Towards energetic circularity

greenhouse-supermarket-dwelling energy exchange

P.N. ten Caat

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greenhouse-supermarket-dwelling energy exchange

MSc thesis Delft University of Technology

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| Lidl & TU Delft

This master thesis research came forth from a TU Delft research. In February 2017, supermarket chain Lidl Holland approached the Technical University of Delft for consultancy on the subject of circularity. The Lidl has the ambition to transform their complete building stock and operations (e.g. transport) into the circular economy. Professor Andy van den Dobbelsteen and researcher ir. Luuk Graamans from the department of Architectural Engineering and Technology (AE+T) took this inquiry upon them and first came up with a general strategy (the *roadmap*, §3.1) on becoming circular. Dobbelsteen and Graamans not only considered the built environment but also elaborated on domestic truck transport and focused on two retail products. In the second part of the research, the strategy was translated into concrete actions for the Lidl to execute.

The final report was submitted in January 2018. More information on this research can be found in §9.6.

Both this thesis as well as the main research relate to the same subject, run parallel to each other and are both in close collaboration with the Lidl. For the rest they are independent from each other. Unlike the study by Dobbelsteen and Graamans is this master thesis is limited to the environmental impact due to the energy demand of the built environment only.

Since the Lidl supermarket has the role of initiator and client, one of their supermarkets was assigned as the research case. This subsequently determined the city block that formed the urban context of this thesis. The assigned Lidl supermarket building is always included in the designed energy systems and the *Design* chapter is written from the perspective of the Lidl.

| Abstract

Problem definition and objective. Since the industrialization in the 18th century, urbanized and industrial countries base their whole economies on the consumption and destruction of fossil fuel and raw materials. In the past decades, after observing gradual global climate change, most governments acknowledge the environmental impact of their system and want a change. One way to reduce the pressure on the earth is by shifting to the circular economy. In terms of energy this means that society should be completely disconnected from fossil based energy and switch to renewable energy.

The objective of this research was to look at the potentials for a local energy network in an existing city context and to design a local energy system. A Lidl supermarket forms the centre of the system. In addition to this, a new element is introduced to the built environment : the urban rooftop greenhouse.

Study design. Broad literature survey on circularity, later converging to energy related literature studies. This is followed an energy analysis of a modern Lidl supermarket and energy balances are calculated for a greenhouse and a supermarket. The energy system is based on these energy balances.

Setting. This research focuses on one residential city block in Amsterdam Oud-West, the Netherlands. The block is enclosed by the Eerste Helmerstraat, Alberdingk Thijmstraat, Tweede Helmerstraat and the Nassaukade (52°21’51.7”N - 4°52’38.1”E). The Lidl located in this city block forms the case study of the research and will be refurbished/modernised in the near future. Two potential residential buildings are identified in this city block and are included in the energy system.

Supermarket analysis. A modern and sustainable Lidl supermarket in Stein is analysed to determine the energy performance of the refurbished Lidl in Amsterdam.

Energy quantification. Energy balances of the Lidl supermarket and the rooftop greenhouse are calculated. The energy system is based on the values retrieved from these energy balances. The heat demand of the local dwelling is determined from the literature survey.

Designing the energy model. The greenhouse, the supermarket and adjacent dwelling form an energetic triangle. First, the possibilities of energetic collaboration between individual components are explored. Secondly, all components are connected with each other through an underground energy storage. The size and indoor climate of the greenhouse are determined based on the required balance of this energy storage.

Urban design. Energy values and schemes are translated into a rough urban design proposal. Also social cohesion is taken into account here.

Results. Energetic interventions are translated into emission cutbacks of CO_2. The present situation, based on conventional climate systems, is compared with the all-electric situation from the designed energy model. The energy system designed in this research results in a cumulative CO_2 emission reduction of 60%.

Design tool. All possible parameters that influence the energetic performance of the system are collected in one Excel design tool. This tool allows for fast alterations to the design to achieve a balanced energy storage and changes are immediately translated to CO_2 emission cutbacks.

How can we combine the energy flows of a supermarket and a greenhouse and connect them to the adjacent dwelling to reduce the cumulative environmental footprint of the three functions?

[main research question]

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| General introduction - Towards Energetic Circularity

Ever since the technological development during the age of industrialisation and urbanisation of modern economies, fossil fuels are depleting more rapidly then ever before. Our mobility, products, economies and political power: a lot has been organized around the steady supply of fossil resources. We have become dependant on it and realizing this rises the question: what if we run out? Academics and politicians have different ideas on when this moment will happen but most of them agree on one thing: it will happen, sooner or later. If we want to keep the lifestyles we have become used to, change is inevitable.

Not only fossil fuels are depleting but also have some of earth's minerals been mined with such an intensity that today there is more of it above ground than under it. Certain technologies and products use so much of these finite raw materials that the first elements will disappear from this planet in the near future. But how is it possible to disappear from the closed system that the earth is? By definition, nothing disappears in a closed system.

So, if we talk about raw materials disappearing from our world, we actually should say that we have shaped, changed and applied those materials in such a way that when lifespan of a material has passed, the material is rendered to be useless. We call it waste and we burn or bury it. The elements have technically not disappeared, but due to improper designing they have lost their economical value.

