ACHIEVING FLOW SYNERGY IN DATA CENTERS WITH A RESIDENTIAL AND GREENHOUSE PROGRAM

Strategies for optimizing electricity, cooling/heating and water flows in a mixed-use urban building that contains a combination of data center, residential and greenhouse program in the urban context of The Netherlands

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ABSTRACT

This paper hypothesizes that data centers can complement the urban environment rather than make a negative impact, both environmentally and spatially. Data centers consume and produce a variety of valuable flows, ranging from electricity, cooling/heating and water use. The aim of this research is to discover whether it is possible to create synergy between these flows in a mixed-use building that contains both data center, residential and greenhouse program. All flows for the different programs are analyzed, quantified and visualized. Through the findings, the flows and programs are linked together. This in turn creates possibilities to redesign and optimize the processes of these flows and reduce the amount of resources needed (input) while at the same time reducing waste (output). No synergy for electricity is established, as no program produces electricity and at the same time all programs require electricity. For cooling/heating, significant decreases in energy consumption for heating and cooling are possible for all programs by reusing data center heat coupled with Aquifer Thermal Energy Storage (ATES). Finally, through reutilizing grey water from the residential and greenhouse program it is possible to reduce additional data center water demand significantly.

Keywords: *data center, energy, water, metabolic flux analysis, housing, greenhouse, architecture*

I. INTRODUCTION

Over the past few decades the internet has become an essential part of our daily lives. Worldwide it is transforming societies and economies at high speed. We're sharing ideas, creating new ones and taking in information and news like never before. Whether it be to improve our lives, for entertainment or for work: a lot of societies rely heavily on digital infrastructure. We are constantly increasing our demands on this infrastructure as every year we consume and create more data than the year that came before it. Developments in technology such as quantum computing, artificial intelligence and 5G will contribute even further to an increase in future data demand. Research shows that data traffic is expected to increase more than 20 times by 2030 compared to 2020 (ING Economics Department, 2019).

Data centers are the fundamental component on which digital infrastructure is based. Located in these facilities is equipment such as computers, storage systems and network infrastructure that allows for data to be stored, processed and distributed. Energy use in data centers is high as a result of both IT hardware and the supporting infrastructure such as cooling equipment. Almost all of the electricity consumed in IT equipment is converted to heat and therefore servers have to be cooled to prevent overheating and damaging of equipment (Rasmussen, 2007). Cooling systems use a lot of energy and often consume almost 40% of total energy used by a data center. In addition to this, the generated heat by IT equipment is in most instances lost to the atmosphere, even though various solutions already exist for reusing data center waste heat in district heating systems or for water heating (Ebrahimi et al., 2014). The environmental impact of data center facilities is high. Research from the International Energy Agency (2020) estimated that data centers account for 300 Mt CO_2-eq in 2020 (including embodied emissions) which is equivalent to 0.9% of energy-related GHG emissions (or 0.6% of total GHG emissions).

Data centers can be located in both urban areas where they often come in the form of stacked facilities as well as in more rural landscapes where they are frequently single-story buildings. Examples are shown in Appendix A. Data centers have a large spatial demand with so called hyperscale facilities taking up many hectares of land. Urban data centers often have a smaller footprint due to their vertical configurations. However, in both cases monofunctional zones in the landscape are created. Any additional mixed-use building program is not common in these types of facilities. In addition, data centers are in most cases fenced off for safety reasons and an even stronger disconnect from the surrounding context is created as a result.

This paper hypothesizes that data centers can complement the urban environment rather than make a negative impact, both environmentally and spatially. Data centers consume and produce a variety of different flows, ranging from electricity, cooling/heating and water use. These flows could prove useful to be integrated and optimized with different programs rather than go to waste as they most often do. As there is an almost limitless scope of possible building programs to be researched, the research of this paper is limited to two possible additional programs which are selected due to their current topicality and hypothesized potential by the author.

- Affordable housing is a large contemporary issue related to the urban environment across the world (Wetzstein, 2017). Related to affordability are household expenses such as rising energy costs (e.g. heating, electricity) which can prove to be a major financial burden for a large portion of households. This paper hypothesizes that heat generated by data centers can be reused for heating dwellings and their warm water supply. In addition, the grey water from these households can be used as a water source for cooling data centers.
- Food security is of major importance for communities across the world. As a result of climate change, global food security has come under threat due to less reliable crop yields (Lobell & Gourdji, 2012). In addition, political and economic issues can often create problems in supply chains, resulting in food insecurity. The use of greenhouses in which climatic conditions can be precisely controlled can make crop yields more reliable. Producing (and consuming) food locally strengthens self-reliance of communities. It is hypothesized that data centers can

provide year-round heating to greenhouses and that grey water from greenhouses can be utilized as a source of water for cooling data centers.

In order to test these hypotheses this paper will research the possibilities of combining data center, residential and greenhouse program in one single building in the context of The Netherlands. The context is chosen as both affordable housing and energy crisis are relevant issues in this context. In addition, The Netherlands has a strong position as a worldwide data center hub. The capital, Amsterdam, is one of the European locations that are in high-demand for data processing together with London, Paris and Frankfurt. This is in large part thanks to its geographical location in Europe, the proximity of many submarine cable landing points as well as the presence of the Amsterdam Internet Exchange (AMS-IX) which is one of the largest internet exchanges in the world (Rijksoverheid, 2019). Much of the cross-border internet traffic as well as data flows in the Netherlands are handled through the AMS-IX network. The Netherlands is also a major and leading player in the European Union greenhouse horticulture sector (Viola et al., 2012). Therefore, many innovative technologies related to crop production are researched and developed in the country.

Research will be carried out methodologically. First, by analyzing electrical, cooling/heating and water flows of data centers it is possible to quantify the amount of resources needed for daily operation. Secondly, this same flow analysis will be performed for a residential and greenhouse program. After performing flow analysis, the flows of data center, residential and greenhouse program can be linked together. This creates possibilities to redesign and optimize the processes of these flows and reduce the amount of resources needed (input) while at the same time reducing waste (output).

The main research question in this paper is as follows:

Is it possible to create synergy between flows in a mixed-use building that contains both data center, residential and greenhouse program?

In order to answer the main research question, the following sub-questions are introduced in order to gather the relevant information:

1. *What are the electricity flows in a mixed-use building that contains a data center, residential and greenhouse program?*
2. *What are the cooling/heating flows in a mixed-use building that contains a data center, residential and greenhouse program?*
3. *What are the water flows in a mixed-use building that contains a data center, residential and greenhouse program?*
4. *How can data center flows benefit a residential and greenhouse program and vice versa?*

Various methods and techniques will be used to answer these questions. The first method is by researching existing literature on electricity, cooling/heating and water flows for the individual programs. This includes research into strategies for reducing overall environmental footprint. The second technique is through case studies of existing data centers, residential buildings and greenhouse buildings in order to better understand their spatial requirements, functioning, performance and implemented environmental strategies.

II. RESEARCH

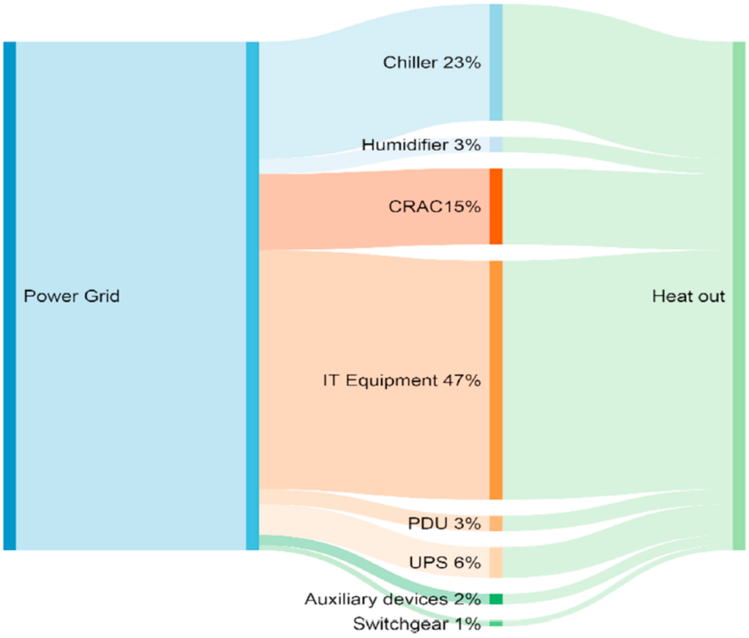
2.1. DATA CENTER PROGRAM

2.1.1. DATA CENTER ELECTRICITY FLOWS

In 2020, research from the International Energy Agency (2020) estimated that global data center electricity use was 220-320 TWh or around 1.3% of global electricity demand. IT equipment and cooling equipment take up the largest portion of total energy consumption in data centers. Approximately 50% of the energy used in a data center goes to IT loads and roughly 40% goes to cooling equipment. In addition, power supply systems and other miscellaneous power loads account for the remaining 10% (Rasmussen, 2006). The power flow diagram for a typical data center facility can be seen in Figure 1.

Figure 1.

Sankey diagram showing power flow in a typical data center, $PUE = 2.13$ (Luo et al., 2019. Adapted from Rasmussen, 2006).



Data centers and their IT equipment operate 24 hours a day, 7 days a week and 365 days a year in most instances and therefore demand a constant flow of electricity. Within the IT equipment, servers account for 80-90% of energy consumption. Communication equipment and storage devices account for the remaining 10-20%. A typical rack of servers in a data center consumes about 8 kW as of 2020. Higher densities of 20 kW and above are often seen in modern data centers. Due to advancements in ultra-dense computing architectures it will become more common to see rack densities of 50 kW and higher in the near future (Uptime Institute, 2020). On average, 65% of data center floor space is dedicated to IT equipment which is called the data center white space. The remaining 35% is devoted to other necessary equipment, the so-called data center grey space. An area value of 2.6 m^2 per rack is typically used (Rasmussen, 2005).

IT devices convert almost all of their electricity to heat. Excess heat can lead to malfunctioning and damaging of these devices. Damaged equipment can increase the risk of fire and other safety issues. Therefore, data centers must remain cool during their operation. This requires the use of cooling systems (such as air conditioning units and cooling towers) in order to keep the IT equipment at a safe temperature.

Existing data center infrastructure relies on power grids which are mostly powered by fossil-based fuels as their primary source of energy. Fossil-based fuels are the primary source of greenhouse gas emissions and are non-renewable resources. However, renewable sources of energy, such as wind and solar energy, are gaining more attention in the data center industry and many of them are now designed or redeveloped with renewable energy in mind. This renewable energy can either be generated on-site, off-site or provided by a third-party (Oró et al., 2015). Another essential strategy in which environmental impact of data centers can be reduced is through reduction of their overall energy needs. As servers and cooling systems have the most substantial impact on power loads, reducing energy consumption of these components is an essential part for sustainable development of data centers.

In order to measure energy efficiency of data centers many different metrics exist of which the Power Usage Effectiveness (PUE) and the Datacenter Infrastructure Efficiency ($DCiE$) are the most widely used and accepted (Brady et al., 2013). Power Usage Effectiveness is defined as the ratio between total facility power in a data center divided by energy delivered to the IT equipment. The purpose of the metric is to show how much energy is used by the computing equipment compared to cooling and other overhead power demands that support the IT equipment. Even though it is named Power Usage Effectiveness it actually measures energy use.

In Equation 1 the definition of Power Usage Effectiveness can be seen, which is defined as:

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} \tag{1}$$

Datacenter Infrastructure Efficiency is the inverse of PUE which is defined in Equation 2:

$$DCiE = \frac{IT\ Equipment\ Power}{Total\ Facility\ Power} \tag{2}$$

IT equipment power consists of the energy load associated with all of the IT equipment, such as computers, storage equipment, network equipment and auxiliary devices.

