to calculate and compare possible heat recovery potential. Then the same calculations are applied to seven scenarios which are based on potential heat demands and the ambitions of realizing datacentres in the West Port. Various reports and articles are used to estimate the heat demand of the city of Amsterdam as a whole and the heat demand of Havenstad (adjacent residential development project). These calculations can be found in appendix 8.4.

In order to answer sub question 5; ''*How will these flows be integrated into an architectural design within the West Port of Amsterdam?*'' the influence of architectural design choices on the MFA diagram are reviewed. Finally, a reflection on the connection of flows between programs on the urban scale will be made.

Two interviews have been performed in order to gain more specific knowledge on the functioning of the four researched programs. These interviews have been performed online via Teams, due to the current pandemic situation.

- Ruud Stevens; employee at Vattenfall, about the transformation from coal plant to hydrogen electrolyser of the Hemwegcentrale
- Ramses Rodenburg; employee at info.nl (IT-company in Amsterdam), who is a customer and relatively frequent visitor of datacentres.

Attempts have been made for an interview with a designer or technical advisor who worked on the design of the Noorderparkbad in the North of Amsterdam. Unfortunately, no response was received.

III. RESEARCH

3.1. MFA separated programs

Datacentre:

The total energy consumption of a datacentre is used mostly by the IT-equipment and the cooling system. A relatively small part is used for the UPS (Uninterruptible Power Supply), PDU (Power Distribution Unit, auxiliary devices and other building functions. Because the main function of a datacentre is made possible by the IT, the efficiency is based on the percentage of energy consumed by the IT-equipment. This efficiency is indicated by the PUE-value (Power Usage Effectiveness);

$$\text{PUE} = \frac{\text{Total Facility Energy}}{\text{IT equipment energy}}$$

In theory the most efficient datacentre would have a PUE of 1, meaning all consumed energy is used by the IT-equipment. Equinix AM3-AM4, designed by Benthem and Crouwel architects in 2017 and located in the South-East of Amsterdam, has a PUE of 1,2 (Sanders, 2017). This datacentre provides recovered waste-heat for the adjacent University. The datacentre in Zeewolde will have a PUE-value of 1,15. The PUE can be influenced by the efficiency of the equipment, efficiency and type of cooling system, building design and surrounding climate. Most traditional datacentres have a CRAC-unit; Computer Room Air Conditioning, which is connected to a chiller and cooling tower. Large datacentre-companies are often more efficient; the use of one server type makes it possible to use liquid cooling which is 50% more efficient compared to air-cooled datacentres (Allepuz, Martorell, Oró, & Salom, 2017). This was confirmed by Rodenburg in the interview (full transcript can be found in appendix 8.8).

In order to calculate the potential for heat recovery, the energy consumption and produced heat for each process in the datacentre is drawn. Unfortunately, many diagrams for the energy flows in datacentres are dated (2016 or older) making them no longer representable for newer datacentres with much better energy performances. Therefore, a combination of articles is used to construct a three model-datacentres. The first is based on the research by Andersen et al. (2019), the second model is based on Equinix AM3-AM4 with a PUE of 1,2 and total capacity of 51,5 MW (DatacenterWorks, 2014) and the third model is based on the plans for the datacentre in Zeewolde from the company Meta (holder of Facebook), which has a PUE of 1,15. For all datacentre-models it was assumed they run 24 hours per day, 365 days per year.

Pool:

For the construction of the MFA pool model the model constructed by Mees (2019) is used, which can be found in appendix 8.2. This diagram reflects an average indoor swimming pool and as the diagram shows, the majority of the consumed energy is gas. In the research by Mees, several innovative techniques are presented to reduce the energy consumption of the pool, these are used in the final MFA-model.

3.2. Impact

Impact calculations are made with the goal of finding out the potential heat recovery of the model-datacentres Equinix, Zeewolde and the model introduced by Andersen et al. (2019). Thereafter, the heat demand of the model pool, Havenstad residential area, municipality ambitions and total demand of Amsterdam are used to calculate the necessary datacentres to provide this waste-heat. By comparing the consumed energy to the number of servers and white space of Equinix, an estimation is made on the resulting size of the model datacentre.

Datacentres produce most waste-heat in summer, when outdoor temperatures are higher, and in winter the waste-heat is limited caused by a free-cooling effect of the outdoor temperature (Manganelli, Martirano, Ramakrishna, & Soldati, 2021) (Ruijs, 2019) (Figure 1). The heat-demand of the city is the exact opposite; therefore, a heat-storage is necessary. Equinix AM3-AM4 uses an Aquifer Thermal Energy Storage (ATES), which consists of a ground-water hot and cold storage (DatacenterWorks, 2014) (Arts & Ning, 2016).

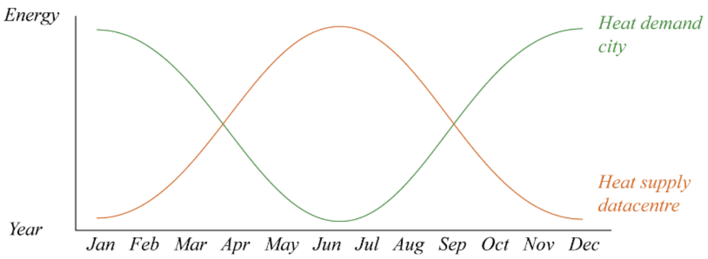


Figure 1 seasonal paradox datacentre waste-heat, elaborated from "Warmteprofiel" (Ruijs, 2019. p.34).

3.3. Integration in Architecture

The metabolic flux diagram can be used as a guideline for the program; the necessary installations, number of servers, estimated white space and total pool size can be derived from the MFA. Furthermore, the MFA can be used as guideline for the spatial layout of the program, in order to minimize transport of flows. However, most of the program was based on the interviews and reference studies of the Noorderparkbad (Cie Architecten, sd), Geusseltbad (Geusseltbad) and an article called; ‘’*Hoe werkt een datacentre*’’ published by the Dutch Datacentre Association (2020).

Additionally, during this research several design interventions were found in the refence projects and articles. These interventions cannot be retrieved from the MFA directly, as they do not represent a process. They could be considered passive climate design choices, which indirectly influence the flow diagram, for instance; sun-orientation and higher insulation values will influence the amount of heat loss from the pool. These interventions will be listed in chapter 4.

IV. RESULTS

4.1. MFA combined

Connecting the cooling system of a datacentre to the heat system of a pool made it possible to establish a relationship between the two system boundaries. The energy demand of the pool consists of a heat-demand and an electricity demand, only the heating-demand can be connected to the waste-heat-flow from the datacentre. The amount of heat exchangers can be limited due to the close proximity of datacentre and pool, therefore heat exchangers are only placed in the pool and the hot coolant exchanges its heat here with water. Similarly, the hot coolant can be transported to the ATES storage or another consumer and transfers the heat in the end. The now cooled down coolant is transported back to the datacentre where it can absorb the heat of the datacentre again. This is visualized in the metabolic flux analysis diagram in appendix 8.3.

4.2. Impact

Three models for the datacentre were calculated; A) the model presented in the study by Andersen et al., B) the model representing Equinix AM3-4 and C) the model representing the datacentre in Zeewolde. Based on the findings of Bai and Ni (2016), which showed up to 90% of the energy from IT-equipment can be recovered in heat, it is assumed that there is a 10% energy loss in the IT-equipment. This energy loss could be caused by the data transportation, heat loss over cables or transmissional losses from the equipment. The liquid cooling system which is traditionally applied to the IT-equipment only, is also applied to other functions in the datacentre. This way, waste-heat produced by these functions can also be recovered, increasing the total heat recovery potential drastically. The efficiency of this heat-recovery was estimated 70%, assuming it would be lower than the 90% efficiency of heat recovery for the IT-equipment.

Normal heat exchangers have a relatively low efficiency, therefore the use of them in transportation of heat should be limited. In the combined datacentre-pool model the use of heat exchangers could be reduced to one (for each heating function), due to the close proximity of the functions which makes it possible for the coolant of the datacentre to run to the pool and exchange its heat there to the water. In the calculation model the heat exchanger with an efficiency of 68% was therefore added. The resulting calculation model shows the amount of heat that can be recovered as well as a percentage of this heat recovery compared to the total input energy, see table 1.