Everything we create with the elements we mine from the earth reaches the end of its lifespan at some point. Products expire, wear out, break down, lose their efficiency, name it. Technological advancement and increasing desire for more comfort and health makes us want to update our products more often. Every year a new phone is put out on the market. We buy it because we consider the old one to be obsolete, even though it probably still works just fine. Consuming is rooted deep in the behaviour of the industrialized modern Western citizen.

More and more people come to realize that we have to start taking full responsibility towards the finite resources we mine from this planet. There are countless of recycling programs and over a decade ago the cradle-2-cradle ideology has been developed. Even though these are all steps towards the right direction, there is still an urge for a system that takes 100% responsibility for all the elements that it claims from this planet. We have come to the point where we have to research the possibilities and opportunities of the *circular economy*.

Circular economy in the building industry is about putting an end to the irresponsible use on raw virgin earth materials and prioritise full material reuse by means of smart designing and future-driven thinking.

In terms of energy demand, the circular economy strives to speed up the transition to renewable and infinite energy sources and a complete disconnection from fossil based energy. Disconnecting the urban environment from finite resources cuts down a large part of the global CO_2 emission, subsequently lowering the ecological footprint of the building on the planet.

Urban Greenhouses
A new element is added to the city context: the urban rooftop greenhouse. Constructing a greenhouse in the adjacency of a supermarket is not an unimaginable combination. By bringing food production to the place where it is also consumed, some transportation lines can in theory be shortened or even be removed. Cutting down on transport lines is one way to reduce the operational carbon dioxide emission of the Lidl. Growing a handful of products on-site will of course not solve the CO_2 issue of the transportation sector, but it is a step in the right direction and it shows the goodwill of the Lidl. Urban farming would contribute to the sustainable image the Lidl is striving for, which is of course of great value from a commercial point of view. A greenhouse has a large visual impact and is in sharp contrast with its concrete and stone surroundings, which may contribute to the overall attractiveness of the neighbourhood.

The main reason for including an urban greenhouse in the energy system is to have it work as a large and functional solar collector for the local energy system.

Towards Energetic Circularity (TEC) encompasses the transition of the existing urban environment to a system in which no longer fossil energy is used. For now, achieving absolute energetic circularity remains one bridge too far with the current state of technological development in the building industry hence the word *towards* in the title.

| Problem statement

Problem statement

The complete research framework can be retrieved from the TU Delft repository. Search on research title or author name.

Through all layers of government, sustainability goals are defined and strategies are thought up. As part of the European Union, the Netherlands has signed the 202020 climate agreement, in which is stated that 14% of our national energy demand should come from renewable source by the year 2020. Being a flat country with a tempered sea-climate and a long coastline, our primary renewable energy source is wind energy. All kinds of large scale wind energy projects are rushed into completion to meet the EU demands. The effect of these mega projects is large, however there are also energetic potentials waiting to be uncovered on the smaller building, cluster or neighbourhood scale and don't forget: many small streams make a big river.

Reaching circularity in the energetic field is a challenging task. Currently we are able to make energy neutral and energy positive buildings. Also, the latest Lidl supermarkets are already disconnected from the gas network. It is however not yet possible to be fully disconnected from the national electricity grid and even the most efficient supermarket is therefore not fossil free. It is a matter of time until renewable energy generating technologies or (electrical) energy storage capabilities have developed enough to sustain the building throughout the whole year, and not only during the summer. When this moment arrives, we could theoretically call the supermarket building fossil free.

In a supermarket, products are cooled or frozen 24/7 and the sales floor is also kept on a low temperature. This constant cooling results in an endless flow of excess heat.

Depending on the crop type, a greenhouse requires a warm, illuminated and humid environment for the crops to grow. In the summer this is achieved with the energy from the sun, but in the winter additional heating is necessary in order not to lose the whole harvest.

Adjacent dwellings within the building block date back to the early 1900's combined with sixties-seventies gallery flats. These buildings require high temperature heating in winter and that could be achieved with the flows of the greenhouse and the supermarket.

This is just a rough energetic description of the supermarket, a greenhouse and dwelling. Energetically speaking, a lot is happening in the three building types. It is valuable to explore the possibilities of energy exchange as a method of reducing the energy demand of the buildings. In this study, an energy system is purchased in which all functions can profit from each other's flows in such a way, that synergy will arise. When energetically connected, the buildings might get closer towards energy circularity than when the buildings operate individually from each other. This research is about exploring these synergy possibilities.

This research is hypothetical: the assumption that a greenhouse can contribute the mitigation of the total energy demand is researched.

| Research goals & research questions

Research goals

Main objective Lidl:
Exploring the opportunities of the circular economy for their complete building stock (supermarkets, distribution centres and offices) and operational processes, of which transport is the largest subject.

Main objective thesis:
Developing a local energy grid that energetically connects a Lidl supermarket, a rooftop greenhouse and the adjacent dwelling to reduce the cumulative energetic footprint.