Total facility power consists of:

- Power loads of delivery infrastructure such as Uninterruptible Power Supply (UPS), switchgear, (backup) generators, Power Distribution Unit (PDU), batteries, and any transmission and distribution losses not related to IT equipment.
- Cooling system power loads such as chillers, computer room air condition units (CRACs), pumps and dry/fluid coolers.
- IT equipment power loads such as computer, storage equipment, network equipment and auxiliary devices.
- Other miscellaneous power loads within the data center such as lighting, fire protection and security alarms.

In an ideal situation, a PUE value of 1.0 would indicate 100% efficiency which translates to all data center power being utilized by IT equipment only. High values are indicative of system inefficiencies. Apart from power loads from equipment, the data center building design and local climate also influence PUE values.

According to research from the Uptime Institute (2020) the average PUE for data centers is around 1.58. PUE values have reduced significantly over the years. For example, the average PUE was 2.5 in

2007. In 2022, PUE values for Google's data centers as low as 1.10 are regularly reported (Google, 2022). One of Google's hyperscale facilities in Quilicura, Chile, reports PUE values as low as 1.08 sustained over a 12-month period. This means that almost that almost 93% of the energy consumed by this data center was being used to power IT equipment and 7% was used for cooling, power delivery infrastructure and other loads such as lighting.

Although PUE is the industry standard and the most effective in comparison to other metrics, it does come with issues and problems:

- PUE is limited to energy consumption, not generation. PUE doesn't take into account whether energy is sourced from fossil fuels or renewables. Wind energy is treated the same as electricity from a coal plant.
- Heat recovery strategies don't factor into PUE calculation, therefore it doesn't reward such sustainability measures.
- Other resources used in data centers such as water for cooling are not taken into account in PUE. Water treatment is common before use in cooling systems and can require a significant amount of energy. A new metric, PUE_{source} (similar to WUE_{source}, see 2.1.3), could be proposed which includes power required for water treatment in addition to facility power.
- PUE does not consider the efficiency of IT equipment in a data center. This can be problematic, as every year IT components are getting more efficient (more computational power is available per watt).
- The local climate in which a data center is located does not factor into PUE. A data center located in a colder climate can thus not be compared to a data center in a warm climate. Colder climates reduce reliance on a cooling system, as free cooling (see 2.1.2) can be utilized from outdoor air temperatures. For example, a data center in a cool climate may have a PUE of 1.2 while one in a warm climate has a PUE of 1.6. PUE ignores the fact that the latter may have more energy efficient components and that if it happened to be in a colder climate it may achieve a lower PUE value.

In order to provide a complete assessment of data center energy efficiency PUE should not be solely relied on. Complementing metrics such as Carbon Usage Effectiveness (CUE), Energy Reuse Factor (ERF) and Water Usage Effectiveness (WUE) are some examples of additional performance metrics that can be used (Van De Voort et al., 2019). However, it should be noted that PUE is an industry standard for various reasons. Firstly, the metric can serve as a reliable benchmark for data centers and if it is calculated often it allows for efficiency changes to be measured over a period of time or through seasonal changes. Secondly, it can also serve as a tool for implementing energy efficient practices (e.g. turning off servers when they are not needed or replacing inefficient components) as this will influence PUE due to an effect on overall facility power and IT equipment power. Lastly, PUE stimulates competition in the data center industry as PUE is frequently used as a marketing tool. This competition can lead to increased efficiency and new technological innovations as companies will strive for low PUE values of their facilities.

2.1.2. DATA CENTER COOLING/HEATING FLOWS

Around 90% of electrical power in data centers is ultimately converted into low-grade waste heat (Luo et al., 2019). At the same time, the electrical power consumed by IT equipment is almost fully converted into heat. Different components of the equipment produce different temperatures (Huang et al., 2020). This means that different server configurations have different types of heat dissipation and can therefore create different heat densities in data centers. Conventional data centers have dissipation rates within the range of 430-861 W/m^2, while high power facilities can achieve values that are at least ten times higher in comparison (6.548-10.764 W/m^2).

Heat in data centers has to be removed in order to create an indoor environment in which equipment does not overheat nor gets damaged. If temperature and/or humidity level go above certain values it can lead to damaged equipment. Optimal temperatures for server inlets are between 18–27 °C

(Steinbrecher & Schmidt, 2011). On the other hand, extreme cold and/or low humidity leads to problems as well. Many data centers can however operate in very cold temperatures and some are even located in cold climates in order to reduce need of additional cooling. Inlet temperatures of 5 °C and lower are possible but can reduce performance or damage equipment.

As additional heating is rarely needed due to heat generated from equipment, data centers mostly rely on cooling systems to keep their indoor climates in check. Due to a large variance in heat dissipation rates, different cooling techniques have been developed for data centers and their cooling needs. In general, cooling can be divided into air cooling and liquid cooling. These are also the most common systems.

- The majority of data centers use air cooling as their main cooling system. Server racks are arranged into both hot aisles and cold aisles (often called HACA). The cold aisles provide cool intake air to each server while the hot exhaust air exits the servers in the hot aisles (Ebrahimi et al., 2014). The racks are commonly arranged back-to-back to create hot and cold aisles in order to maximize the efficiency of the cooling as this avoids the mixing of hot and cold air. Different configurations for air-cooled data centers include computer room air conditioner units (CRAC), computer room air handler units (CRAH), in-row cooling and rear door cooling. The differences are mostly related to data center size and rack capacity. CRAC is mostly utilized for small data centers (less than 100 kW loads). CRAH is more common for larger data centers (100 kW loads and higher). In-row cooling is commonly applied for medium to high rack loads of > 10 kW per rack. Rear door cooling is common in very high loads of > 35 kW (Oró et al., 2015). Schematics of these various air-cooled systems can be seen in Appendix A.
- For data centers with high power densities air-cooled systems are not the best solution when it comes to efficiency and reliability. In addition, they simply aren’t powerful enough to remove high heating loads in high power facilities. Therefore, liquid cooling systems have been developed. Water is often used as well as other liquids. This liquid is brought directly to the racks and sometimes even right up to the processors. Liquids in general are far more efficient at transferring heat and through direct contact with IT components they achieve higher heat transfer rates compared to air-cooled systems. As a result of high heat transfer efficiency, low temperature differences between cooling liquids and server components are possible leading to a reduction in energy needs. Liquid coolant with a significantly high temperature can be used (temperatures of 60 °C to 75 °C are not uncommon). The reduced temperature difference between components and coolant allows for high quality waste heat to be recovered (Brunschwiler et al., 2009).

As stated previously (2.1.1), data centers can take up a significant amount of total data center energy consumption. A cooling system which takes advantage of favorable climatic conditions in which a data center is located is one of the most effective ways to obtain energy savings (Zhang et al., 2014). This method, called free cooling, uses the cooling capacity of ambient air, (sea)water or ground to keep the data center cool. This is not always possible as the climate of a location may be too warm. Free cooling is very common in data centers in colder climates where outside temperatures are often sufficient for year-round free cooling of the server rooms. Any form of mechanical refrigeration consumes high amounts of energy and thus free cooling is frequently preferred from an environmental point of view if non-renewable sources are used for energy production.

As data center power capacity will only further increase, increases in heat loads will occur as well. Several new technologies for cooling are being developed to support rising power densities, such as fully immersed direct liquid-cooled, micro-channel single-phase flow cooling or micro-channel two-phase flow cooling (Capozzoli & Primiceri, 2015).

2.1.3. DATA CENTER WATER FLOWS

Water is used in data centers for two different purposes: the first is (indirectly) for electricity generation in case the data center is powered by thermoelectric power and the second use is for cooling. In addition, humidification plays a role in the cooling process as humidity levels have to be constantly monitored and maintained. If a data center becomes too humid the risk of condensation increases which could lead to damage, corrosion and ultimately equipment failure. Too little humidity in the data center increases the risk of electrostatic discharge, which can also lead to failure.

Water requirements can be classified into water withdrawal or water consumption. Consumption refers to water that is lost in a process (usually through evaporation), whereas water withdrawal refers to water taken from a source (e.g. surface water, underground water, reclaimed water or treated potable water) which is then later returned to the source (Pan et al., 2018). Water scarcity is a growing threat worldwide and data centers have effect on this due to their water use. The water that is used in data centers and electricity generation frequently has to meet specific quality demands. In order to prevent corrosion, scaling and biological growths water is often treated before use, requiring additional energy use and the addition of chemicals. This creates a source of wastewater which has to be treated again in order to prevent harmful chemicals to be deposited in the environment. Potable water is the main source of water in data centers as it contains low levels of dissolved solids (which could damage installations). This can lead to an increase of already high levels of water stress in certain regions.

Apart from electricity generation, water is also used in data centers for cooling and humidification. As previously stated (2.1.2), there are several different mechanisms for data center cooling and water is commonly used in cooling systems. In these systems water is used as a heat transfer mechanism for reducing air temperatures. A small 1 megawatt (MW) data center that utilizes a system of water-cooled chillers and cooling towers can consume 68.000 liters of water per day (Mytton, 2021). It is important to note that water use in data centers can vary throughout seasons and also varies across different climate zones and equipment. For research purposes, it is assumed that 75% of supplied water is used in cooling towers while humidifiers account for 25%. This was estimated through calculation of available data (Evans, 2004). Strategies that can reduce water use range from technologies such as free cooling or the implementation of air-cooled chillers (and therefore not using water in the cooling system at all). However, some of these systems may be less efficient than technologies based on water as they can require a larger amount of energy for similar results of cooling. Depending on how energy for a data center is generated, this could mean that water use at the generation site (e.g. power plant) will go up and the overall data center water use may increase.

Data center performance can be represented in several metrics, of which Power Usage Effectiveness (PUE) is the industry standard for measuring the infrastructure energy efficiency (2.1.1). Similarly, Water Usage Effectiveness, in short WUE, is a metric often used for data center water consumption (Azevedo et al., 2011). It is defined in Equation 3 as the following:

$$WUE = \frac{Annual\ Water\ Usage}{IT\ Equipment\ Energy} \tag{3}$$

Unlike PUE, which is unitless, WUE has units which are liters per kilowatt-hour (L/kWh). WUE has an ideal value of 0 as it would indicate that no water use is associated with the operation of a data center. Like PUE, WUE only considers part of the life cycle of a data center as it only considers the operational phase and not the construction phase nor the manufacturing of components. In addition, WUE offers a limited view of water use as it only considers the water consumed on-site. As mentioned previously, water from electricity generation is a large component of data center water use. Therefore, a different metric called WUE_{source} exists that includes water use at both the power generation source as well as on-site. It is defined in Equation 4 as the following:

$$WUE_{source} = \frac{Annual\ Source\ Energy\ Water\ Usage + Annual\ Site\ Water\ Usage}{IT\ Equipment\ Energy} \tag{4}$$

According to a survey by the Uptime Institute (2020) only half of their respondents (n=431) say their organization collects water usage for their data center operation. In addition, relatively few data centers regularly report their WUE values. Meta (2021) is one of the only large technology companies to provide metrics while others such as Google (2022) and Microsoft (2021) publish total water consumption but don’t publish related water efficiency metrics.

From here on, only WUE will be considered in this research and will be based on the available data from Meta in 2021 (WUE = 0.26). This decision has been made due to the use of renewable power sources in the research as they do not involve water in the generation process and therefore WUE_{source} is not applicable.

2.2. RESIDENTIAL PROGRAM

2.2.1. RESIDENTIAL ELECTRICITY FLOWS

In 2019 the residential sector accounted for 6.072 TWh of electricity consumption, or roughly 25% of the total worldwide consumption of that year (International Energy Agency, 2019). In 2011, for lack of newer data, residential buildings accounted for approximately 11% of global CO_2 emissions due to their electricity consumption.