	Heat recovery potential	**PUE**	**% E_{IT} (based on PUE)**	**Heat recovery IT**	**% $E_{other\ functions}$ (based on PUE)**	**Heat recovery other functions**	**Heat recovery Heat Exchanger Pool**	**Overall heat recovery efficiency**
		ratio	*%*	*%*	*%*	*%*	*%*	*%*
A	Model paper	1.8	56%	90%	44%	70%	68%	55.2%
B	Equinix AMS3	1.2	83%	90%	17%	70%	68%	58.9%
C	Zeewolde	1.15	87%	90%	13%	70%	68%	59.4%

Table 1 Heat recovery potential Datacentre Models A, B & C. (Own source).

The difference in outcomes of the overall heat recovery efficiency is due to the difference in the PUE and the difference in efficiency of heat exchange of the IT and the other functions. If the PUE is closer to 1, less energy is lost to cooling and other functions, the heat recovery potential increases. However, if the heat recovery from the 'other functions' had the same efficiency, the PUE and thus the efficiency of the datacentre itself would not influence its potential for heat recovery. The Zeewolde datacentre (model C) has a potential of 59,4% of heat recovery. If the heat recovery from other functions is neglected, this would be 6,2% lower, the difference is relatively small due to the low PUE. For model A, this difference was 21%.

The same calculation model is applied to seven scenarios in order to calculate the size of the datacentres required to produce this heat, outcomes are presented in table 2. The green column shows the area of white space for each datacentre. Figure 2 (appendix 8.6) is used to illustrate the dimensions of these imaginary datacentres compared to Equinix AM3-4.

	Demand scenarios	**Heat demand / Output heat**	**E_{total}**	**white space**	**Servers**
		MJ	*MJ*	*m^2*	*n*
1	*Pool by Mees (gas)*	4,475,250	7,530,784	53	581
2	*Pool by Mees (Heat Pump)*	389,147	654,842	5	51
3	*Maximum residential heat demand Amsterdam 2040*	15,818,400,000	26,618,612,818	188,199	2,053,076
4	*Minimum residential heat demand Amsterdam 2040*	13,082,270,148	22,014,355,678	155,646	1,697,952
5	*Havenstad heat demand 2040*	1,629,536,976	2,742,123,972	19,387	211,498
6	*Heat demand Havenstad + pool model (HP)*	1,629,926,123	2,742,778,814	19,392	211,549
7	*500MW datacentres ambition for west port*	9,370,305,391	15,768,000,000	128,205	1,398,601

Table 2 Demand scenarios (Own source).

4.3. Integration in Architecture

In the calculation model, energy loss in the form of heat at the point of heat exchange are included. These heat losses are caused by convectional heat losses (hot installations heat up the surrounding air in the building) or there is an energy loss as result of the transportation of data. For the IT-equipment is 10%, for other functions it is estimated at 30%. However, if the datacentre building is physically connected to a heat demanding program such as the indoor pool, any convectional heat losses are beneficial to the heating of the pool. The physical connection can be compared to the passive design strategy used in the Noorderparkbad by Cie architecten; buffer zones use natural traits of heat flow to their advantage.

1) Enclose the datacentre with the pool around it. The pool functions as a buffer to collect the heat-losses from the datacentre.
2) The datacentre can be built as a hot shell around the pool program to prevent heat losses from the pool.

Both strategies have their benefits and disadvantages; in the first strategy, the hot buffer zone around the datacentre prevents convectional heat losses which increases the cooling demand of the datacentre and possibly increases the energy consumption of the cooling system and thus the PUE. The second strategy risks heat-losses to the air which cannot be recovered for city heating and contribute to the urban-heat-island effect. The first strategy has a higher heat recovery potential, whereas the second one benefits the functioning of the datacentre.

The goal of this research is to recover as much of the input energy of the datacentre as possible and not simply to produce more heat. Therefore, making both the datacentre and the pool more sustainable is desirable. Interventions that were found to decrease the overall energy demand of both programs are listed in Table 3 (appendix 8.5).

4.5. Generic guidelines

To reduce energy consumption, avoiding the need for new datacentres is the best solution. However, if these datacentres are being built anyway, it is desirable to use all the consumed energy as effectively as possible. By using the waste-heat in a second program which is (physically) connected to it, most of the consumed energy can be recovered. ~~This principle could potentially be applied to any heat-producer and could be used as a guideline in sustainable city development. The heating network would then become a guiding infrastructure for the placement of new programs in the city and producers and consumers will no longer be separated spatially (in an industrial area).~~ *Small-scale decentralized datacentres as 'heating elements' in public buildings could become part of a microgrid heating network system spread out over the city. Datacentres would no longer be hosted by private companies and built as independent facilities, but become part of a larger city-organized heat exchange plan. These decentralized datacentres would be facilitated by the municipality. Figure 9 is a diagrammatic representation of this principle.* Programs which can be connected to datacentres are; greenhouses, bio energy plants, hospitals, office buildings, shopping malls, schools and libraries. If the heat demand fluctuates throughout the seasons a storage system is required.

For architects, this increases the importance for heat recovery of their designs, which can be achieved by installations, but also passive design choices. The buffer-zone strategy can be used to recover almost 100% of the produced heat. An example of a buffer zone strategy is applied to the design of the Noorderparkbad (Cie Architecten, sd) (Huang, Li, Li, & Nord, 2021).

Additionally, a new task for the architect is the merging of an industrial- with an urban program. Not only does this demand for technical design skills which improve the energy transfer between both programs, but also for a challenging aesthetic design.

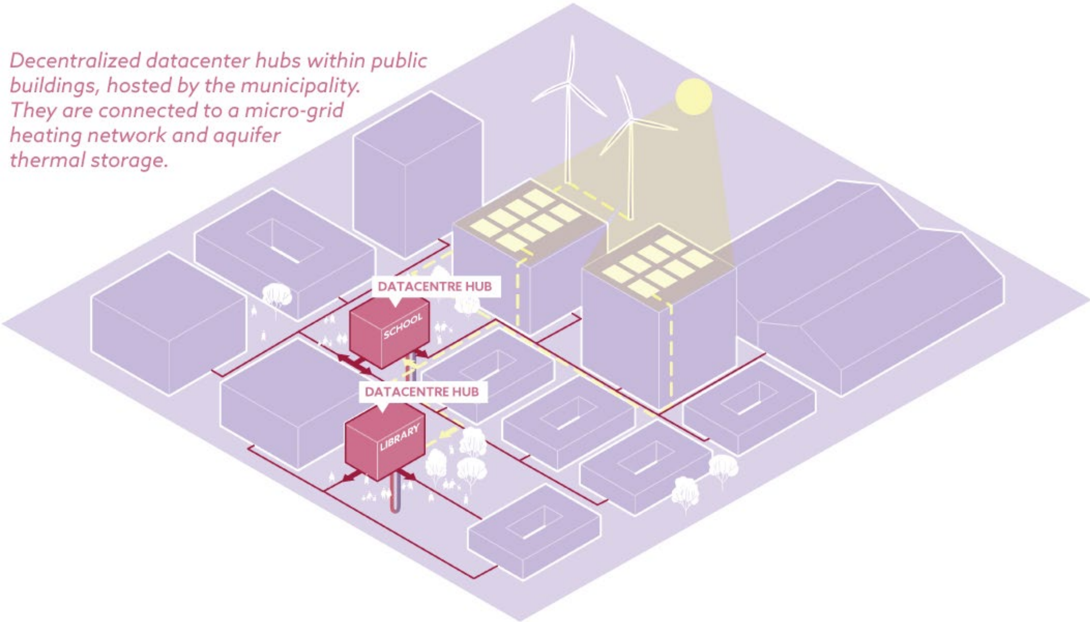


Figure 9 Microgrid with decentralized datacentres in public building. Own creation.

V. CONCLUSIONS

The aim of this research was to find out How connection between flows of a datacentre and public swimming pool can increase sustainability and restore the relationship between port and city. Research showed that by connecting a datacentre to a heat-demanding program 59,4% of the consumed energy by the datacentre can be recovered. The physical connection of the two programs makes it possible to integrate the cooling system of the datacentre to the heating system of the pool. The heat exchanger on the side of the datacentre can be eliminated if the coolant is transported to the pool program and exchanged with the water flow there. This elimination increases the heat recovery drastically, because the heat exchangers are the limiting factor due to their relatively low efficiency. By surrounding the datacentre with the program of the pool and creating ''buffer zones'', the percentage of heat recovery can be increased even more.

The research showed that heat recovery of datacentres is realistic and feasible. Considering the current and future energy demand of the growing sector of datacentres, sustainability should be the first priority and secondly, recovering as much energy as possible. The calculation model proved that with the 500MW datacentres ambition for the West Port of Amsterdam, 60-70% of the residential heat demand of Amsterdam in 2040 can be supplied with heat recovery.