Sub objectives

- Identify and quantify the energy flows in the supermarket;
- Identify and quantify the energy flows in a greenhouse;
- Define the energy demand of a standard Amsterdam household;
- Find ways to store energy for later use;
- Design a balanced energy system with the identified potential components from the city block.
- Reduce the energetic demand and by that the CO_2 emission of all the components included in the energy system;

Research questions

Main research question
How can we combine the energy flows of a supermarket and a greenhouse and connect them to the adjacent dwelling to reduce the cumulative environmental footprint of the three functions?

Sub questions

- What are the energetic flows in a supermarket, a greenhouse and dwellings that can be brought into an energy grid?
- What are the possibilities of energetic synergy between a supermarket, a greenhouse and adjacent dwellings (+additional functions if needed)?
- What are the possibilities of energy storage?

Assessment of the energy system
The environmental footprint is expressed in CO_2 emission as a result of the energy demand of the buildings. The CO_2 emission of the present *conventional* system is compared with the CO_2 emission of the new all-electric energy system (chapter 8).

Validation by the Lidl
This research is conducted in close contact with Lidl Holland. In §10.5, more information on this TU Delft-Lidl collaboration can be found and some of Lidl's first remarks on this graduation thesis are mentioned.

The Lidl Supermarket

Part I

1.1 | The Lidl Supermarket - Company profile

By origin, the Lidl supermarket (figur1.1) is a German retail chain that opened it's first store in the seventies. Nowadays the Lidl supermarkets are part of the Lidl Stiftung & Co. KG, a limited partnership, which again is part of the Swartz Gruppe holding company. The Lidl is primarily active in the Western and central countries of Europe and has ambitions to expand to the Eastern regions of Europe and North-America. In the spring of 2015 the Lidl became the largest supermarket of Europe, passing the Carrefour, with a turnover of 79.3 billion Euros (Brandes, 2015).

In 1996 the Lidl settled in The Netherlands. Today, the chain has over 400 supermarkets and 6 distribution centres spread around the country (Figure 1.2).

Lidl supermarkets operate within the discount segment of retail. This means the store offers its products systematically for a lower price compared to conventional supermarkets. By only selling fast running products, displaying and selling the groceries from boxes or pallets, not offering top brands but only carefully selected house brands and making customized purchasing contracts with their suppliers, the Lidl presses the food prices down. Currently the Lidl offers ~1500 different types of food which is regulated nationally. Next to this, the supermarket has a non-food section, which is Europe-wide organized.

The company operates around the slogan 'Op weg naar morgen' (On our way to tomorrow), implying that its ambitions are aimed at the future. The Lidl's sustainable strategy is organized around the four pillars (Lidl, 2015b):

- Assortment
- Climate
- Society
- Employees.

More about the Lidl and its sustainable operations, the climate pillar, in the next chapter.

Figure 1.1: The company logo

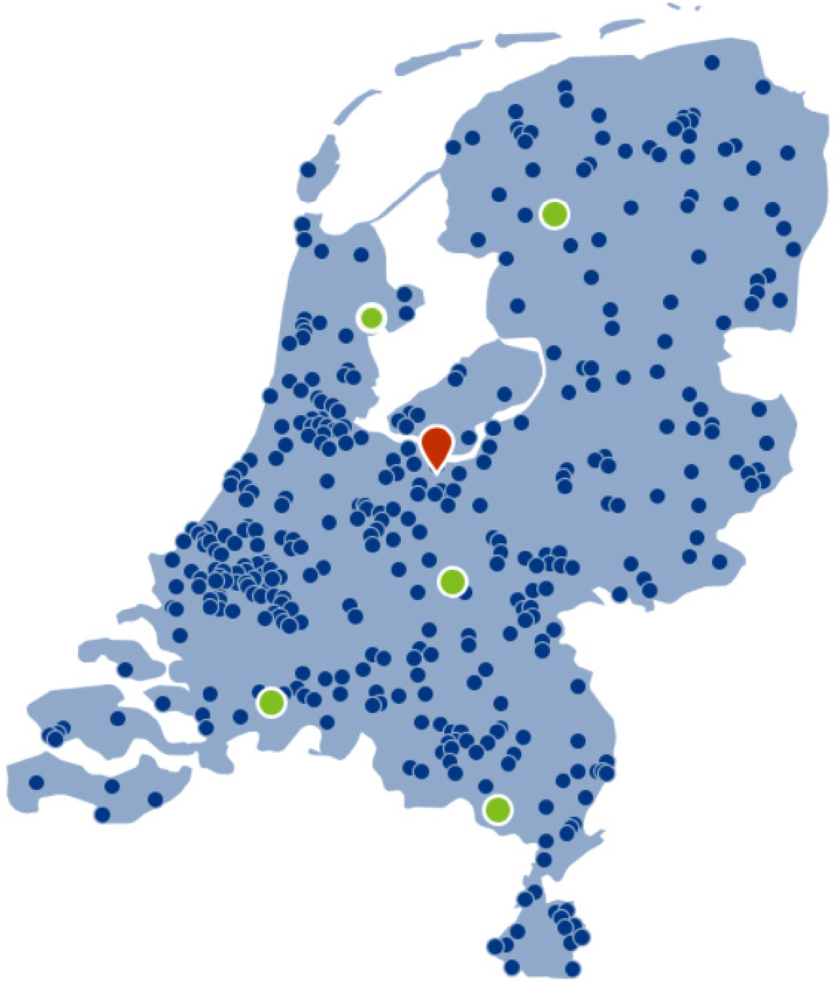


Figure 1.2: Lidl supermarkets and distribution centres spread around the Netherlands. The main office, red arrow, is located in Huizen (Utrecht). The latest distribution centre in Waddinxveen is not yet pictured.