Around 80% of people in the world have access to electricity. It is important to note that consumption and thus CO_2 emissions per capita varies between regions and countries. The average per capita consumption of electricity in a developed country is much higher compared to a developing country. In the United States three-person household electricity consumption averages around 11.000 kWh per year, in France it is 6.000 kWh, in the United Kingdom it is 4.000 kWh, in The Netherlands around 3.000 kWh (Centraal Bureau voor de Statistiek [CBS], 2022a) while China and India hover around 1.000 kWh. Average electricity consumption for households worldwide was estimated at 3.500 kWh in 2010.

The majority of the world still relies on fossil fuels such as oil, coal and gas for electricity generation. Reducing electricity demand and increasing energy efficiency of the residential sector is crucial in order to lower emissions and mitigate risks of global climate change while transitioning to low-carbon renewables. In order to make informed decisions for electricity use in the residential sector it is essential to know how electricity consumption is influenced in the first place.

Electricity is used in residential buildings due to a need for facilities such as lighting, space cooling/heating, cooking and other electrical devices. This is influenced by a complex series of interlinked and interacting socio-economic, dwelling and appliance related factors. Literature shows over 62 factors in these categories that potentially have an effect on residential electricity use (Jones et al., 2015). Of these 62 factors, four of the socio-economic factors, seven of the dwelling factors, and nine of the appliance related factors were found to have a significant positive effect on electricity use (meaning an increase in electricity consumption). For other factors it was unclear whether they would have a significant effect, significant negative effect or non-significant effect due to conflicting results or a lack of existing research.

- Within the socio-economic factors research shows that household composition is essential in electricity consumption. The number occupants, the presence of teenagers, increased household income and disposable income lead to a significant increase in electricity consumption. None of the socio-economic factors have a clear negative effect (contributing to a reduced electrical energy demand).
- Dwelling factors such as dwelling age, number of rooms, number of bedrooms, and total floor area have a significant positive effect on residential electricity use. Electricity use increases significantly in homes with an electric space heating system, air-conditioning or an electric water heating system.

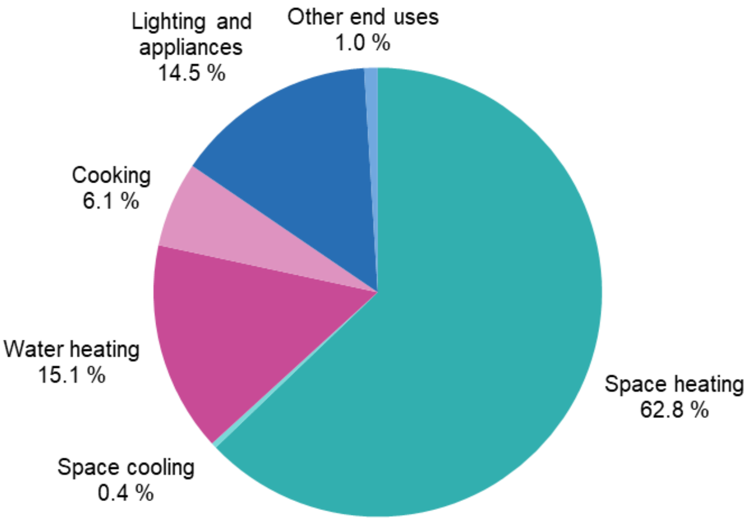
- Appliance factors such as a higher number of appliances, the ownership of a computer, television, electric oven, refrigerator, dishwasher, washing machine and tumble dryer result in an increased electricity use.

Figure 2 shows the typical distribution of energy consumption in the EU residential sector by use. It is important to note that electricity is part of energy consumption and not interchangeably used as a synonym. In 2020, EU final energy consumption in the residential sector consisted of natural gas (31.7%), electricity (24.8%), renewables (20.3%), followed by petroleum products (12.3%), derived heat (8.2%) and coal products (2.7%). For example, in The Netherlands space heating, water heating and cooking are mostly powered by natural gas while other appliances are powered by electricity. Space cooling is uncommon in the residential sector of The Netherlands.

For research purposes it will be assumed that the current distribution as shown below will be all-electric in the future. Both space heating as well as warm water will be provided through a heat pump (see 2.2.2). This assumption has to be made due to a lack of data on the distribution pattern in all-electric households.

Figure 2.

Final energy consumption in the residential sector in 2020 by use in the EU (Eurostat, 2022).



2.2.2. RESIDENTIAL COOLING/HEATING FLOWS

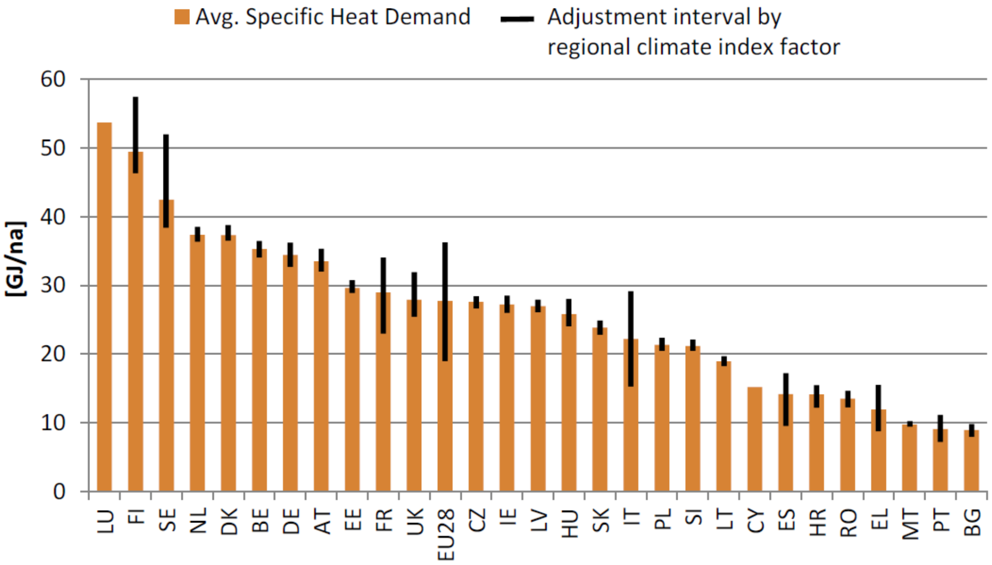
Within the residential program, heating is used for both space heating and water heating. Cooling is used for space cooling. Heating often relies on fossil fuels as the source of energy, either directly (as a source of heat) or indirectly (through electricity generation), but can be sourced from renewables. Cooling mostly relies on electricity which can either be generated from fossil fuels or renewables.

Climate factors such as temperature, humidity, wind and solar irradiation have the largest impact on cooling and heating requirements (Chen et al., 2012). In addition, these demands are influenced by both building design (e.g. insulation, orientation) and local levels of comfort. The latter is defined by the fact that in some regions people are regulating indoor climatic conditions to a lower difference between indoor and outdoor temperatures or controlling only certain parts of a house.

In countries with a temperate climate more than half of consumed energy is typically used for heating. Figure 3 shows that European Union heat demand values range from approximately 10 to 50 GJ per-capita with a European average at around 28 GJ per-capita per year (Persson & Werner, 2015). The demand per surface area for The Netherlands is approximately 0.3 GJ/m^2 or 7.5 koe/m^2 (kilogram of oil equivalent) per year. As described earlier (2.2.1) it will be assumed for research purposes that the residential program will function all-electric. Therefore, all heating demands will be provided through a heat pump. Heat pumps can significantly reduce electricity consumption by absorbing energy from the ground, air or water. A ground source heat pump is chosen for calculations with a Coefficient of Performance (COP) of 4. This means that 4 kW of heating power is achieved for each kW of power used by the pump's compressor (Lund et al., 2004).

Figure 3.

Average per-capita heat demand for space heating and hot water preparation in EU member states (Persson & Werner, 2015).



In warm countries cooling loads takes up a large portion of energy needs. Within the European Union, the amount of energy used for cooling in residential buildings represented 0.4% of the total final energy consumption in 2020 (Figure 2). This percentage is much higher in countries such as Malta (11%), Cyprus (10%) and Greece (5%). Cooling demand ranges from 0.03 TWh per year in Lithuania, 0.48 TWh per year in The Netherlands, 3.52 TWh per year in France and up to 11.92 TWh per year in Spain (Werner, 2016). For research purposes it will be assumed that natural ventilation in combination with passive climate design suffices for cooling in the context of The Netherlands (temperate climate).

2.2.3. RESIDENTIAL WATER FLOWS

Water in a residential program is used for purposes such as drinking, preparing food, showering and bathing, flushing toilets, washing clothes and dishes, watering gardens etc. Compared to agricultural and industrial water use, residential demands for water are relatively small, hovering around 11% of total water withdrawals on average. The majority of countries use less than 30 percent of withdrawals for domestic purposes. A high share of residential water use in a countries total water usage can in most cases be attributed to low demands from agriculture and industrial uses or for example as a result of agriculture that is largely rainfed, therefore increasing the residential share (Ritchie & Roser, 2017).

Research from Mayer et al. (1999) shows that toilets are the appliance with the largest residential water consumption indoors (26.7% of total), followed by clothes washers (21.7%), showers (16.8%), faucets (15.7%), leaks (13.8%), other residential fixtures (2.2%), baths (1.7%) and dishwashers (1.4%). Average per capita consumption for household purposes can vary a lot, even between high-income countries such as The Netherlands at 130 liters per capita per day (CBS, 2019) and the United States at 300 liters per capita per day (Dieter, 2018). Average per capita water consumption can be explained through complex dynamics between a range of socio-economic, dwelling and appliance factors. These can all affect water consumption and include factors such as the number of people in a dwelling, age of residents, education levels of residents, income of residents, lot size of dwellings, efficiency and ownership of water consuming equipment (such as pools and garden irrigation systems), but also includes attitudes, beliefs and behaviors of residents (Willis et al., 2011).

Access to potable water has become more unreliable as a result of both an increasing population and climate change induced effects (Bates et al., 2008). Therefore, sustainable water management practices are essential in ensuring water supply security. These practices focus in part on reducing consumption and thus reducing the demand on water supplies and on resulting wastewater treatment. Supplying knowledge and tools to communities on water consumption is part of water management, whether it be through incentivizing reduced use, reducing the amount of appliances that use water or replacing appliances with appliances that are more water efficient. Other measures such as rainwater harvesting, reusing treated grey water (from appliances such as sinks, showers, tubs) or even treated black water (from toilets) can reduce dependency on global water supplies in the first place.

2.3. GREENHOUSE PROGRAM

2.3.1. GREENHOUSE ELECTRICITY FLOWS

Within the European Union, the largest greenhouse sectors can be found in The Netherlands, Spain, Italy and Greece. This research will mainly focus on The Netherlands. Greenhouses in The Netherlands account for almost 4 TWh of electricity consumption on a yearly basis spread over a greenhouse surface area of around 11.000 hectares (Viola et al., 2012).

Greenhouse crops have requirements for photosynthesis such as light, temperature, water, CO_2 and nutrients. One of the most common ways in which some of these requirements are met in the sector is through the use of a process called Combined Heat and Power (CHP). This process, which relies on natural gas, simultaneously produces electrical energy, thermal energy (which heats water) and has CO_2 as a byproduct. Around 58% of greenhouse electricity was produced directly at the greenhouses by CHP in The Netherlands, while 42% was purchased from other suppliers (Paris et al., 2022).