Connecting the datacentre to a heat demanding program such as an indoor swimming pool can achieve a higher recovery potential and provides the complete heat-demand of the pool. Because the model pool used in this research has a relatively small heat demand of 389.147 MJ per year, the total energy reduction of the both buildings is also small. Connecting a bigger heat-demanding program would increase the impact. By collecting the heat in an underground energy storage system, the produced heat can be used all year round by other heat-consumers or a residential area. This research proved that city program organization based on heat supply and demand and heating-infrastructure can make cities more sustainable through use of otherwise lost heat. Non-hazardous industries could then be placed inside the urban fabric where they can be physically connected, or in close proximity, to heat demanding functions. This finding counters the city development of the past centuries, where industrial areas have moved to the outskirts of cities.

The architectural and urban design consequences of this strategy need further research. Also, further research is necessary to; 1) improve the efficiency of heat exchangers, which are now the most limiting factor in the heat recovery system. 2) find out if passive design can make one-directional heat transfer between two adjacent programs possible, and 3) find out if peak-demands can be supplied with stored heat from datacentres, considering pool water is refreshed a few times a year at which the heat demand is higher compared to the daily demand.

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VII. Appendix

8.1 Current and future flows in the port

The following table is the result of the preliminary research. ‘X’ means the strategy was mentioned in the document. The green columns highlight the strategies that are mentioned in most documents and are thus more likely to be executed.

Document	Actor	Vision for West Port of Amsterdam															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Increase of livability	Bio-energy from biomass	AEB waste to energy plant	Use of hemwegcentrale as gas plant	Datacentres with heat recovery	Hydrogen electrolysis (for e-kerosine or other purpose)	Green energy storage in hydrogen	Geothermal energy	Surface water heat recovery	Waste or drinking water heat recovery	Expanding wind turbines and solar fields in port	3D printing	Urban mining	Mentioning (energy) hubs	Circulair economy	Extra remarks
(Visie 2030 Port of Amsterdam, Port of Partnerships, 2015)	Port of Amster dam	X	X	X		X	X					X	X	X	X	X	Maki ng the port clean (p.26)
(Circular Amsterdam; A Vision and Agenda for the City and Metropolitan Area, 2016)	City of Amster dam		X	X									X	X	X	X	
(Omgevingsv isie Amsterdam 2050, een menselijke metropool, 2021)	Gemee nte Amster dam	X	\	X		X	X		X	X	X	X			X	X	
(Concept RES, 2020)	Noord Hollan d-Zuid	X	X	X	X	X						X			X		
(Het Amsterdamse bronnenboek, 2019)	Gemee nte Amster dam	X	X	X	X	X	X	X	X	X	X	X					
(De circulaire Westas, 2017)	Econo mic actors in port	X	X	X		X									X		

The following table is the result of the preliminary research. Possible strategies from the previous table were compared based on their energy or heat production potential and sustainability.

	Unit	Programs compared									
		1	2	3	4	5	6	7	8	9	10
		Bio energy from biomass	AEB waste to energy plant	Datacentres with heat recovery	Datacentres with heat recovery liquid cooling	Deep geothermal energy	Surface water heat recovery	Waste or drinking water heat recovery	Hydrogen electrolysis (for e-kerosine or other	Blue battery	Green battery
(Waste) Heat production	MW-th	5,5	150						-	-	-
Produced temperature	°C	120	120	25-35	75	120	20	20	-	-	-
Energy consumption									41% efficiency	70% efficiency	
CO_2 emissions	Kg/GJ	13	13								
Environmental impact		Only sustainable if biomass consists of 100% organic waste. Often transported from far.		Energy consumption is gigantic. Without heat recovery, all this energy would be lost. Sometimes drinking water is used to cool. Back up generators run on diesel.	Similar to air-cooled datacentre. The cooling system is 50% more efficient.		If return water is higher in temperature, it might affect ecosystem surfacewater.		Flammable and explosive under high pressure. Substances produced are clean.	No impact apart from spatial use.	Extreme pH value of water
Performance remarks		The aim for reducing the amount of waste, counteracts the biomass	The aim for reducing the amount of waste, counteracts the biomass	Waste-heat production is highest in summer and lowest in winter. Storage is a must.			X	Sewer sludge fermentation produces barely enough to heat the RWZI itself.			

Green energy and H_2O + NaCl (Salt water)	NaOH + HCl (sodium hydroxide and hydrochloric
Green energy and brackish water (H2ONaCl)	(Storage of water H2O and salt water H2O NaCl + energy)
Green energy and water	(Storage of H2 and O2 + energy)
Black water Gray water Surface water	Relatively clean water, sewer sludge and heat
Cold water Elektricity Data	
Fertilizer, food, plant-based oils and (animal) fats, wood.	
Yearly 350000 m3 industrial waste water and 120.000 ton unwrapped supermarket-food and other organic wasteflows.	3500 ton fertilizer per year 350000m3 clean water per
Input	Output

8.2 MFA OF EACH PROGRAM

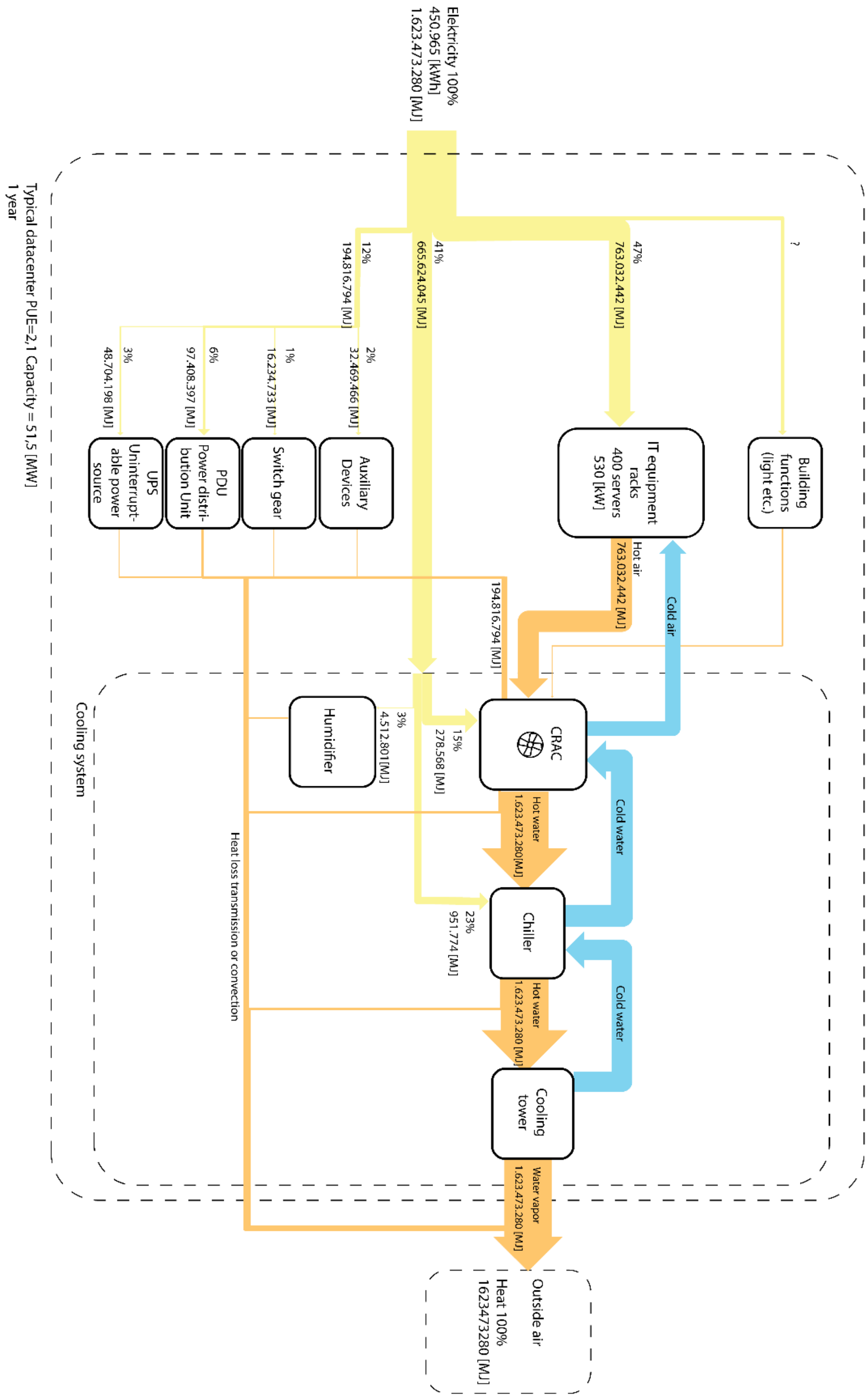

Figure 2 Flow diagram datacentre model. Own creation.