1.2 | Current sustainability program Lidl Holland

Sustainable climate goals set by the government. Increasing customer awareness and expectations about sustainability. Rising energy prices. All good reasons for a supermarket to gradually shift to a sustainable operation. Since practically all of the competition is investing in sustainability, it would be reckless to ignore this new standard.

The Lidl claims they are always looking for new developments and innovations to downsize the ecological footprint of their buildings and operational processes. In 2013 the supermarket built a distribution centre (DC) in Heerenveen with the *excellent* BREEAM certification. Three years later, a Lidl DC with an *outstanding* BREEAM certification opened its doors in Waddinxveen. In 2018, the seventh Lidl DC will be built in Oosterhout and this one will even be more sustainable then the previous two (Dijkhuizen, 2016).

Not only energy efficient distribution centres are built in a fast paste, also all Lidl's future supermarkets will meet the requirements to earn the *A^{++++} energy label*. Their renovated branch in Stein (Limburg, The Netherlands) is their first A^{++++} supermarket and now sets the standard for all future Lidl supermarkets, see box 1.

In the annual year report, Lidl discusses the progress they have made, show their current consumption and explain sustainability goals for the coming years. General sustainability targets that have been set by the Lidl Nederland are (2015a):

- Between 2010 and 2020, 20% more energy efficient. The goal is set on 2% annually;
- 10 supermarkets will be fitted with PV systems per year;
- All new Lidl buildings will have energy label A^{++++};
- From 2018 onwards, all Lidl buildings are disconnected from the gas network;
- All Lidl employees are trained to work in a sustainable way, according to the ISO50001;
- The Lidl strives to maximize to loading factor of their trucks. Currently it is above 90%;
- Lidl is seeking the consult of the TU Delft to explore the opportunities of the circular economy.

Lidl Zero

The next step in the Lidl sustainability ambition is the *Lidl Zero* concept. Lidl Zero indicates that a supermarket has an Energy Performance Coefficient (EPC) of 0, including both the building related and the operational energy consumption. This energetic performance is equal to the Dutch *nul-op-de-meter* concept. These new supermarkets should theoretically compensate all the energy they use with renewable energy that has been generated on site (or close to the site). It goes without saying that achieving this performance is preceded with efficient energy reducing measures, preferably on a passive way.

The concept goes beyond the ambitions of the government: Dutch law formulates that from 31-12-2020 all new buildings should have an EPC of near zero, <u>only</u> including the building related energy consumption and <u>excluding</u> the user related energy. Taken that the major part of the total electricity consumption of a supermarket is demanded for product cooling (= user related energy), achieving the first proven Lidl Zero supermarket is tough challenge.

[1] *http://www.rvo.nl/initiatieven/energiezuiniggebouwd/lidl-filiaal)*

(1) A^{++++} Lidl in Stein

The new Lidl supermarket in Stein (Limburg) is the first building in the Netherlands with Energy label A^{++++}. This is the highest possible rating of this label and the supermarket chain has promised to keep this performance as the standard for all future supermarkets. An energy rating this high is achieved by the following measurements (Lidl Nederland, 2015a):

- *338 PV-panels generate electricity. On a sunny day they generate enough electricity for the whole building;*
- *100% energy saving LED lighting are installed and lights are activated by motion sensors;*
- *The building is not connected to the national gas network;*
- *Extra high insulation values;*
- *HR+++ triple layer insulating windows;*
- *Use of sustainable building materials. All used wood is demonstrable from sustainable sources;*
- *Charging points are installed to stimulate electrical customer transport;*
- *Rainwater is collected from the roof and the parking lots and is infiltrated into the earth underneath the site.*