Research from The Netherlands shows that around 82% of electricity consumed in greenhouses is used for lighting and 18% for other equipment. Regarding electricity used for other equipment, more than half of it was used for providing energy in and around the boiler room (54%). This is followed by general equipment such as refrigeration cells and equipment in the greenhouse such as fans (both 18%). The remaining 10% is used for the water supply, which is where water is treated (Van der Velden & Smit, 2013).

One of the predominant lighting technologies in the worldwide greenhouse sector is so called high-intensity discharge lighting which uses high-pressure sodium grow lights that provide both light and heat (Posterity Group, 2019). Around 25% of electricity consumption for greenhouse lighting in The Netherlands is used for growing of vegetables, while the remaining 75% is used for flower nurseries.

This paper will focus on the cultivation of vegetables in order to provide food to local communities. It will focus on 3 different crops which have been selected based on their prominence in the greenhouse horticulture sector in The Netherlands. These are tomatoes, bell peppers and cucumbers.

Electricity requirements for the selected crops are as follows:

- Tomatoes require lighting with an intensity of 105 W/m^2 in The Netherlands. The lighting is utilized for 2.300 hours per year. This averages to 254 kWh/m^2 on a yearly basis (Van der Velden & Smit, 2013).
- Bell peppers require lighting with an intensity of 45 W/m^2 in The Netherlands. The lighting is utilized for 1.250 hours per year. This averages to 59 kWh/m^2 on a yearly basis.

- Cucumbers require lighting with an intensity of 80 W/m^2 in The Netherlands. The lighting is utilized for 1.250 hours per year. This averages to 105 kWh/m^2 on a yearly basis.

By using available data on the gross floor area of vegetable greenhouses in The Netherlands and dividing it by the total vegetable crop cultivation area (CBS, 2022b; CBS, 2022c) it is possible to estimate the floor space efficiency. Approximately 85% of a greenhouse can be used as crop cultivation area while the remaining area (15%) is used for corridors, installations and functions such as storage, offices and processing.

2.3.2. GREENHOUSE COOLING/HEATING FLOWS

Greenhouse horticulture can produce high yields, even outside of the cultivation season. This is possible by controlling and maintaining growth factors such as light, temperature, humidity and nutrients at a year-round optimum level in the greenhouse. As a result, it can lead to reduced time required for cultivation, improvement in quality and an increased yield (Esen & Yuksel, 2013). Performance of a greenhouse is dependent on many factors, such as greenhouse size, type of cultivation, local climate, equipment and building materials.

Most of the climate in a greenhouse is regulated passively by utilizing solar energy. The transparent (roof) surfaces allow for sunlight to provide light and heat to the greenhouse which allows crops to grow. In summer, windows can be opened to cool down the greenhouse. However, a variety of systems are often necessary to provide sufficient heating and cooling when passive climate design doesn’t suffice.

As previously explained in 2.3.1 the majority of additional heat in greenhouses is supplied through the burning of natural gas in a process called Combined Heat and Power (CHP). The heat is then spread around the greenhouse through heat pipes. As the Combined Heat and Power process is almost constantly occurring, the generated heat could exceed demand at certain moments. Buffering warm water by storing it in a thermal energy storage tank for later use increases efficiency in this case and minimizes loss (De Zwart et al., 2019).

Research from Van der Velden & Smit (2020) shows that approximately 74% of total greenhouse energy consumption can be attributed to heating and the remaining 26% to electricity. Heat demand in greenhouses averages between 12 m^3 per m^2 and 18 m^3 per m^2 of natural gas a year.

When it comes to greenhouse cooling, natural ventilation is often very effective for cooling in temperate climates. Additional solutions such as ventilators, exhaust fans, reflective screens and other shading techniques are common for when maximum ambient air temperatures are less than 33 °C. In environments where temperatures exceed 40 °C, evaporative cooling is commonly used (Sethi & Sharma, 2007). As the context of this paper is The Netherlands, which is in a temperate climate, this will not be required in all but most extreme cases.

To conclude, heating requirements for the three selected crops (tomato, bell pepper, cucumbers) are as follows:

- Tomatoes require 23 m^3 of natural gas per m^2 of greenhouse in The Netherlands. The yield is 68 kilograms per m^2 (De Gelder et al., 2012).
- Bell peppers require 22.2 m^3 of natural gas per m^2 of greenhouse in The Netherlands. The yield is 30.6 kilograms per m^2 (De Gelder et al., 2011).
- Cucumbers require 20 m^3 of natural gas per m^2 of greenhouse in The Netherlands. The yield is 78.1 kilograms per m^2 (Schuddebeurs et al., 2015).

2.3.3. GREENHOUSE WATER FLOWS

Water is an essential component for growing crops in greenhouse horticulture. Irrigation water often has to be of high quality for optimal crop growth. To reduce their environmental impact, many greenhouses use rainwater as a primary source of irrigation water.

Both water withdrawals as well as the discharge of wastewater can cause environmental issues. Greenhouse wastewater frequently contains high concentrations of both nutrients (e.g. nitrate and phosphorus) and pesticides which can harm the environment. This can cause performance issues at municipal wastewater treatment plants where the water often gets discharged to. In addition, high concentrations of nutrients and pesticides are frequently found in regions with greenhouse cultivation, harming local environments (Baltus & Verboom, 2005).

The consumption of water in greenhouses is heavily dependent on the utilized cultivation system. In general, there are two cultivation systems that are utilized in greenhouse horticulture. These are direct soil cultivation and off-the-ground cultivation. Off-the-ground cultivation can be further subdivided into substrate cultivation and cultivation in pots/boxes. Substrate cultivation grows crops in a root medium (e.g. mineral wool, peat, clay granules) which is physically separated from the ground. The main differentiator between these options is the possibility of reutilizing drainage water in substrate cultivation. Typically, a drain percentage of at least 20-25% is used in substrate cultivation to prevent salinization in root zones (Pardossi et al., 2011). Capturing and reutilizing water in direct soil cultivation is more complicated as the collection of drainage is difficult. Apart from that, drainage water in direct soil cultivation is frequently mixed in the drainage network with seepage or percolation water which results in low quality irrigation water (Van der Velde et al., 2008). There are solutions (such as double drainage networks) to overcome these problems. However, only off-the-ground cultivation will be considered in the rest of the research as it is more water efficient.

Most greenhouses rely on natural ventilation for greenhouse cooling as previously described in 2.3.2. In some cases, additional cooling systems may be required. In those instances evaporative cooling is common (particles of water evaporate which leads to a reduction in temperature as a result of increased humidity). These cooling systems can consume a large amount of water, depending on type of greenhouse, cultivation methods, local climate etc. While excess heat can lead to crop damage and even total crop failures, humidity is also an important factor in the climate of a greenhouse. If it is too low, crop transpiration will be too high and lead to damage. If it is too high, crops are more prone to fungi and mold. Additional humidification and dehumidification can reduce these issues. However, due to the context of the research which focusses on The Netherlands (temperate climate), this will not be required in all but most extreme cases. Natural ventilation in combination with equipment such as ventilators, exhaust fans, reflective screens and other shading techniques should suffice in this context.

To conclude, requirements for the three selected crops (tomato, bell pepper, cucumbers) are as follows:

- For tomatoes, 15 liters of irrigation water is required to yield 1 kilogram of crops. This is a large reduction compared to open field production which requires 60 liters per kilogram of produce (Van Kooten et al., 2006).
- For bell peppers, 22.8 liters of irrigation water is required to yield 1 kilogram of crops. This is a very large reduction compared to open field production which requires 300 liters per kilogram of produce.
- For cucumbers, 14 liters of irrigation is required to yield 1 kilogram of crops. This is a large reduction compared to open field production, which requires 60 liters per kilogram of produce.

The minimum values described above are attainable in a system which captures drain water, where CO_2 enrichment is provided to the crops and where climate-controlled glass is applied throughout the greenhouse.

III. RESULTS

Using the findings from the previous chapter it is now possible to visualize and quantify the flows for the data center, residential and greenhouse program.

For all programs base calculations have been made for 10.000 m^2 of surface area per program. These calculations can be found in Appendix C (data center), Appendix D (residential) and Appendix E (greenhouse). A graphical and quantitative representation of the programs in the form of material flow analysis can be found in Appendix F (data center), Appendix G (residential) and Appendix H (greenhouse). Flow calculations distributed over gross floor surface area per program can be found in Appendix I.

The final sub-question of this research consists of researching how data center flows can benefit a residential and greenhouse program and vice versa. Analysis is performed per flow, through which opportunities for synergy can be derived. After analyzing all flows and programs, it is possible to combine the flows to create a new synergetic system.

3.1. ELECTRICITY FLOWS

Separate flows: all programs require electricity for their functioning. Per m^2 of program the data center has the highest share on a yearly basis (99,1% of all three programs combined), followed by the greenhouse (0.6%) and residential program (0.3%).

Opportunities for synergy: all programs require electricity as input. Only the greenhouse program creates electricity within the system through the combined heat and power process. This electricity is however fully utilized within the program of the greenhouse. In addition, the use of natural gas in this process is not a sustainable way of electricity generation.

Therefore, no sustainable system for reuse can be created for this flow. The separate programs do not create synergy and are not beneficial to each other regarding electricity flows. Recommendations regarding electricity flows are producing and utilizing the electricity as effective as possible through high efficiency of systems and components. This can reduce the required electricity in the first place, therefore limiting overall environmental impact. Electricity can be generated by utilizing systems such as solar panels and wind turbines but these generation processes fall outside the scope of the research. Flows are only analyzed within their respective processes.

3.2. COOLING/HEATING FLOWS

Separate flows: regarding cooling, only the data center program requires additional (liquid) cooling due to large amount of heat generation from equipment. For the residential and greenhouse program it is assumed that natural ventilation suffices (see 2.2.2 and 2.3.2) and no mechanical cooling is necessary.

Regarding heating, the data center program generates large quantities of heat which negatively impacts performance. Meanwhile, the residential program and greenhouse program have heat demands. When comparing heat output per m^2 of data center (+) on a yearly basis, the residential program heat demands (-) per m^2 only account for 0.5% of the data center heat output. Demands for the greenhouse program (-) account for 0.8% of the data center heat output. Therefore, there exists possibility to create synergy between supply and demand.

Opportunities for synergy: a data center produces large amounts of heat on a year-round basis. Most heat is produced in summer, when outdoor temperatures are higher. In winter, the production of waste heat can be limited as a result of the free-cooling effect (2.2.1). The heat demand of the residential and greenhouse program is inversely correlated to the heat supply of the data center as these programs demand most of their heating in winter. Therefore, there is a need to store the heat supply for later use in the year.

Aquifer Thermal Energy Storage (ATES) is a heat storage system that has very high storage capacity and is often used in The Netherlands due to suitable soil conditions (Fleuchaus et al., 2018). In this system, heat and cold are stored in a water-carrying sand layer in the ground. It stores warm water in a warm well and cold water in a cold well. Both the cold and the warm wells are interconnected with a loop coupled by a heat exchanger. In the summer a building can be cooled with groundwater from the cold well whilst extracted heat is stored in the warm well. In winter a building is heated with groundwater from the warm well whilst extracted cold is stored in the cold well. Groundwater is pumped back and forth between the cold well and the warm well. Recovery factors for warm thermal energy in the ATES system vary from 57% to 89%. The recovery for cold thermal energy is approximately 90% (Kleyböcker & Bloemendal, 2020). It is assumed that a medium temperature (MT) ATES system will be used by applying liquid cooling in the data center. The liquid cooling system is not just applied to the IT-equipment but also applied to other equipment in the data center. High efficiency heat recovery can be achieved through this strategy. For example, the Aquasar system at Eidgenössische Technische Hochschule (ETH) Zurich in Switzerland uses water-based cooling with a 60 °C coolant temperature and achieves 80% heat recovery from liquid cooled equipment (Zimmermann et al., 2012).