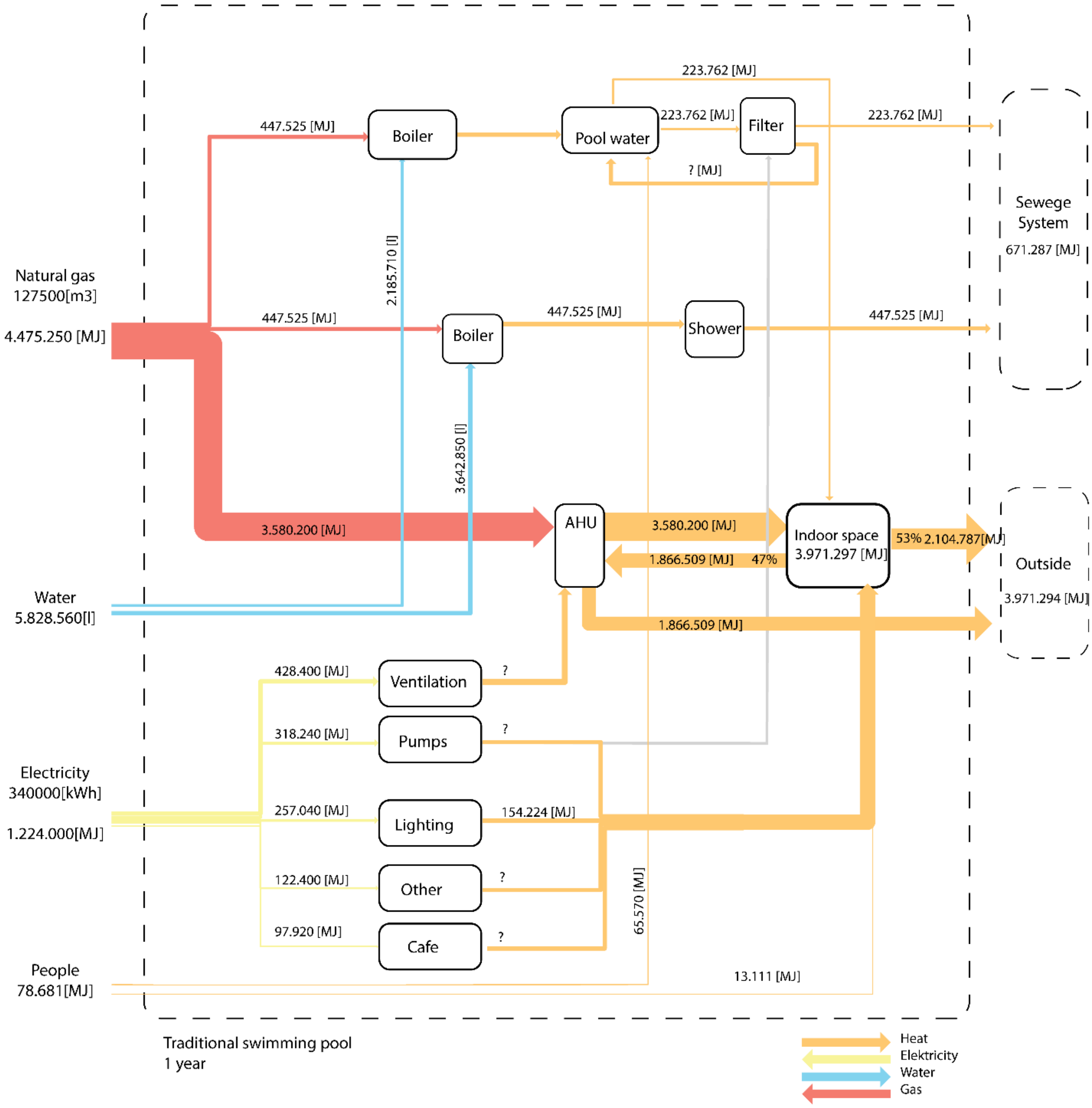

Figure 3 Flow diagram pool 1. Elaborated from; "Detailed flow diagram of the reference swimming pool in the current situation". Mees (2019).

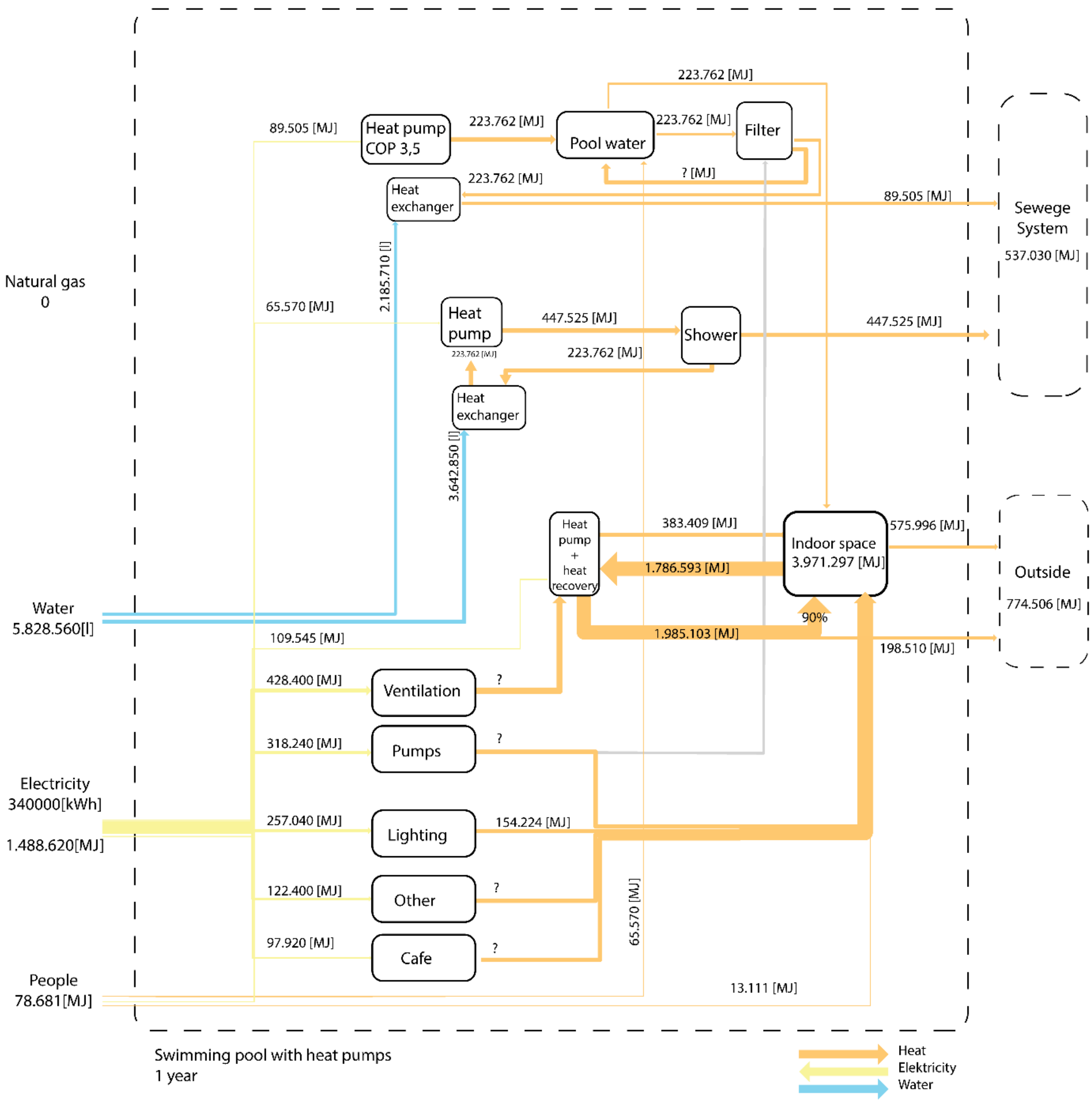

Figure 4 Flow diagram pool 2. Retrieved from; "Detailed flow diagram containing a combination of interventions."