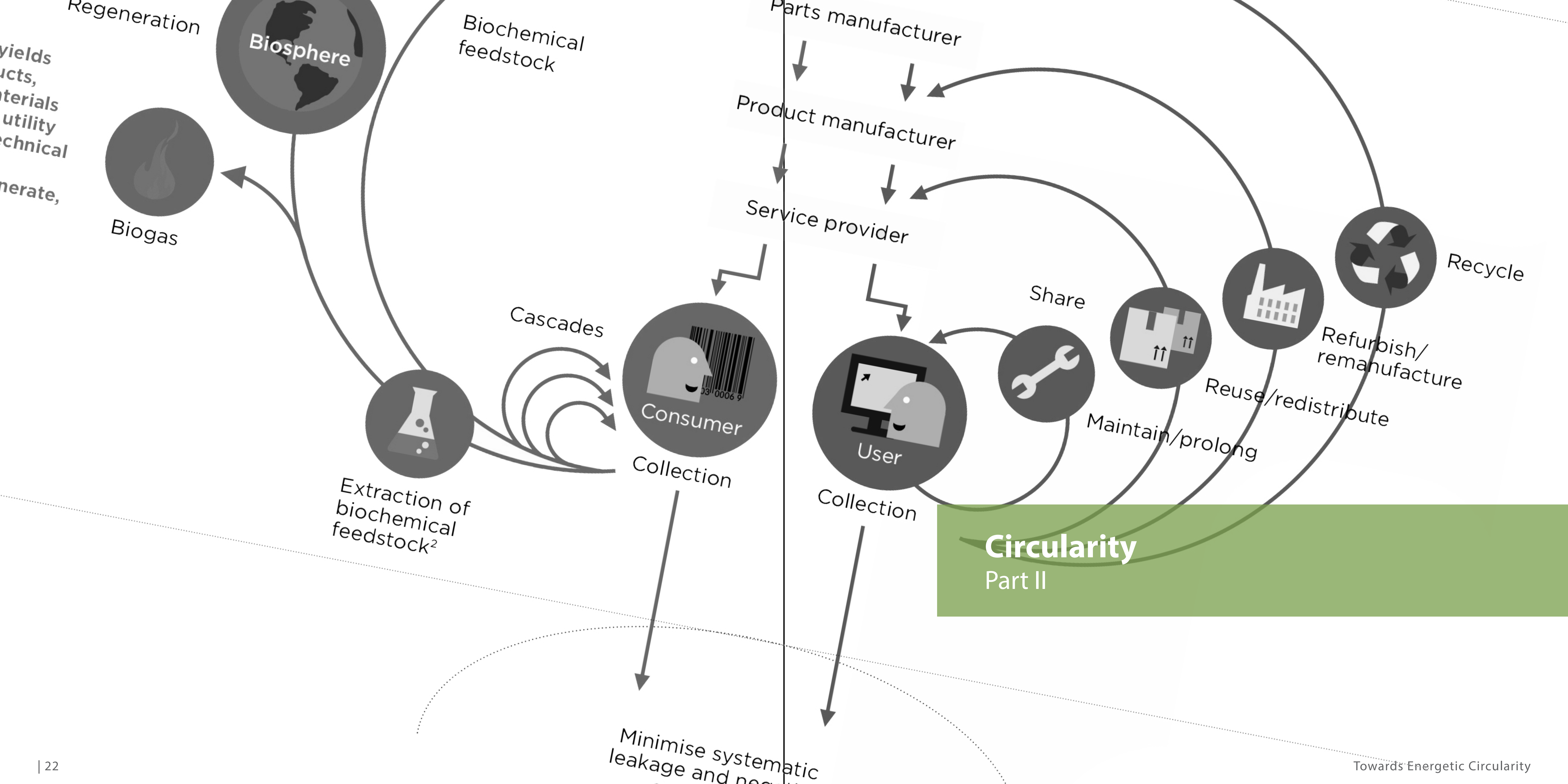
According to RVO.nl, this Lidl supermarket has an EPC value of 0.3[1].
The <u>operational processes are excluded</u> from this EPC calculation!

Conclusion

By realizing only high performance A^{++++} supermarkets and BREAAM Outstanding distribution centres, the Lidl puts itself in the news regulary.

Lidl's annual sustainability reports pay a lot of attention to the climate and sharp + testable energetic goals have been established.

By proposing the Lidl Zero concept, the supermarket rises the energetic performance to a higher level. However, compensating the total energy demand and not only the building related energy demand with renewable energy is a very good target, the supermarket most likely still needs to address fossil resources during winter.



Circularity

Part II

2.1 | The concept of circularity

Problem statement: the linear model

Roughly since the industrial revolution, the economical system in the industrialized parts of the world is based on the linear model. This model follows the *take-make-use-dispose* pattern. Raw materials are harvested from the earth, processed into products, sold to the consumer and disposed of after they lost their function or efficiency. Discarded products are incinerated as waste and the energy generated by this process gets labelled as *green energy* in the Netherlands. Building material waste, retrieved from construction sites or demolished buildings, is pounded down to gravel and later used in the foundations of roads, new residential projects and industrial estates (Schut, Crielaard, & Mesman, 2015).

Today, companies begin to take notice that the linear model increases exposure towards risk. It becomes harder and more costly to harvest important raw materials on the one hand and to meet the demand of the increasing world population on the other. Besides this, the call for products, assembled from raw materials, increases even more now that the purchasing power of the world increases, exampled by the upcoming economies in Asia and the Middle-East. (World Economic Forum, 2014, p.13 ; Bastein, Roelofs, Rietveld & Hoogendoorn, 2013, p.6).

Economical growth goes hand in hand with the extraction of extra natural resources, which is mainly caused by the increasing urbanization and changing consumption patterns. Urbanization requires raw materials for new commercial, residential and industrial areas and infrastructure. Also there is an increasing need for transportation from and to the urban centres. All this comes with a rising concentration of pollution and waste flows. As the wealth ratio shifts, consumer behaviour and patterns change with it and the call for luxurious products and food gets louder. All this is only possible if we address to natural resources.