It is important to note that ATES systems require to be balanced between the amount of imported heat and cold and the amount of exported heat and cold. An energy imbalance in cold and hot storage clusters can cause permanent temperature changes in the soil that could reduce the overall storage potential of the system and lead to environmental damage (Dvorak et al., 2020). Solutions exist to discard of surplus heat or cold, this would however mean a waste of energy and therefore a lack of synergy which is not desirable. Cooling capacity of the ATES system will be reused by the data center program, but requires additional demand from the other program to balance the ATES.

3.3. WATER FLOWS

Separate flows: all programs require water in varying quantities. Per m^2 of program, data centers account for 69.3% of the total of the three programs combined on a yearly basis. This is followed by the residential program at 19.4% and finally the greenhouse program at 11.3%.

Opportunities for synergy: as mentioned before (2.3.1), data center water has to be of good quality but does not have to be potable. A number of data center operators rely on flows of partially treated grey water from households for supplying data centers. For example, with Google’s system, treated grey water is used for 100 percent of cooling needs (Brown, 2012). Therefore, there is potential for creating synergy. Total data center water use can be significantly reduced through utilizing partially treated grey water from the residential and greenhouse program.

3.4. COMBINED FLOWS AND PROGRAMS

By using the previous findings it is possible to combine all flows and programs together. For this research, it will be assumed that the greenhouse is all-electric and thus no natural gas is used. The data center and residential program were already fully electric in previous calculations.

Some additional data is required to calculate total electricity demand for the combined programs. Research shows that energy consumption for space heating and cooling of buildings can be decreased by 40-80% by using an ATES system (Beernink et al, 2019). This electricity is mainly used for moving water between the wells. A heat pump will not be needed to raise temperatures in most instances due to the relatively high temperatures already used in the ATES system. Finally, grey water quality will have to be treated to improve quality for reuse in the datacenter. This is an additional power load on top of the existing power loads. Approximately 0.6 kWh/m^3 is required for this process (Hamza et al., 2022).

First, the aim is to achieve heat balance by combining data center with either the residential or greenhouse program. The results are as follows:

- Combined flow calculations show potential of 10.000 m^2 data center program providing enough waste heat for heating over 1.200.000 m^2 of residential program per year. Heat balance at 0 MJ, meaning all residual heat is used. Water surplus. These calculations can be found in Appendix J.
- Combined flow calculations show potential of 10.000 m^2 data center program providing enough waste heat for heating over 700.000 m^2 of greenhouse program per year. Heat balance at 0 MJ. Water surplus. These calculations can be found in Appendix J.

The second aims is to achieve water balance by combining data center program with either the residential or greenhouse program. The results are as follows:

- Combined flow calculations show potential of roughly 75.000 m^2 residential program providing enough grey water to supply 10.000 m^2 data center program with water for a year. Water balance at 0 L. Heat and cold surplus. These calculations can be found in Appendix K.
- Combined flow calculations show potential of roughly 245.000 m^2 greenhouse program providing enough grey water to supply 10.000 m^2 data center program with water for a year. Water balance at 0 L. Heat and cold surplus. These calculations can be found in Appendix L.

The calculations show that cooling will always be in surplus due to high recovery factors and a relatively small cooling demand in the data center as a result of low PUE. None of the other programs have a significant cooling demand as a result of the assumptions made in previous sections. Therefore, cold stored in the cooling well will either be discarded (not sustainable) or it has to be used in a different program that has a cooling demand.

Ideally, synergy (i.e. balance) is achieved for all flows. For electricity it has been shown that synergy is not achievable as all programs require electricity but no program generates electricity. Regarding heating and water flows, the calculations show that synergy is possible, The calculations will have to be scaled down however, as the gross floor area calculated for balance is simply too large if the data center program remains at 10.000 m^2. Otherwise, all programs will not realistically fit in a single building in the urban environment.

Therefore, a strategy will be recommended. In this strategy, both data center program (8.500 m^2), residential program (56.000 m^2) and greenhouse program (25.000 m^2) are combined in one single building to create a total gross floor area of 89.500 m^2. Yearly water balance is achieved, which allows to significantly reduce demand on water resources while still achieving a diverse building program. In addition, both the residential program and greenhouse program are fully supplied with their yearly heat demand. The surplus of heat capacity left in the ATES system is connected to a district heating network, therefore providing a lot of heat to the urban environment. The consumers of heat can range from even more homes and greenhouses to schools, theaters, offices, pools, hospitals etc. This also applies to cooling, as there is a large surplus of cooling supply in all of these calculations. Connecting the ATES system to a district cooling network to for example any of the previously mentioned functions is recommended. The calculations for this strategy can be found in Appendix N. The material flow analysis diagram can be found in Appendix O.

It is important to note that the surface area of the recommended strategy has been chosen to prove the potential of flow synergy. The data center does not have to be 8.500 m^2, it can almost have any size. It does not matter which surface area is chosen: as long as the ratio between the programs as shown in Appendix N (85:560:250) is maintained the same relative amount of synergy will be achieved. In addition, the ratio shows that the minimum requirements for synergy are 85 m^2 data center combined with 560 m^2 residential and 250 m^2 greenhouse.

IV. CONCLUSIONS

The aim of this research is to discover whether it is possible to create synergy between electricity, cooling/heating and water flows in a mixed-use building that contains both data center, residential and greenhouse program. All flows for the different programs have been analyzed, quantified and visualized. Through the findings, the flows and programs have been linked together. This in turn created possibilities to redesign and optimize the processes of these flows and reduce the amount of resources needed (input) while at the same time reducing waste (output). No synergy for electricity could be established, as no program produces electricity and all programs require electricity. For cooling/heating, significant decreases in energy consumption for heating and cooling have been made possible for all programs by reusing data center heat coupled with Aquifer Thermal Energy Storage (ATES). Finally, through reutilizing grey water from the residential and greenhouse program it is possible to reduce additional data center water demand significantly.

Further research into different contexts in relation to flows is needed. The research has mainly been focused on The Netherlands, where mechanical cooling loads for the residential and greenhouse program have largely been dismissed. The data center, residential and greenhouse program could have significantly different cooling and heating requirements in a different context, which might potentially change the balance of the ATES system and impact the overall synergetic system. Finally, it has briefly been discussed that there is possibility for electricity to be generated in each program by utilizing systems such as solar panels and wind turbines. These generation processes fall outside the scope of this research, but they could potentially be part of the solution to create electrical synergy between programs.

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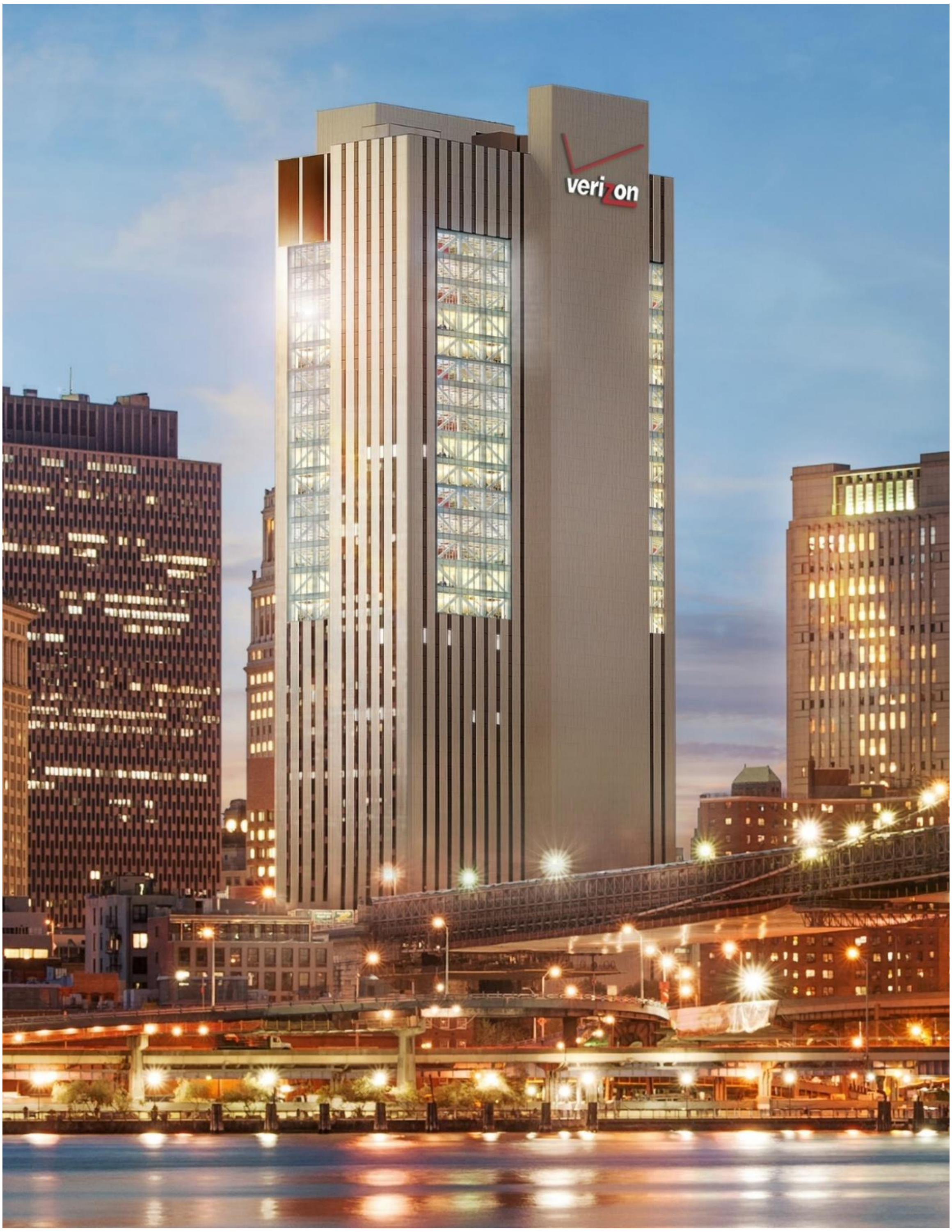
APPENDIX A

Photographs of data centers in a rural context as well as in an urban context.

Google data center in Eemshaven, The Netherlands (Google, n.d.).

Altice data center in Covilhã, Portugal (Price, 2018).

APPENDIX A (continued)



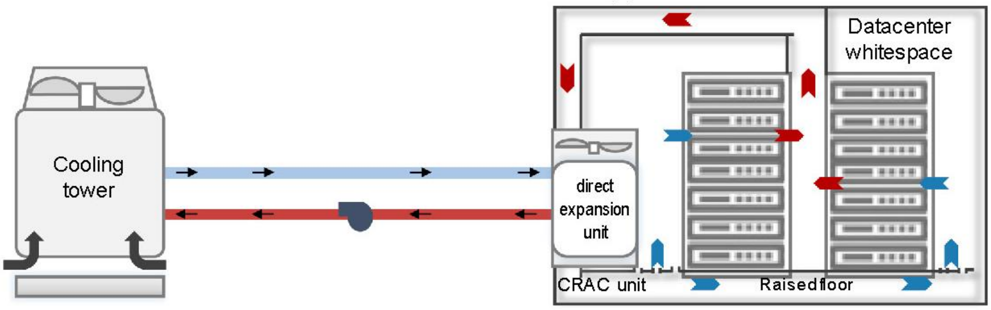
Rendering of 375 Pearl Street data center in New York, United States (Sabey, n.d.).