8.3 MFA COMBINED

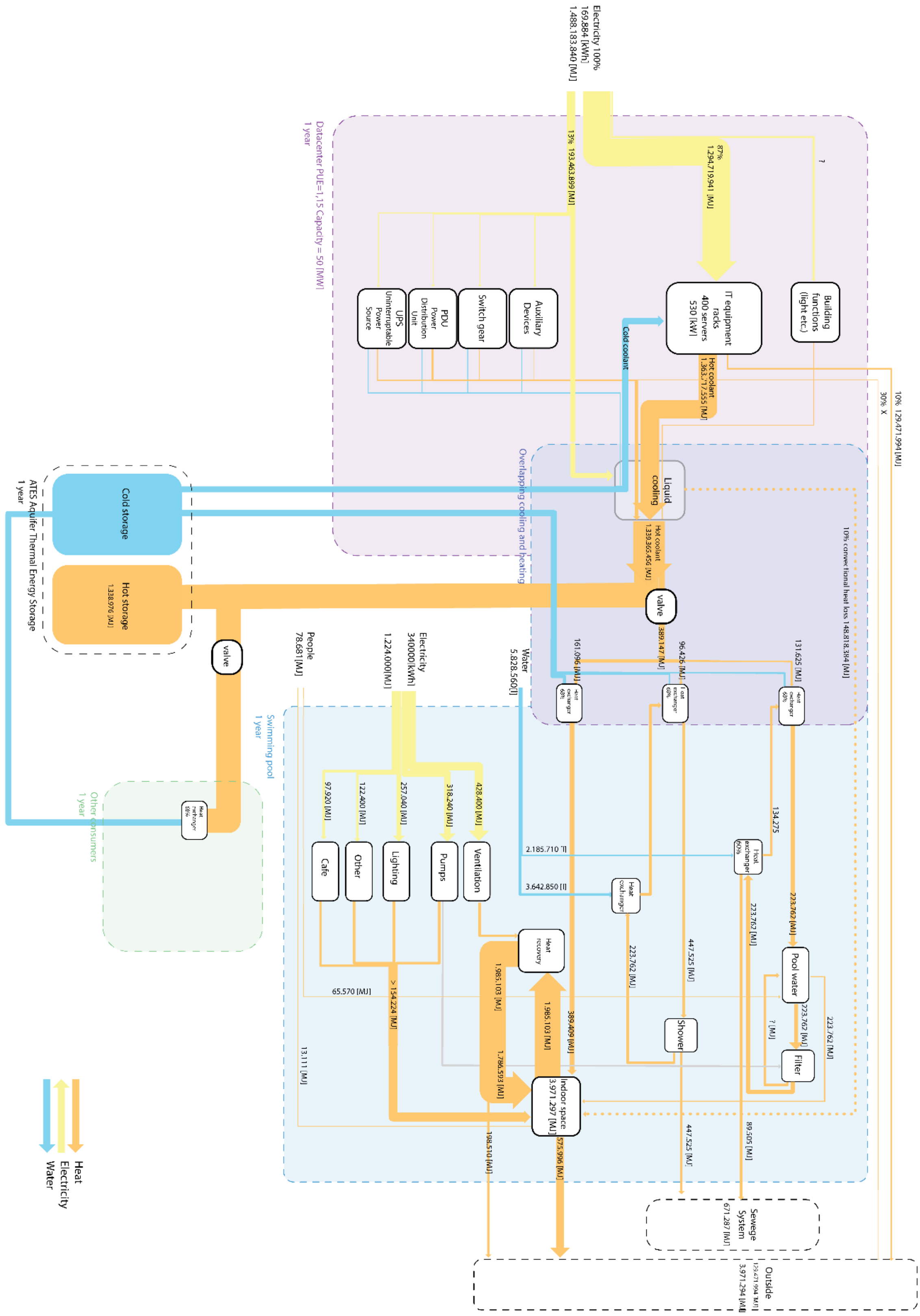

Figure 5 Flow diagram datacentre, pool and ATES combined. Own creation.

8.4 Calculations

The calculations of the heat demand of Amsterdam in 2040 are elaborated from the calculations by Ruijs (2019) in ‘*’Het Amsterdamse Bronnenboek*’’.

Existing city (2018)

	kWh/m2	Units	M2	Energy use GWh	Temperature of heating C
Historic buildings	112.3	191400	13171900	1479	90-70
Insulated residential buildings	96.8	187900	14278000	1382	90-40
Well insulated residential buildings	99.1	51900	4567600	453	90-20
	Total	431200	32017500	3314	

Development projects untill 2040

	kWh/m2	Units	M2*80m2/unit	Energy use GWh
1 High x High scenario	60	225000	18000000	1080
2 Low x Low Scenario	40	100000	8000000	320
3 High x Low scenario	40	225000	18000000	720
4 Low x High scenario	60	100000	8000000	480

Total heat consumption 2040

		Energy use GWh	MJ
1 High x High scenario	Unsustainable growth	4394	15818270148
2 Low x Low Scenario	Lowest energy consumption	3634	13082270148
3 High x Low scenario	Undesired development	4034	14522270148
4 Low x High scenario	Sustainable growth	3794	13658270148
		Between 3634-4394 GWh	

Total residential heat consumption 2040 range

Total residential heat consumption Amsterdam 2040	Between	3289	and	4394	GWh

Havenstad (2040)

	kWh/m2	Units	M2	Energy use GWh	MJ
Well insulated residential buildings*	99.1	1500	4567600	453	1629536976
*Assumed everything is new-built					

Table 3 Heat demand Amsterdam. Own creation.

The following table is an overview of the excel file added to this document. It shows the calculations of the three model datacentres and the seven scenario models that were based on the heat demand calculations from table 3.

Legend	
P_{IT}	Capacity IT equipment
P_{total}	Capacity datacentre total (IT equipment + cooling and building functions)
E_{total}	Energy consumed by total datacentre in one year, assumed the datacentre is on every hour every day
PUE	Ratio effectiveness datacentre
White space	Floor space used for IT-equipment
	Data found in references (or previous calculations) which is used for calculations
	Paramters which were estimated

	Datacentre models	P_{IT}	PUE	P_{total}	E_{total}	white space	white space per P_{IT}*	Servers	white space per server*
		MW	ratio	MW	MWh	m²	m²	n	m²
A	Model paper	0.53	1.8	0.954	8357	136	256	400	0.33974359
B	Equinix AMS3	42.90	1.2	51.48	450965	11000	256	120000	0.091666667
C	Zeewolde	137	1.15	157.5342466	1380000	35125	256	383178	0.091666667

	Heat recovery potential	PUE	% E_{IT} (based on PUE)	Heat recovery IT	% $E_{other functions}$ (based on PUE)	Heat recovery other functions	Heat recovery Heat Exchanger Pool	Overall heat recovery efficiency
		ratio	%	%	%	%	%	%
A	Model paper	1.8	56%	90%	44%	70%	68%	55.2%
B	Equinix AMS3	1.2	83%	90%	17%	70%	68%	58.9%
C	Zeewolde	1.15	87%	90%	13%	70%	68%	59.4%

	Demand scenarios	Heat demand / Output heat	Overall heat recovery efficiency based on Zeewolde model ©	E_{total}	E_{total}	P_{IT}	white space	Servers
		MJ	%	MJ	MWh	MW	m²	n
1	*Pool by Mees (gas)*	4475250	59%	7530784	2092	0.21	53	581
2	*Pool by Mees (heat pump)*	389147	59%	654842	182	0.02	5	51
3	*Maximum residential heat demand Amsterdam 2040*	15818400000	59%	26618612818	7394059	733.97	188199	2053076
4	*Minimum residential heat demand Amsterdam 2040*	13082270148	59%	22014355678	6115099	607.02	155646	1697952
5	*Havenstad heat demand 2040*	1629536976	59%	2742123972	761701	75.61	19387	211498
6	*Heat demand Havenstad + pool model (HP)*	1629926123	59%	2742778814	761883	75.63	19392	211549
7	*500MW datacentres ambition for west port*	9370305391	59%	15768000000	4380000	500.00	128205	1398601

	Demand scenarios	Heat demand / Output heat	E_{total}	white space	Servers
		MJ	MJ	m²	n
1	*Pool by Mees (gas)*	4,475,250	7,530,784	53	581
2	*Pool by Mees (heat pump)*	389,147	654,842	5	51
3	*Maximum residential heat demand Amsterdam 2040*	15,818,400,000	26,618,612,818	188,199	2,053,076
4	*Minimum residential heat demand Amsterdam 2040*	13,082,270,148	22,014,355,678	155,646	1,697,952
5	*Havenstad heat demand 2040*	1,629,536,976	2,742,123,972	19,387	211,498
6	*Heat demand Havenstad + pool model (HP)*	1,629,926,123	2,742,778,814	19,392	211,549
7	*500MW datacentres ambition for west port*	9,370,305,391	15,768,000,000	128,205	1,398,601

Table 4 Calculations of model datacentres. Own creation.