The growing world population and increasing purchasing power cannot be slowed down. To guarantee we can always answer to the call for resources, we need to change the way we are handling those natural resources. Large steps in the right direction have already been made in the past decades. In 2005, the world economy harvested 30% less natural resources to produce 1 Euro GNP compared to 25 years earlier in 1980. Still, in absolute sense, the world consumption (and destruction) of resources has increased significantly in the same period. Standard actions we take to increase the efficiency in the way we harvest, process and reuse raw materials, nutrients and energy is not sufficient. We have to search for a construction that leads to an increasing prosperity for more people and that also reduces the pressure on our environment in the absolute sense (Bastein et al, 2013, p.7).

The best situation that is theoretical achievable is an absolute disconnection from natural resources and a system that completely runs on renewable energy. The challenge we face today is to make the transition to a world economy that takes responsibility for the materials that it extracts from the earth. A concept that has gained attention in the past years and that contributes to this absolute disconnection is the *circular economy.*

One solution: the circular economy

Switching to a circular economy (CE) is one way to abandon the destructive linear economy. The circular economy is an economical and industrial system that is organized around the recyclability of products and raw materials and the regenerative power of natural resources.

In the CE, raw materials and natural resources keep their value throughout the take-make-use sequence and strives to stop the destruction of value at the end of the chain. This is only achievable if, already in the design phase of products and systems, preventing waste streams at the tail of the chain is the determining factor.

The circular economy resolves around core principles:
- To stop the depletion of natural resources;
- Cut down on waste flows;
- Stop the emission of greenhouse gasses;
- Stop the use of toxic materials;
- Run on only 100% renewable energy.

The targets stated above are not hit by holding on to the current sustainability and recycling programs, that are also mainly focused on just optimizing the linear economy. The transition to a circular economy requires a complete alteration of systematically thinking.

Ideally, the circular economy contributes to a reliable and affordable supply chain of raw materials because all rest flows, waste flows and emissions are used for the creation of new value. Only if this works and is optimized, the first CE initiatives could successfully compete with the linear model.

In the Netherlands, certain circular initiatives have already been put into practise and proven their potentials. There is an broad recycling infrastructure and, on the scale of the consumer, the separation of waste is embedded in the daily routine. The first industrial symbiosis projects are realized, in which residue heat flows are cascaded between factories and thermal energy is saved, or where waste (water) and residue materials for one is the foundation for another.

In addition to the core principles, there are two more principles of the CE that are heard frequently. A circular economy should:

- Systematically support and enhance biodiversity. One of the principles to enforce within the CE is the preservation of complexity. In the CE, biodiversity is a complex achievable valuable and habitats should not structurally suffer from human activity. This is -in a way- also acknowledged by the Ellen McArthur foundation, where shorter tech-cycles (which means more complex products) preserve more value in the material and consume less energy to recirculate (page 27);
- Stimulate social cohesion and preservation of human culture. Cultural diversity is also a form of resilience. According to Eva Gladek, founder and CEO of Metablic, “Activities that structurally undermine the well-being or existence of unique human cultures should be avoided at high cost”

2.2 | Circularity: two pioneers, two perspectives

Braungart & McDonough | Cradle-2-Cradle

In 2002, American architect William McDonough and German chemist Michael Braungart published their book *Cradle-to-Cradle - Remaking the way we make things* in which they shined a light on the concept of Cradle-2-Cradle design. Also their famous quote "less bad is not good enough" is and *waste equals food* frequently mentioned in this publication. Al though it were Braungart and McDonough that elaborated C2C ideology and brought it to the public, it was Herman Daly that introduced the concept of the *steady state economy (SSE)* in 1977. Daly describes the SSE as '*an economy with constant stocks of people and artifacts [sic], maintained at some desired, sufficient levels by low rates of maintenance throughput, that is, by the lowest feasible flows of matter and energy from the first stage of production to the last stage of consumption*' (CASSE, p.1). This basically means that populations numbers and consumption are always in balance with the regenerative and assimilative (of waste) capacity of nature.

To foresee in our need for prosperity we need technical materials like heavy metals or diluent. These should never reach the bio-cycle since it will bring (irreversible) damage to these regenerative and assimilative processes. To make *waste equals food* work, we should segregate biological nutrients and technical raw materials in separate waste streams and reprocess them in their own cycle.

Upcycling and Downcycling - Braungart and McDonough described a lot of our recycling processes as downcycling: the product or materials loses value in their next life stage. Upcycling is the opposite to this and the goal we should strive for.

Ellen McArthur Foundation

The Ellen MacArthur Foundation was established in 2010 with the aim of accelerating the transition to the circular economy. Since its creation the charity has emerged as a global thought leader, establishing the circular economy on the agenda of decision makers across businesses, governments and academia[1].