APPENDIX A (continued)

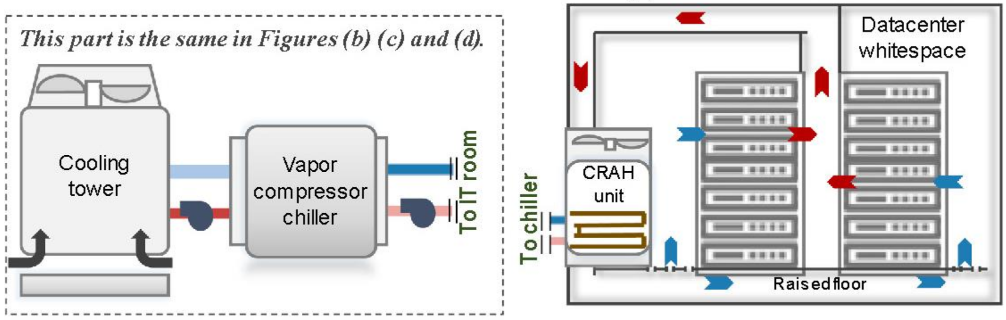
Competition entry of Mecanoo architects for a data center in Shenzhen, China (Mecanoo, 2018).

APPENDIX B

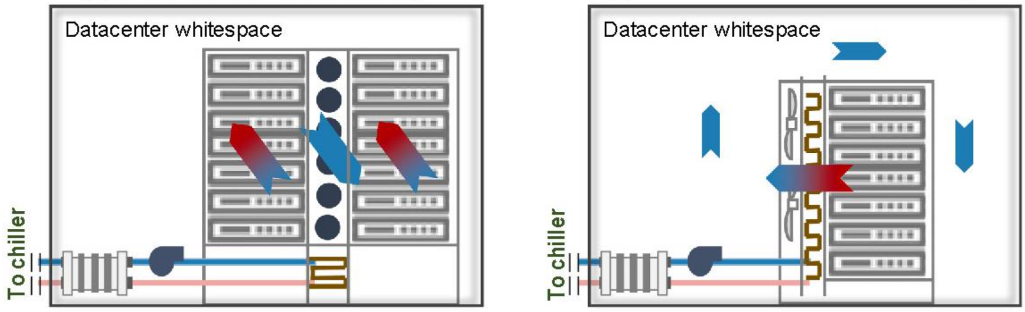
Schematics of different air-cooled systems (a) Schematics of CRAC units (b) Schematics of CRAH units (c) Schematics of in-row cooling (d) Schematics of rear door cooling. (Huang et al., 2020).



(a) Schematics of CRAC units



(b) Schematics of CRAH units



(c) Schematics of in-row cooling

(d) Schematics of rear door cooling

APPENDIX C

Flow calculations for a data center with 8 kW racks. Low PUE and WUE.

Program:	**data center**		
Gross floor area (GFA):	10.000	m^2	
Time period:	1 year		
Location:	The Netherlands		
Data center grey space:	3.500	m^2	35% of total (Rasmussen, 2006)
Data center white space:	6.500	m^2	35% of total (Rasmussen, 2006)
Number of racks:	2.500	racks	2.6 m^2 per rack (Rasmussen, 2005)

Electricity flows

Power per rack:	8	kW	average 2020 (Uptime Institute)
Total rack power:	20.000	kW	80% of total IT load
Rack power per white space m^2:	3	kW/m^2	
Additional IT equipment power:	5.000	kW	20% of total IT load
Total IT equipment power:	25.000	kW	
IT equipment power per white space m^2:	3,8	kW/m^2	
PUE (power usage effectiveness):	1,1		performance from Google (2021)
Total facility power:	27.500	kW	
Facility in use per year:	8.760	hours	year-round 24 hours a day
Electricity consumed per year:	240.900.000	kWh	

Cooling / heating flows

Electricity converted to heat:	90%		low-grade waste heat (Luo et al., 2019)
Heat output per year:	780.516.000	MJ	1 kWh = 3,6 MJ
Heat output per m^2 data center:	78.052	MJ/m^2	
Cooling demand per year:	43.362.000	MJ	based on Appendix F, 5% of total
Cooling demand per m^2 data center:	4.336	MJ/m^2	

Water flows

WUE (water usage effectiveness):	0,3		performance from Meta (2021)
Water usage per year:	62.634.000	L	

APPENDIX D

Flow calculations for 10.000 m^2 residential program in The Netherlands. Adjusted for all-electric.

Program:	**residential**		
Gross floor area (GFA):	10.000	m^2	
Time period:	1 year		
Location:	The Netherlands		
Form factor (ratio GFA/LFS):	80%		new construction
Lettable floor space (LFS):	8.000	m^2	
Lettable floor space per apartment:	65	m^2	
Number of apartments:	123	units	
Residents per apartment:	3	persons	assumed for 1 household
Total residents:	369	persons	

Electricity flows

Yearly per household electricity consumption (excl. heating + cooking):	3.000	kWh	rounded (CBS, 2022a)
Yearly per household natural gas consumption (= heating + cooking):*	*1.000*	*m^3*	*rounded (CBS, 2022a)*
Calorific value of natural gas:	*35,17*	*MJ/m^3*	
Energy in natural gas:	*9,77*	*kWh/m^3*	*1 kWh = 3,6 MJ*
Heat pump coefficient of performance (COP):	*4*		*ground source heat pump*
Yearly per household heating electricity consumption:	2.293	kWh	excl. cooking (Eurostat, 2022)
Yearly all-electric per household electricity consumption:	5.889	kWh	
Total yearly all-electric household electricity consumption:	724.839	kWh	

Cooling / heating flows

Yearly heat demand per household (= excl. cooking):	33.025	MJ
Total heat demand households:	4.064.570	MJ

Water flows

Water usage per capita per day:	130	L	CBS, 2019
Water usage per household per year:	142.350	L	
Water usage per year for all households:	17.520.000	L	

* saved on a yearly basis due to all-electric

APPENDIX E

Flow calculations for 10.000 m^2 high-yield greenhouse in The Netherlands. Powered with natural gas.

Program:	**greenhouse**		
Gross floor area (GFA):	10.000	m^2	
Time period:	1 year		
Location:	The Netherlands		
Greenhouse crop-free area:	1.500	m^2	15% of total (CBS, 2022b; CBS, 2022c)
Greenhouse crop cultivation area:	8.500	m^2	85% of total
Growing area for tomatoes:	2.550	m^2	30%
Growing area for bell peppers:	2.975	m^2	35%
Growing area for cucumbers:	2.975	m^2	35%
Yearly yield for tomatoes:	173.400	kg	68 kg/m^2 (De Gelder et al., 2012)
Yearly yield for bell peppers:	205.275	kg	69 kg/m^2 (De Gelder et al., 2011)
Yearly yield for cucumbers:	208.250	kg	70 kg/m^2 (Schuddebeurs et al., 2015)
Total yearly yield	586.925	kg	

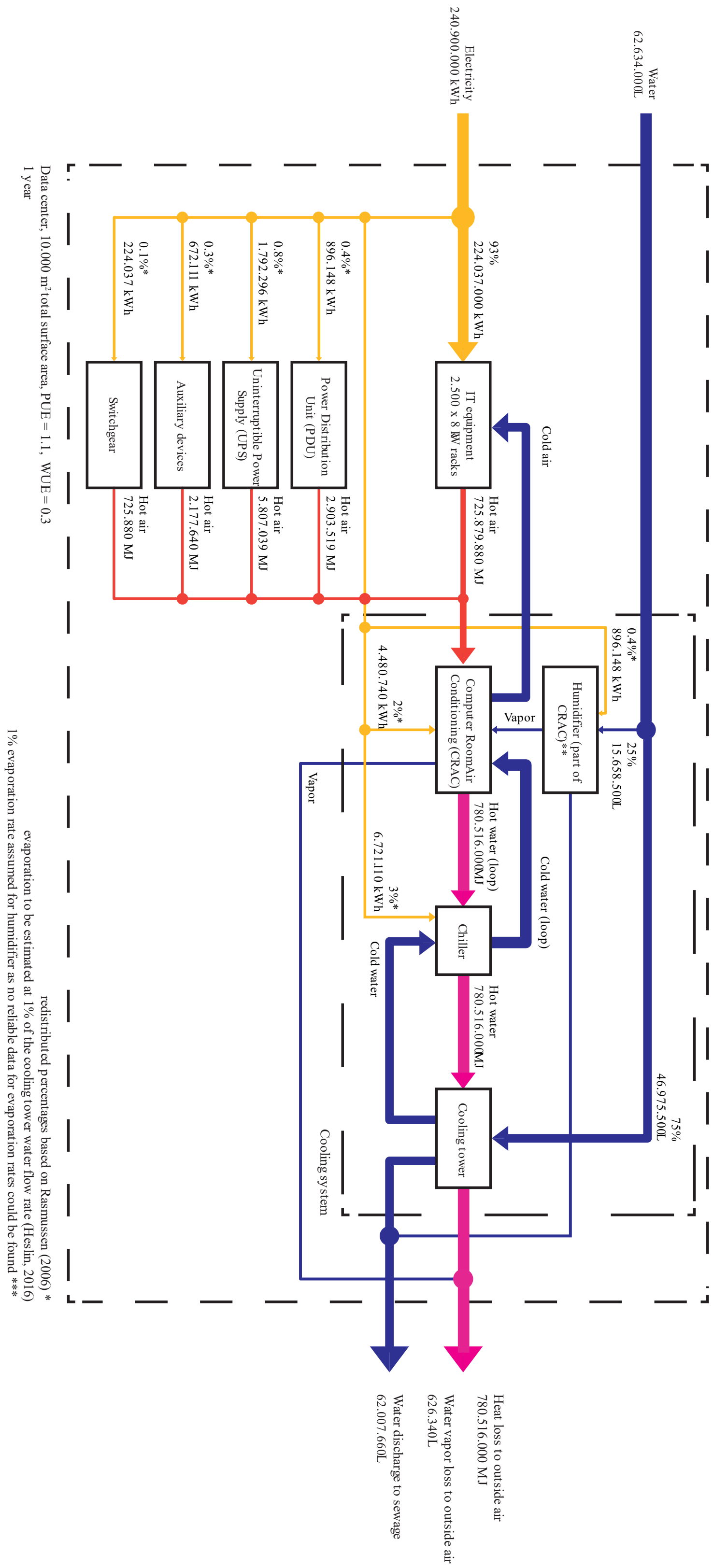
Electricity flows			
Lighting for tomatoes, yearly:	647.700	kWh	254 kWh/m^2 (Van der Velden & Smit, 2013)
Lighting for bell peppers, yearly:	175.525	kWh	59 kWh/m^2
Lighting for cucumbers, yearly:	312.375	kWh	105 kWh/m^2
Electricity used for lighting, yearly:	1.135.600	kWh	82% of total
Electricity used for other equipment, yearly:	249.278	kWh	18% of total
Total electricity used, yearly:	1.384.878	kWh	

Cooling / heating flows			
Yearly natural gas consumption for tomatoes:	58.650	m^3	23 m^3/m^2 (De Gelder et al., 2012)
Yearly natural gas consumption for bell peppers:	66.045	m^3	22.2 m^3/m^2 (De Gelder et al., 2011)
Yeary natural gas consumption for cucumbers:	59.500	m^3	20 m^3/m^2 (Schuddebeurs et al. 2015)
Total yearly gas consumption:	184.195	m^3	
Calorific value of natural gas:	*35,17*	*MJ/m^3*	*average for The Netherlands*
Yearly heat demand for tomatoes:	2.062.721	MJ	
Yearly heat demand for bell peppers:	2.322.803	MJ	
Yearly heat demand for cucumbers:	2.092.615	MJ	
Toteal yearly heat demand:	6.478.138	MJ	

Water flows			
Water demand for tomatoes:	2.601.000	L	15 liters per kg (Van Kooten et al., 2006)
Water demand for bell peppers:	4.680.270	L	22.8 liters per kg
Water demand for cucumbers:	2.915.500	L	14 liters per kg
Total water demand:	10.196.770	L	

APPENDIX F

Material flow analysis diagram for a 10.000 m^2 data center. Calculations can be found in Appendix C.