8.5 ARCHITECTURE

Interventions which reduce energy consumption of indoor pools	***Interventions which reduce energy consumption of datacentres***
Building orientation (passive sun heating/light)	Building orientation
Insulation	Insulation
Shower heat recovery	Heat recovery
Pool heat recovery	Liquid cooling
Heat pumps for additional heating	Use of natural cold source for cooling
Pool covers	LED light with lighting control
LED light	Low-power servers
PV/PVT panels	Location with cold climate*
Buffering warm areas with medium warm areas (Gemeente Amsterdam, 2019)	
Sources; Mees (2019) (Cie Architecten, sd) (Gemeente Amsterdam, 2019)	*Sources; (Manganelli, Martirano, Ramakrishna, & Soldati, 2021) (Andersen, Clarke, Luo, Maroto-Valer, & Rajendra, 2019) (DatacenterWorks, 2014)*

**A cold climate decreases the power consumed by the cooling system, because convectional heat losses are considered 'free cooling'. However, due to the heating of the surrounding environment this strategy is not considered sustainable.*

Table 5 Interventions for sustainable design of an indoor pool and datacentre.

Datacentre

White space	19,387m^2 (Necessary to heat Havenstad and 2500m^2 pool.)	IT-equipment 211,498 servers
Installation space	±3900m^2	Liquid cooling, pumps, PDU, UPS, Switch Gear, auxiliary devices, space for wires
ATES underground storage		Underground
Lobby	*50m^2*	*Welcome-desk* *Waiting/work-space* *Coffee corner*
Office	*30m^2*	*Kitchen* *Worktable*
Bathrooms	*20m^2*	*2 customer bathrooms* *1 employee bathroom*
Screening gate	*10m^2*	*Metal detectors* *Entrance control gate*
Control room	*40m^2*	*4 Desks*
Janitor storage	*20 m^2*	
Total Datacentre	*±23.457 m^2*	
Pool		
25m bath	*525 m^2*	*25x21m* *Depth 3,08-3,18m* *Heat recovery* *Pool covers* *8 lanes* *Diving board* *25°C*
Recreational bath	*300 m^2*	*25 x 12m* *Depth 1-4m* *Heat recovery* *30°C*
Toddler pool	*50 m^2*	*Max 0,2m deep* *Heat recovery* *33°C*
'Hot tub'	*2 x 5m^2 (round)*	*Heat recovery* *1 Bubble bath* *33°C* *1 Cold bath* *5°C*
Slide with pool	*(Bath) 15 m^2*	*5 x 3m* *Depth 1m* *Heat recovery*
Healing bath	*200 m^2*	*8x25m* *For elderly, patients and babies* *Flexible depth 1-1,8m* *Heat recovery*

		Pool covers *33°C*
Outdoor 25m pool		*25x21m* *Depth 3,08-3,18m* *Heat recovery* *Pool covers* *8 lanes* *25°C*
Outdoor toddler pool		*Max 0,2m deep* *Heat recovery* *Pool covers* *25°C*
Showers	*20 m^2*	*12 shower heads* *Heat recovery* *33°C*
Installation space	*200 m^2*	Heat pumps Heat exchangers Filters Ventilation Pumps
Entrance hall	*30 m^2*	*Entrance desk* *Waiting space* *Ticket-gates*
Cafe	*25 m^2*	
Kitchen	*16 m^2*	
Changing rooms	*80 m^2*	*Lockers* *Single changing rooms* *Family rooms* *Club-rooms*
Bathrooms	*25m^2*	*20 Toilets* *2 disabled toilets*
Offices	*3 x 16 m^2*	
Storage space	*30 m^2*	*Pool supplies* *Other storage*
Janitor storage	*6 m^2*	
Other	*1000 m^2 (probably much more)*	*Walking space around pools* *Sitting areas*
Total pool	*±2500 m^2 indoor space*	

Table 6 Program datacentre and pool (Own creation).

8.6. Scenarios

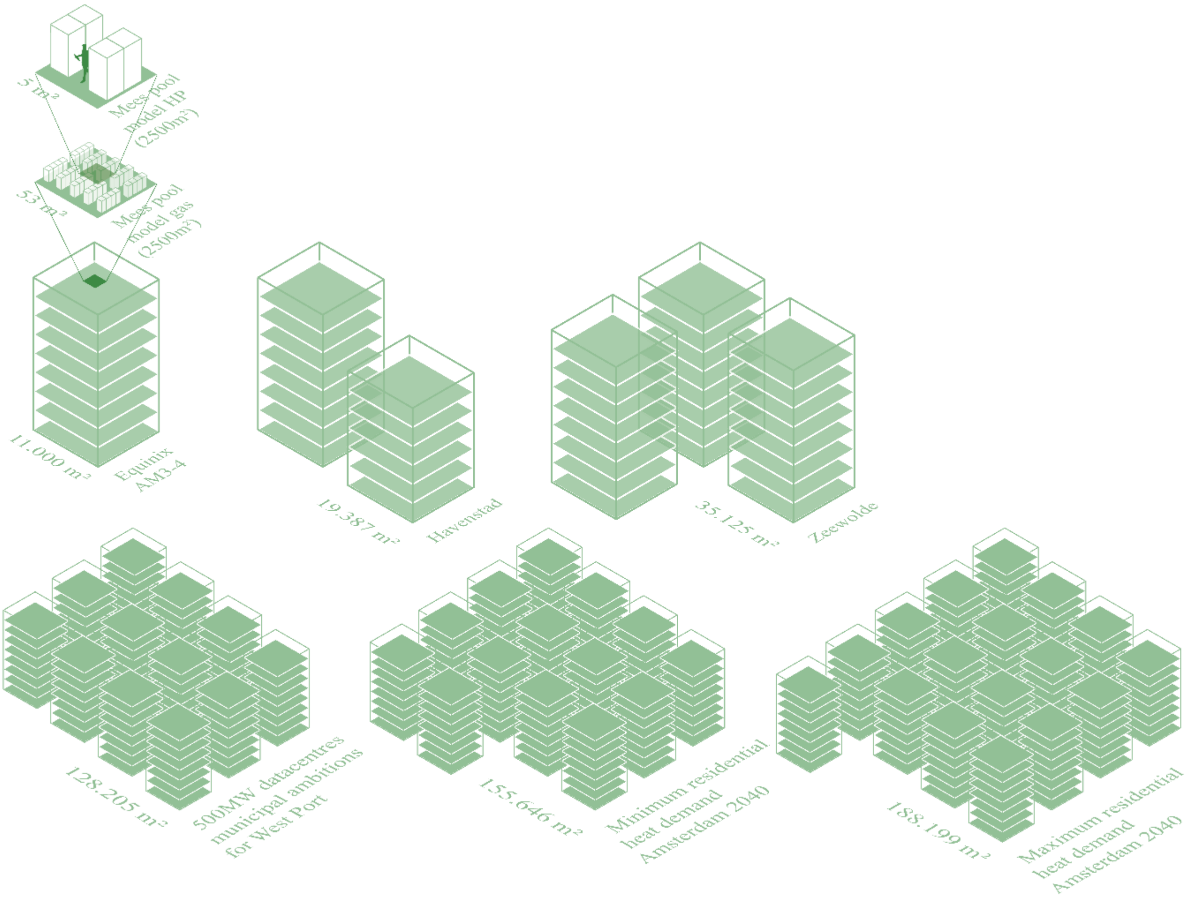

Figure 6 Dimensions of scenario-datacentres (Own creation)