The EllenMcArthur foundation revolves around four core principles (WEF, 2014, p.15):

- *The power of the inner circle.* Smaller cycling loops, displayed in the scheme on the right, have more profit potential compared to outer loops. Maintenance and repair make sure a lot more value remains in the material than complete recycling on the raw material scale.
- *The power of circling longer*. The value increase is higher after materials repeatedly go through cycles or remain in cycles for a longer period of time.
- *The power of cascade use*. Basically this means that if materials can no longer be used in a cycle, the first option should not be to recycle immediately on the raw material scale but to first seek the opportunities for recycling on an higher complexity level. This saves the value of the materials and energy.
- *Power of pure*. Reuse, repair and recycling profit if already in the design of the product, the end-life phase is thought over and taken into account. For example: no toxic components and products that are assembled or hybrid materials that are composed in such a way that they are easy to separate again.

[1] www.ellenmacarthurfoundation.org

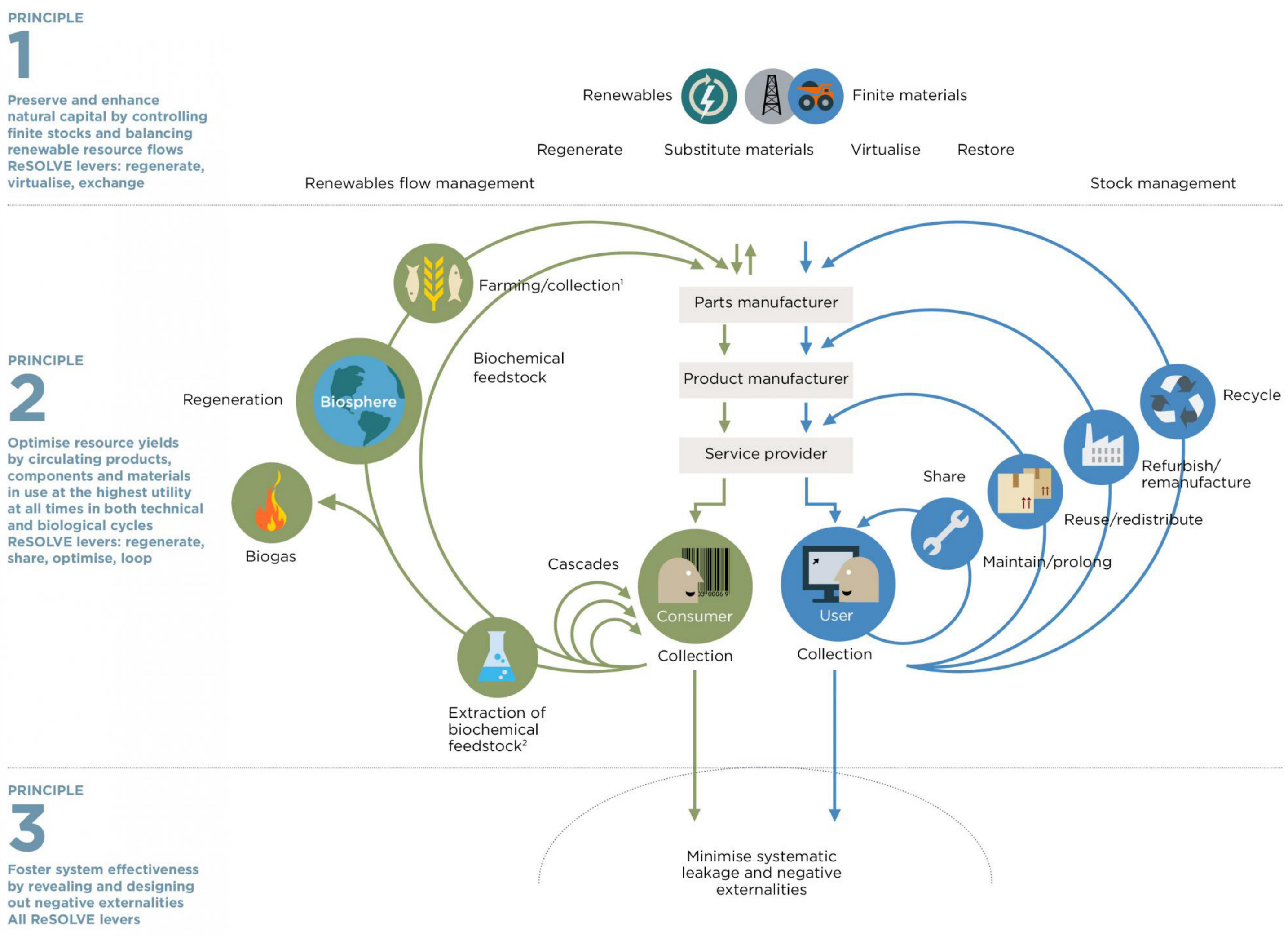


Figure 2.1: The circular economy according to the Ellen McArthur foundation (EMF) > based on the work of McDonough & Braungart (2002).

Figure 2.1: First, circularity is about out-designing waste. Products are designed and optimized to be brought back in a cycle after the end-life phase. Second: circularity has a strict differentiation between consumable and durable components of a product. On the left side the bio-cycle is shown and is in it's core about sending biological ingredients or nutrients back to nature. On the right side you can find the tech-cycles.

Products and materials are designed or composed with the idea to be reused. This makes them suitable to be easily upgraded and flexible towards technological advancement and continuously changing customers standards and expectations. Finally, energy needed to fuel this system comes from renewables (World Economic Forum, 2013, p.15).