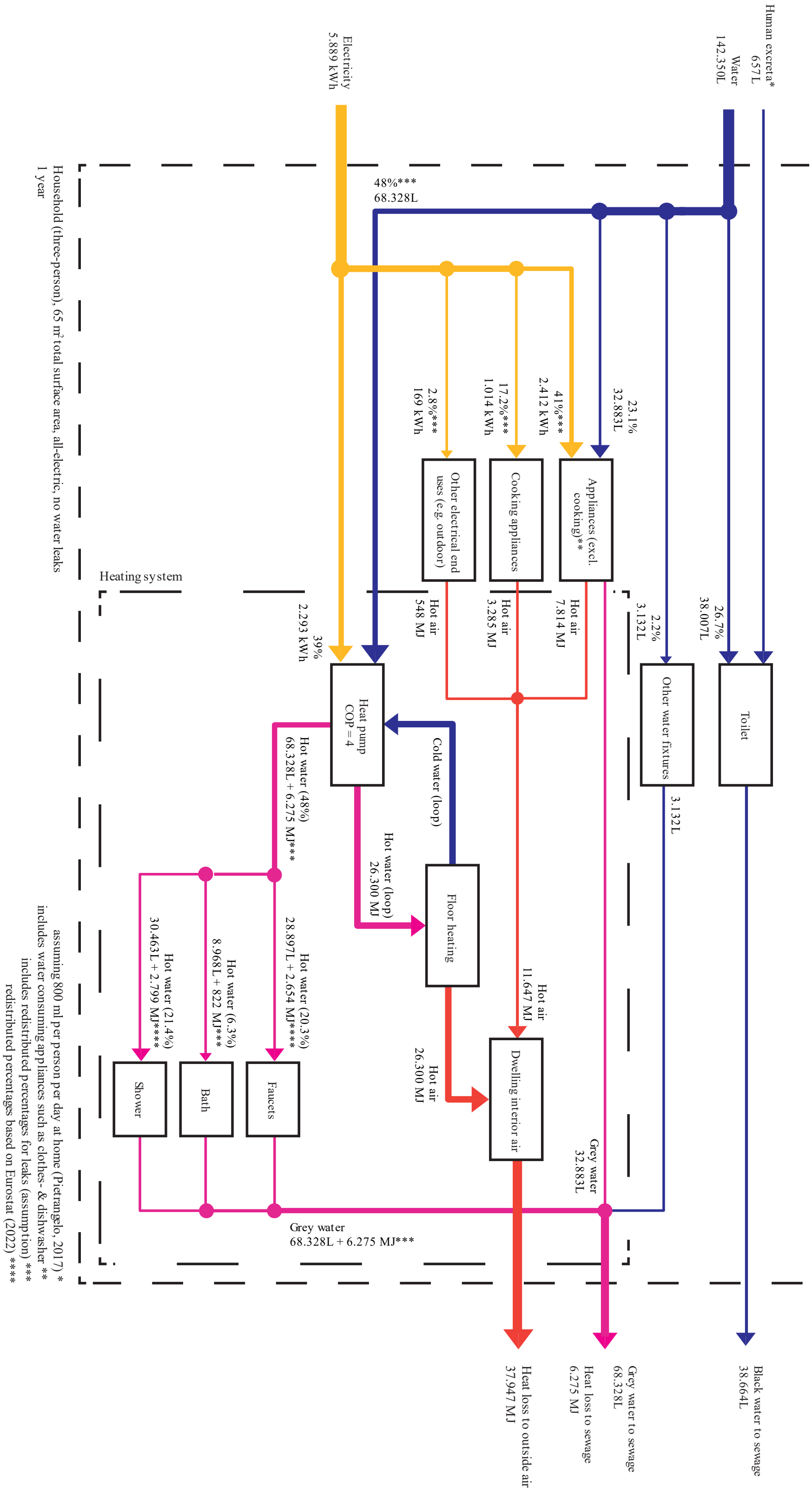
redistributed percentages based on Rasmussen (2006) *

evaporation to be estimated at 1% of the cooling tower water flow rate (Heslin, 2016)

1% evaporation rate assumed for humidifier as no reliable data for evaporation rates could be found ***

APPENDIX G

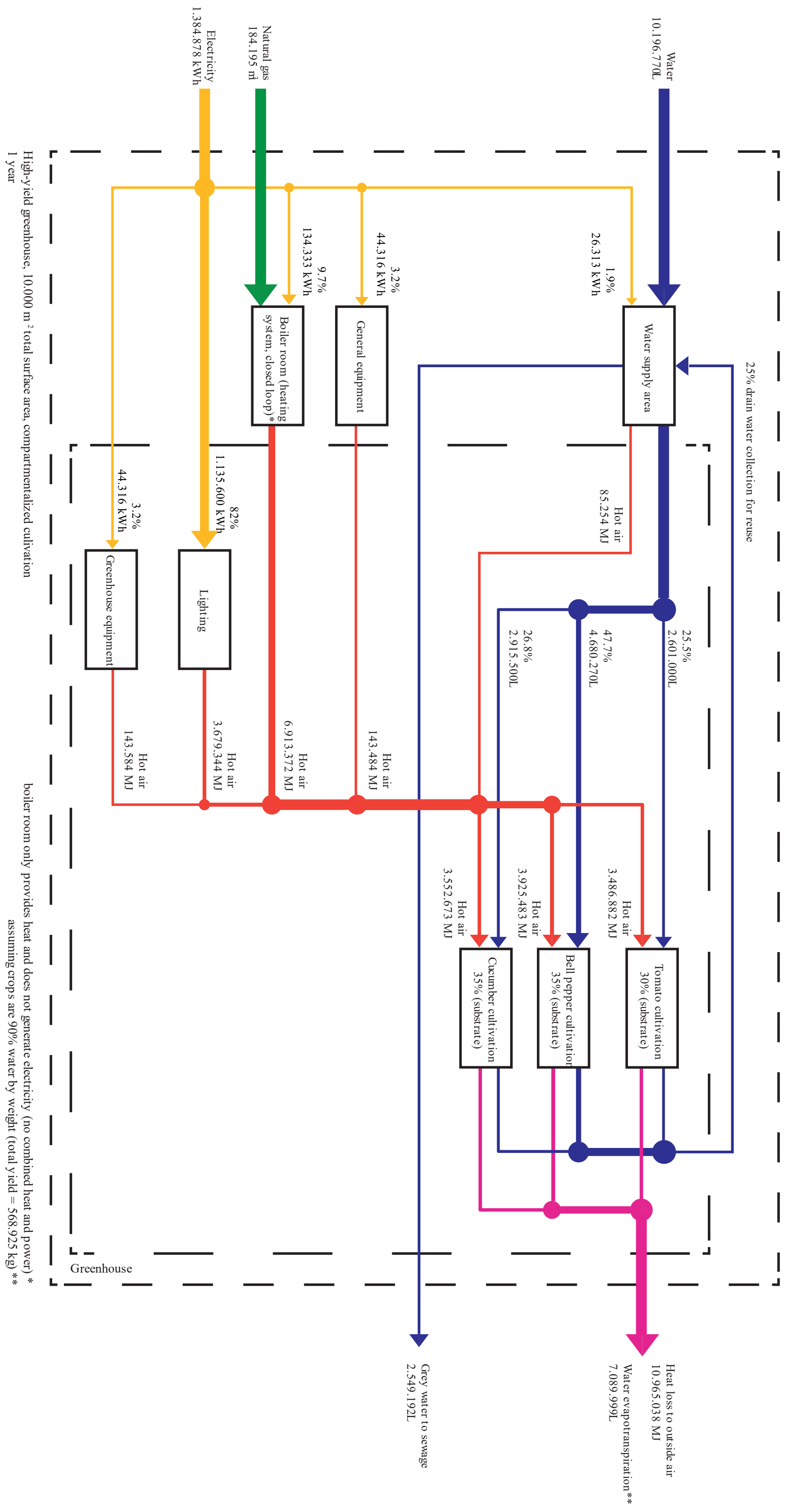
Material flow analysis diagram for a household. Calculations can be found in Appendix D.



assuming 800 ml per person per day at home (Pietrangelo, 2017) *
includes water consuming appliances such as clothes- & dishwasher **
includes redistributed percentages for leaks (assumption) ***
redistributed percentages based on Eurostat (2022) ****

APPENDIX H

Material flow analysis diagram for a 10.000 m^2 greenhouse. Calculations can be found in Appendix E.



APPENDIX I

Flow calculations distributed over gross floor surface area per program.

Data center program

Electricity demand	24.090	kWh/m^2	
Cooling demand	4.336	MJ/m^2	based on Appendix F, 5% of total
Heat output	78.052	MJ/m^2	
Water demand	6.263	L/m^2	

Residential program

Electricity demand	72	kWh/m^2	
Heat demand	406	MJ/m^2	
Water demand	1.752	L/m^2	
Grey water output	841	L/m^2	based on Appendix G, 48% of total program

Greenhouse program

Electricity demand	138	kWh/m^2	not adjusted to include heating
Heat demand	648	MJ/m^2	
Water demand	1.020	L/m^2	
Grey water output	255	L/m^2	based on Appendix H, 25% of total

APPENDIX J

Combined flow calculations showing potential of 10.000 m^2 data center program providing enough waste heat for over 1.200.000 m^2 of residential program. Heat balance at 0 MJ. Water and cold surplus.

Data center program

Base scale factor:	*100%*		*calculates parameters from Appendix A*
Gross floor area:	10.000	m^2	
Number of racks:	2500	racks	
Heat output per year:	780.516.000	MJ	
Cooling demand per year:	43.362.000	MJ	based on Appendix F, 5% of total
Heat recovery factor (liquid cooling):	80%		Zimmermann et al., 2012
Yearly heat supply to ATES:	624.412.800	MJ	
Water usage per year:	62.634.000	L	

Residential program

Base scale factor:	*12289,86730%*		*calculates parameters from Appendix B*
Gross floor area:	1.228.987	m^2	
Number of apartments:	15.126	units	
Yearly heat demand:	499.530.240	MJ	
Grey water output per year:	1.033.528.680	L	based on Appendix G, 48% of total program

Greenhouse program

Base scale factor:	*0%*		*calculates parameters from Appendix C*
Gross floor area:	0	m^2	
Total yearly yield:	0	kg	30% tomatoes, 35% bell peppers & 35% cucumbers
Total yearly heat demand:	0	MJ	
Grey water output per year:	0	L	based on Appendix H, 25% of total

Aquifer Thermal Energy Storage (ATES)

Yearly heat supply to ATES:	624.412.800	MJ	
ATES heat recovery factor:	80%		Kleyböcker & Bloemendal, 2020
Yearly heat recovery:	499.530.240	MJ	
ATES cold recovery factor:	90%		
Yearly cold recovery:	561.971.520	MJ	Kleyböcker & Bloemendal, 2020
Yearly electricity required for ATES system:	9.357.372	kWh	80% energy savings (Beernink et al., 2019)
of which data center share	*2.409.000*	*kWh*	*based on Appendix F, 5% of total program*
of which residential share	*6.948.372*	*kWh*	*based on Appendix G, 39% of total program*
of which greenhouse share	*0*	*kWh*	*based on Appendix H*

Cooling / heating synergy

positive balance indicates a surplus, negative a deficiency

Heat balance	0	MJ	heat recovery minus residential & greenhouse heat demand
Cold balance	518.609.520	MJ	cold recovery minus data center cooling demand

Water synergy

positive balance indicates a surplus, negative a deficiency

Water balance	970.894.680	L	(residential + greenhouse water demand) - data center water demand
Yearly water treatment (grey water):	62.634.000	L	required for water to be used in data center

Electricity demand

Water treatment electricity required:	0,6	kWh/m^3	Hamza et al., 2022
Yearly electricity for water treatment:	37.580	kWh	grey water treatment for data center use
Total yearly electricity demand:	295.277.415	kWh	data center (incl. water treatment) + residential + greenhouse

APPENDIX K

Combined flow calculations showing potential of 10.000 m^2 data center program providing enough waste heat for over 700.000 m^2 of greenhouse program. Heat balance at 0 MJ. Water and cold surplus.