8.7. City-scale MFA

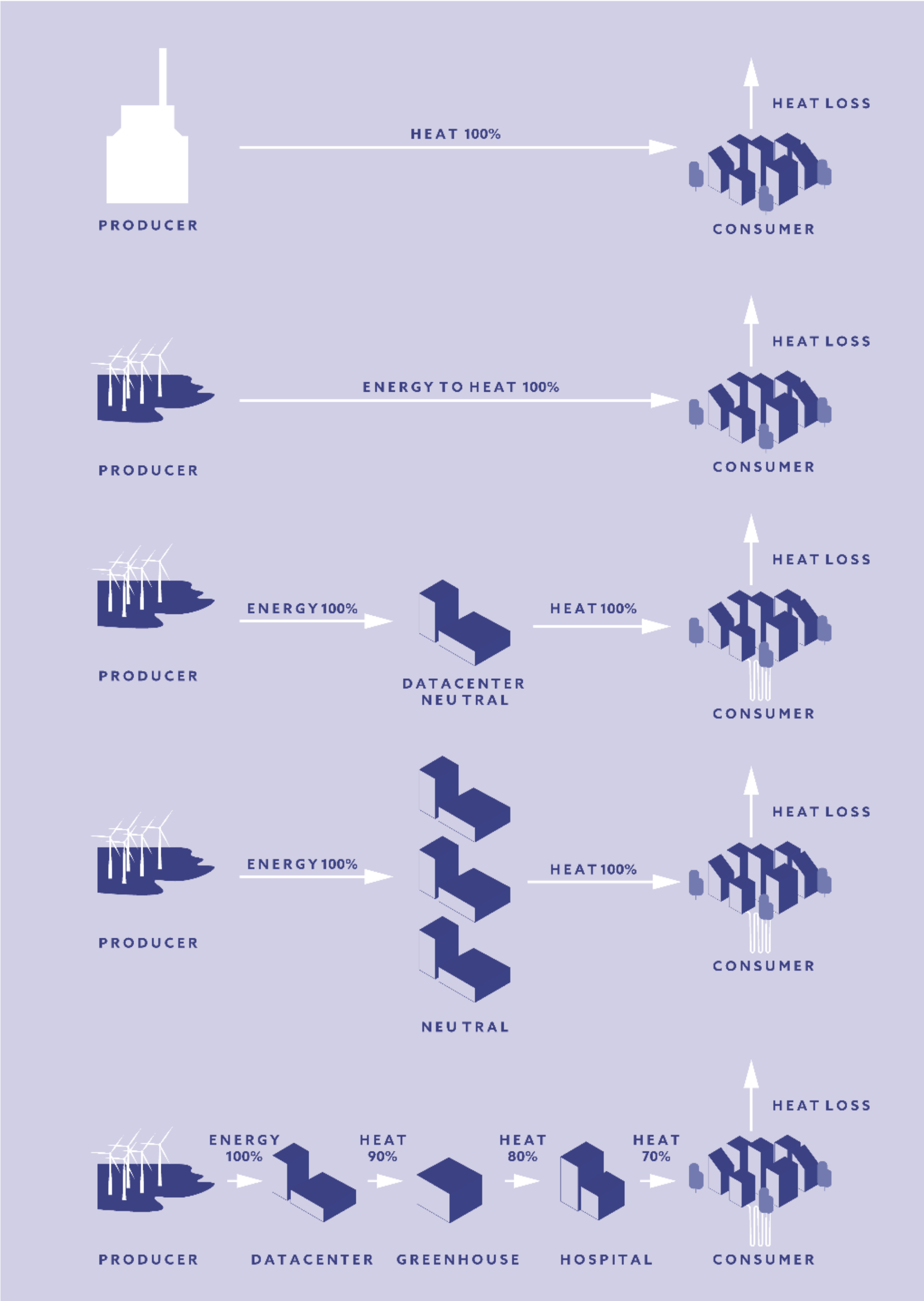

Figure 7 Energy recovery flows on regional scale 1. Own creation.

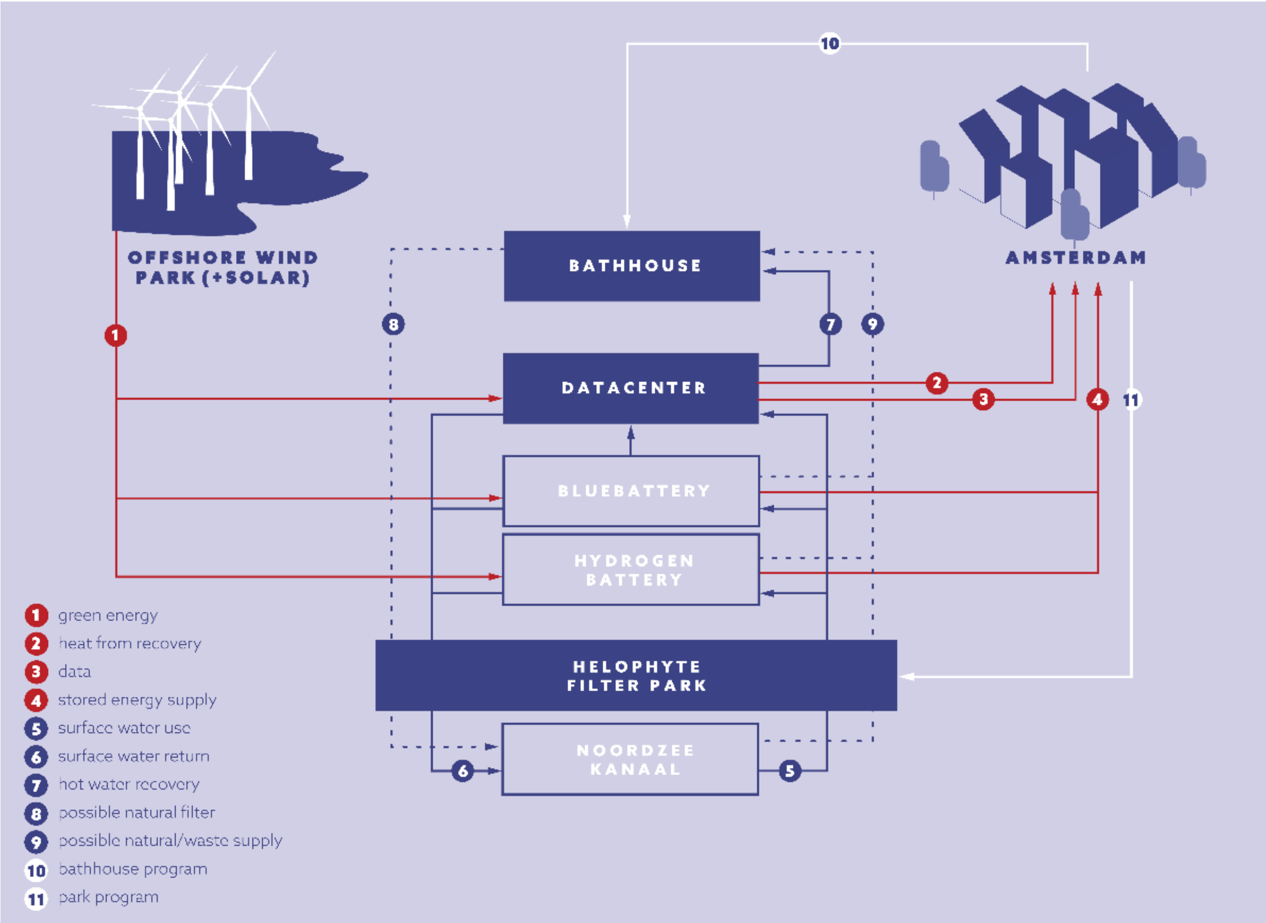

Figure 8 Energy recovery flows on regional scale 2. Own creation.

8.9. INTERVIEWS

Interview – Ruud Stevens (transformation team hemwegcentrale Vattenfall)
22 November 2021, 15:00-15:45, online (teams).
Language; Dutch originally, translated by me.

1. Could you tell me something about your function at the Hemwegcentrale/Vattenfall?

Ruud has been working at Vattenfall for 10 years. For 2 years he has been working on the project of transforming the coal plant. Vattenfall took over the coal plant from Nuon in 2010. They were not aware of the closing of the plant at that time. In 2019 the coal plant was closed as a result of the 'agendafonnis' from the government.
What comes after the coal plant is the assignment he has been working on. The old hemweg coal plant will be completely demolished. On the site there already is an electricity connection, connection to the heat-network of Amsterdam and also the harbour location.

2. What is the reason for Vattenfall to choose hydrogen and not a different sustainable battery (blue battery, basalt battery)?

They want to use techniques that have been tested and proven feasible. They support innovation, but not for commercial purposes. The proven battery like the lithium battery was an option with high efficiency, but does not have a big capacity for storage. Also, they were looking for something to use within 5 years.

3. The municipality and government want to generate energy sustainably, does Vattenfall receive subsides for the transformation from coal to hydrogen?

For the transformation, Vattenfall is not subsidized. However, when they make the electrolyser, they will apply for subsides for this project. If and how much they get is based on competition with other electrolysis projects. The amount of money is based on how much they ask for and the amount of CO_2 they can prevent (not depending on location or city plans).

4. What makes this location suitable (or not) for hydrogen electrolysis on this scale?

They did not particularly choose this location for the hydrogen electrolysis, but a part of their business was gone and they were looking for a new way to fill that gap. This way they can use the existing infrastructure.

5. What are the consequences of hydrogen electrolysis on the environment? Do you have to take into account the future residents of for instance Havenstad?

According to Ruud, hydrogen storage is not explosive. It is as safe as storing gas. In a well-protected area it should not be a problem. It only ignites when there is both oxygen and an ignition source. Safety is not the reason they will not store it on site, mainly costs.

6. What will this hydrogen electrolyser-building look like? How do you consider the (architectural) design process and the context?

There is a rough plan for the composition on site. The gas-plant and current solar fields will remain. The old coal plant will be demolished. The South-East part of the terrain is owned by Tennet/RWS/municipality, there is a ''schakelstation'' located here. This area also includes the ''schakelgebouw''. They will offer a bigger area to Tennet. Also, the municipality is planning to make a highway exit here. They will keep the gas-plant which can still perform for the next 30 years. Slowey they will mix hydrogen with the gas until the gas plant runs 100% on hydrogen. (They will not use their own hydrogen, but take the hydrogen from an underground storage in Groningen). This hydrogen will be a surplus.
They will not store hydrogen on site, only a day-storage for the tanks to load up. The reason for this is that above-ground storage is very expensive, it is better to store large amounts underground.

7. Imagine I would design a hydrogen-electrolyser, what should I take into account?

The main electrolyser building (10MW) is only 20 x 40m with a few machines in a rectangular, high ceiling shed. Important is safety (opening roof for the hydrogen to escape when there is a leak), noise insulation, enough space for maintenance (forklift truck/crane). For the kerosine they will use ships for transport, for the hydrogen they will only use trucks (small amount).

8. What will be the water source? Could you potentially use the water of the Noordzeekanaal? Or precipitation? How much water will it use?

Surface water, rainwater, seawater and any other type of water can be used. It does have to be filtered (dirt and salt). There is no in-between storage necessary. For amount see Q10.

9. You mentioned Vattenfall will connect to the city heating network, will this be the main purpose of the hydrogen electrolyser or will Vattenfall also use it for other purposes?

Vattenfall will make synthetic-kerosine from hydrogen (long term development) which will be brought to Schiphol by ships. This synthetic-kerosine is supposedly very sustainable since it is only made from water and energy, no petroleum necessary. The alternative (LNG) has to be transported from far away. (I think they are actually planning to make this also in the port)

10. What is the goal of Vattenfall? How many households do you expect to support in heat with this electrolyser? And what about 2050 when a second electrolyser will be added?

The plan is to realize a 10MW electrolyser (later a 100MW?) This means the electrolyser uses 10MW of energy, this is transformed into 6MW hydrogen energy (efficiency). For this they make 200kg/h hydrogen. Meaning they need 2000kg/h water equal to 2000L/h water. The storage capacity for a year would be based on the 'vollasturen' (real produced energy expressed in hours per year) from the (offshore) windfarm which is about 5000 hours per year on average. In those hours, the electrolyser will also be producing. So 5000h/y x 2000L/h = 1.000.000L water per year (of course through the energy demand this will fluctuate)

11. (Image BIG waste-plant with ski-slope) In my opinion, awareness about energy consumption is as important as the generating of green energy. Which is why I am questioning if industrial areas like these should become more accessible in the future. Do you agree, or do you think it would be better for these areas to only have an industrial program?

It is a complicated question. Some people move next to Schiphol because they do not mind. But when Schiphol expands, they will lodge an objection. For a company they would rather have space to grow in the future. In 10 years, plans can change, but also the idea of what is sustainable and liveable might change.

He would suggest to look at (industrial) functions within the city that do not have to be there and move them to the port area to make more space in the city. For example, maintenance garages or distribution centres.

12. I read the efficiency of hydrogen electrolysis is 70% and to turn it around 55%, could this be improved?

The efficiency of hydrogen is relatively low (10MW energy produces 6MW hydrogen energy). This efficiency will not double, it might improve a tiny bit.

Interview – Ramses Rodenburg (customer datacentre and employee at IT-company info.nl)
26 November 2021, 10:00-10:40, online (teams).
Language; Dutch originally, translated by me.

1. Could you tell me something about your job at info.nl and your experience with datacentres?
Ramses works at info.nl, they have been customers of datacentres from the beginning. It started with for instance UvA who sublet spaces at science park. Basically, just a room with a power connection where they could set up their own equipment. Over time they went to more professional datacentres with more facilities; cooling, 19inch cabinets, private spaces. In datacentres today, every customer has their own space which is sealed off from other spaces. (This is to prevent fires from spreading or smoke to transfer to other spaces.)

2. Could you shortly explain what a datacentre is and what it does?
A datacentre is basically a company that rents out space for customers who can either place their own routers and servers here, or rent servers and routers. They offer facilities for an electricity outlet, backup generators, cooling equipment, fire safety and network connections (optical fibre). In the building they go to, every second or third floor are used for power generators.

3. Is the location of a datacentre important, or could it be placed anywhere?
The location does not necessarily matter, it could be placed in Groningen, because customers only go there for installation and once in a while for maintenance.

4. Would the Port of Amsterdam be a suitable location?
The West Port of Amsterdam offers the possibility for transportation with trucks. Digging is undesirable for datacentres. Also, Amsterdam has an overloaded energy system, which means blackouts occur more often. Other (non-city) locations would be more preferrable. However, for the reuse of heat and the connection to optical fibre, being nearby the city would be better.

5. Datacentres have to be cooled, could surface water of for instance the Noordzeekanaal be used for this?
He did not know.

6. If I were to design a datacentre, what are the 3 most important things to take into account?
Various power sources, back-up generators, safety (terrorism attack, fires), heavy load-bearing structure. The entrance hall offers a place for customers to waits or work and could have a desk and a coffee machine.
A relatively new development is datacentres that not only rent out space, but also the routers and servers themselves. Only companies with large financial means can do this (Microsoft/google), but or the customer it is cheaper. The equipment is facilitated by the company and can be done on a bigger scale, instead of customers having to arrange a visit themselves. This would mean that the amount of people using the building will be even smaller.
The ventilation their building uses works with air-ventilation. Servers and routers are stored in lockers with the fronts all turned in the same direction (where they suck in air) and from the back they blow out hot air. The building has ventilation floor tiles which blow out cold air in the 'cold corridor' and suck out warm air from the ceiling in the 'warm corridor'. This creates different pressures in both corridors.
The ceiling height in this example is relatively high, 4-5m, which is not mandatory but it offers the possibility for hanging up equipment and wires.
The wires (optical fibre) leave the building from at least 2 corners of the building and make different routes. This way, if wires are cut, it only cuts of part of the customers. These wires need maintenance once in a while so the street needs to be opened. (Undesirable for cities)

7. Safety is very important for datacentres. Do you think it would be a bad idea to connect a datacentre to a building with a public program?

Breaking in should be prevented, screening for those who enters. A public function could be connected but they should be completely separated (entrance). Customers might be attracted to a safer datacentre, compared to one which also has a public function. Maybe in a separate building.

8. Could a datacentre be placed into a vacant building?

As long as the bearing construction and safety can be assured, this should not be a problem. Most datacentres have space for underfloor-ventilation and ceiling space for wires and other equipment. The organization is relatively flexible. Elevators are a necessity. Windows are undesirable, they need maintenance and offer and make the building less safe.

9. Do you think there will be more datacentres in the future, or less due to optimization of IT equipment and clouds?

Probably more. The growth is exponential.

Topics that came up which were not related to the questions:

The amount of MW power is probably referring to the commercial useable power, but the consumed energy amount is probably not far from this since it is the same amount + building functions and cooling which is relatively low.

To use datacentres for waste-heat recovery would be ideal. The energy that they use is almost 100% transformed into heat and it could easily be collected.

Hosting crowdsources is an existing service, through which people have a small datacentre/server in their home, which produces heat. It is relatively safe when VPN is used, also because of the wide spread it is more stable than all in one building. Maintenance is only once in 2/3 years. The question remains how the amount of heat can be regulated through the whole year and right now it produces too little to heat the whole home.

The Netherlands is located strategically for datacentres, as they offer a central location between countries and the connection with optical fibre.