Data center program

Base scale factor:	*100%*		*calculates parameters from Appendix A*
Gross floor area:	10.000	m^2	
Number of racks:	2500	racks	
Heat output per year:	780.516.000	MJ	
Cooling demand per year:	43.362.000	MJ	based on Appendix F, 5% of total
Heat recovery factor (liquid cooling):	80%		Zimmermann et al., 2012
Yearly heat supply to ATES:	624.412.800	MJ	
Water usage per year:	62.634.000	L	

Residential program

Base scale factor:	*0%*		*calculates parameters from Appendix B*
Gross floor area:	0	m^2	
Number of apartments:	0	units	
Yearly heat demand:	0	MJ	
Grey water output per year:	0	L	based on Appendix G, 48% of total program

Greenhouse program

Base scale factor:	*7711,01555%*		*calculates parameters from Appendix C*
Gross floor area:	771.102	m^2	
Total yearly yield:	45.257.878	kg	30% tomatoes, 35% bell peppers & 35% cucumbers
Total yearly heat demand:	499.530.240	MJ	
Grey water output per year:	196.568.630	L	based on Appendix H, 25% of total

Aquifer Thermal Energy Storage (ATES)

Yearly heat supply to ATES:	624.412.800	MJ	
ATES heat recovery factor:	80%		Kleyböcker & Bloemendal, 2020
Yearly heat recovery:	499.530.240	MJ	
ATES cold recovery factor:	90%		
Yearly cold recovery:	561.971.520	MJ	Kleyböcker & Bloemendal, 2020
Yearly electricity required for ATES system:	30.160.680	kWh	80% energy savings (Beernink et al., 2019)
of which data center share	*2.409.000*	*kWh*	*based on Appendix F, 5% of total program*
of which residential share	*0*	*kWh*	*based on Appendix G, 39% of total program*
of which greenhouse share	*27.751.680*	*kWh*	*based on Appendix H*

Cooling / heating synergy — positive balance indicates a surplus, negative a deficiency

Heat balance	0	MJ	heat recovery minus residential & greenhouse heat demand
Cold balance	518.609.520	MJ	cold recovery minus data center cooling demand

Water synergy — positive balance indicates a surplus, negative a deficiency

Water balance	133.934.630	L	(residential + greenhouse water demand) - data center water demand
Yearly water treatment (grey water):	62.634.000	L	required for water to be used in data center

Electricity demand

Water treatment electricity required:	0,6	kWh/m^3	Hamza et al., 2022
Yearly electricity for water treatment:	37.580	kWh	grey water treatment for data center use
Total yearly electricity demand:	337.367.290	kWh	data center (incl. water treatment) + residential + greenhouse

APPENDIX L

Combined flow calculations showing potential of roughly 75.000 m^2 residential program providing enough grey water to supply a 10.000 m^2 data center program. Water balance at 0 L. Heat and cold surplus.

Data center program

Base scale factor:	*100%*		*calculates parameters from Appendix A*
Gross floor area:	10.000	m^2	
Number of racks:	2500	racks	
Heat output per year:	780.516.000	MJ	
Cooling demand per year:	43.362.000	MJ	based on Appendix F, 5% of total
Heat recovery factor (liquid cooling):	80%		Zimmermann et al., 2012
Yearly heat supply to ATES:	624.412.800	MJ	
Water usage per year:	62.634.000	L	

Residential program

Base scale factor:	*744,79167%*		*calculates parameters from Appendix B*
Gross floor area:	74.479	m^2	
Number of apartments:	917	units	
Yearly heat demand:	30.272.578	MJ	
Grey water output per year:	62.634.000	L	based on Appendix G, 48% of total program

Greenhouse program

Base scale factor:	*0%*		*calculates parameters from Appendix C*
Gross floor area:	0	m^2	
Total yearly yield:	0	kg	30% tomatoes, 35% bell peppers & 35% cucumbers
Total yearly heat demand:	0	MJ	
Grey water output per year:	0	L	based on Appendix H, 25% of total

Aquifer Thermal Energy Storage (ATES)

Yearly heat supply to ATES:	624.412.800	MJ	
ATES heat recovery factor:	80%		Kleyböcker & Bloemendal, 2020
Yearly heat recovery:	499.530.240	MJ	
ATES cold recovery factor:	90%		
Yearly cold recovery:	561.971.520	MJ	Kleyböcker & Bloemendal, 2020
Yearly electricity required for ATES system:	2.830.086	kWh	80% energy savings (Beernink et al., 2019)
of which data center share	*2.409.000*	*kWh*	*based on Appendix F, 5% of total program*
of which residential share	*421.086*	*kWh*	*based on Appendix G, 39% of total program*
of which greenhouse share	*0*	*kWh*	*based on Appendix H*

Cooling / heating synergy — positive balance indicates a surplus, negative a deficiency

Heat balance	469.257.662	MJ	heat recovery minus residential & greenhouse heat demand
Cold balance	518.609.520	MJ	cold recovery minus data center cooling demand

Water synergy — positive balance indicates a surplus, negative a deficiency

Water balance	0	L	(residential + greenhouse water demand) - data center water demand
Yearly water treatment (grey water):	62.634.000	L	required for water to be used in data center

Electricity demand

Water treatment electricity required:	0,6	kWh/m^3	Hamza et al., 2022
Yearly electricity for water treatment:	37.580	kWh	grey water treatment for data center use
Total yearly electricity demand:	244.230.688	kWh	data center (incl. water treatment) + residential + greenhouse

APPENDIX M

Combined flow calculations showing potential of roughly 245.000 m^2 greenhouse program providing enough grey water to supply a 10.000 m^2 data center program. Water balance at 0 L. Heat and cold surplus.

Data center program

Base scale factor:	*100%*		*calculates parameters from Appendix A*
Gross floor area:	10.000	m^2	
Number of racks:	2500	racks	
Heat output per year:	780.516.000	MJ	
Cooling demand per year:	43.362.000	MJ	based on Appendix F, 5% of total
Heat recovery factor (liquid cooling):	80%		Zimmermann et al., 2012
Yearly heat supply to ATES:	624.412.800	MJ	
Water usage per year:	62.634.000	L	

Residential program

Base scale factor:	*0%*		*calculates parameters from Appendix B*
Gross floor area:	0	m^2	
Number of apartments:	0	units	
Yearly heat demand:	0	MJ	
Grey water output per year:	0	L	based on Appendix G, 48% of total program

Greenhouse program

Base scale factor:	*2457,01333%*		*calculates parameters from Appendix C*
Gross floor area:	245.701	m^2	
Total yearly yield:	14.420.825	kg	30% tomatoes, 35% bell peppers & 35% cucumbers
Total yearly heat demand:	159.168.718	MJ	
Grey water output per year:	62.634.000	L	based on Appendix H, 25% of total

Aquifer Thermal Energy Storage (ATES)

Yearly heat supply to ATES:	624.412.800	MJ	
ATES heat recovery factor:	80%		Kleyböcker & Bloemendal, 2020
Yearly heat recovery:	499.530.240	MJ	
ATES cold recovery factor:	90%		
Yearly cold recovery:	561.971.520	MJ	Kleyböcker & Bloemendal, 2020
Yearly electricity required for ATES system:	11.251.707	kWh	80% energy savings (Beernink et al., 2019)
of which data center share	*2.409.000*	*kWh*	*based on Appendix F, 5% of total program*
of which residential share	*0*	*kWh*	*based on Appendix G, 39% of total program*
of which greenhouse share	*8.842.707*	*kWh*	*based on Appendix H*

Cooling / heating synergy

positive balance indicates a surplus, negative a deficiency

Heat balance	340.361.522	MJ	heat recovery minus residential & greenhouse heat demand
Cold balance	518.609.520	MJ	cold recovery minus data center cooling demand

Water synergy

positive balance indicates a surplus, negative a deficiency

Water balance	0	L	(residential + greenhouse water demand) - data center water demand
Yearly water treatment (grey water):	62.634.000	L	required for water to be used in data center

Electricity demand

Water treatment electricity required:	0,6	kWh/m^3	Hamza et al., 2022
Yearly electricity for water treatment:	37.580	kWh	grey water treatment for data center use
Total yearly electricity demand:	271.663.635	kWh	data center (incl. water treatment) + residential + greenhouse

APPENDIX N

Calculations showing recommended program strategy. Consisting of 8.500 m^2 data center program, 56.000 m^2 residential program and 25.000 m^2 greenhouse program.

Data center program

Base scale factor:	*85%*		*calculates parameters from Appendix A*
Gross floor area:	8.500	m^2	
Number of racks:	2125	racks	
Heat output per year:	663.438.600	MJ	
Cooling demand per year:	36.857.700	MJ	based on Appendix F, 5% of total
Heat recovery factor (liquid cooling):	80%		Zimmermann et al., 2012
Yearly heat supply to ATES:	530.750.880	MJ	
Water usage per year:	53.238.900	L	

Residential program

Base scale factor:	*560%*		*calculates parameters from Appendix B*
Gross floor area:	56.000	m^2	
Number of apartments:	689	units	
Yearly heat demand:	22.761.591	MJ	
Grey water output per year:	47.093.760	L	based on Appendix G, 48% of total program

Greenhouse program

Base scale factor:	*250%*		*calculates parameters from Appendix C*
Gross floor area:	25.000	m^2	
Total yearly yield:	1.467.313	kg	30% tomatoes, 35% bell peppers & 35% cucumbers
Total yearly heat demand:	16.195.345	MJ	
Grey water output per year:	6.372.981	L	based on Appendix H, 25% of total

Aquifer Thermal Energy Storage (ATES)

Yearly heat supply to ATES:	530.750.880	MJ	
ATES heat recovery factor:	80%		Kleyböcker & Bloemendal, 2020
Yearly heat recovery:	424.600.704	MJ	
ATES cold recovery factor:	90%		
Yearly cold recovery:	477.675.792	MJ	Kleyböcker & Bloemendal, 2020
Yearly electricity required for ATES system:	3.264.001	kWh	80% energy savings (Beernink et al., 2019)
of which data center share	*2.047.650*	*kWh*	*based on Appendix F, 5% of total program*
of which residential share	*316.609*	*kWh*	*based on Appendix G, 39% of total program*
of which greenhouse share	*899.741*	*kWh*	*based on Appendix H*

Cooling / heating synergy positive balance indicates a surplus, negative a deficiency

Heat balance	385.643.767	MJ	heat recovery minus residential & greenhouse heat demand
Cold balance	440.818.092	MJ	cold recovery minus data center cooling demand

Water synergy positive balance indicates a surplus, negative a deficiency

Water balance	227.841	L	(residential + greenhouse water demand) - data center water demand
Yearly water treatment (grey water):	53.238.900	L	required for water to be used in data center

Electricity demand

Water treatment electricity required:	0,6	kWh/m^3	Hamza et al., 2022
Yearly electricity for water treatment:	37.580	kWh	grey water treatment for data center use
Total yearly electricity demand:	210.404.991	kWh	data center (incl. water treatment) + residential + greenhouse

APPENDIX O

Material flow analysis diagram for recommended strategy. Calculations can be found in Appendix N.