2.3 | Circularity in the Built Environment - Materials

Current material flows

Up to this day, the largest part of the construction waste that is retrieved from demolition projects is being reused. In terms of mass, approximately 95% of the building material is being recycled to serve as foundation granulate for the Dutch infrastructure sector. After the material has served this secondary function, it is again for almost 100% reused for the same purpose (Schut, Crielaard & Mesman, 2015). Holland is leading when it comes to this type of recycling, which actually arose from a necessity. The soil in the most parts of Holland is to unstable and weak to lay roads on directly. With the exception of some regions in the very South, there are no natural resources available that could serve as a foundation. The granulate 'mined' from the building industry is a welcome substitute.

On first hand one could say that the building industry is progressive in circularity, but the opposite is true. The building construction sector reuses approximately only 3-4% of its own waste, for the other 96-97% primary resources are used (Schut et al, 2015, p.16). Shredding bricks and concrete, which in its totality contain enormous amount of embodied energy, into foundation material can not be defined as recycling but should be labelled as downcycling. For the past decades, the recycling industry and the infrastructure industry have taken care of the waste from the building industry.

Nowadays, construction companies recognize and acknowledge the waste problem. Not because there is large amount of scarcity but because of the enormous environmental impact the production of building materials has.

What should change?

As long as there are financial incentives to recycle or reuse a building material or product, the demolishing party will always do this. This is the case for example with construction steel, (antique) roof tiles (easy to remove), copper (high price per kg) and authentic bricks. The demand for authentic bricks can be so high, that the demolisher can raise the price and invest in the expensive and time consuming procedure of separating the concrete from the brick.

The problem is the waste material that makes the most money by simply shredding it down to road foundation. These are the materials that take to much time, effort or expertise to harvest neatly from the building or that are to expensive to transport or store. Profit is usually the incentive that is missing whether to go for reuse instead of downcycling the building waste.

To stimulate and facilitate circularity after the primary use of building materials and products, a number of criteria have to be met. To begin with: the *intrinsic properties* should be according to the principles of circularity (Geldermans & Jacobsen, 2015, p.29). Already in de design phase, the following should be taken into account. Material or products should:

- be of high quality (functional performance). After the first life cycle, the material should still meet the criteria of the regulations.
- be durably manufactured and should allow for durable reincarnation.
- be free of toxic materials. Not time, money and materials should be wasted due to the removal of unwanted toxic elements before bringing a material of product back in a cycle.
- fit in the intended biological or technical cycle. A nutrient, product or material should fit in the cycles of circularity, sorted on increasing edibility (maintenance, redistribution, renovation, refabrication and material recycling).

If a material of construction product meets the criteria above, both complex products as pure materials are equally suitable for the CE. It does not matter if an building element is a complex structure with relative short life cycle or a homo-genius recyclable material.

Secondly and equally important, products need to be fabricated for the future. The product designer has to anticipate on multiple future and equal iterations and therefore these important *relational properties* can be listed (Geldermans & Jacobsen, 2015):

- Standardisation of dimensioning. Building products or components of these products are easily interchangeable if the dimensioning is according to a defined standard.
- Standardisation of product connections. Dry or mechanically connecting elements should be prioritized above chemical connections;
- Diversification between different building layers according to performance duration is as useful as it is crucial in effecting circular flows. A fundamental distinction is that of the load bearing structure and the facade or interior structure;
- Buildings should be designed and detailed with a high commitment to adaptivity. Future changes of the building function should be possible without large financial or materialistic investments.

2.4 | Circularity in the Built Environment | Energy

An economy based on fossil energy

The world runs on finite fossil resources, see Figure 2.2. The Western world has been dependent of it since the beginning of the industrialization and some Middle-Eastern countries base their whole national income on the trade in oil.

This enormous consumption of fossil fuel goes hand-in-hand with large carbon dioxide emissions and so the world climate is affected by it. In the beginning it were just a handful people that acknowledged this climate change and even fewer believed is was civilization itself that was causing it. Since then, general public opinion has taken a different direction, one in which the urgency of change is prevailing.

However "the biggest social problem is not climate change but the depletion of energy reserves; a socio-economic problem rather than a technical one" (Dobbelsteen, Tillie, Joubert, Jager & Doepel, 2009, p.269). If we lose important raw materials or the easy supply of fossil energy that we have gotten used to, we will face consequences and limitations in what can and cannot be done.

Technically, it is possible to build a completely self-sustaining energy system but for the time being, costs are holding these developments back.

Grey energy > Green energy

Traditional power plants burn fossil fuels to generate the heat that is needed to turn water into steam, which on its turn brings a steam turbine into movement. Households receive the energy generated as *grey electricity*, the polluting counterpart of green electricity.

As over the years oil prices rose and a nation wide apprehension on the massive use of fossil fuels slowly entered the peoples minds, the first energy reduction actions were taken. The building code dictated higher minimal insulation values in new dwellings + utilization projects and household devices became more energy efficient.

Since 1995, the Dutch building code dictates minimal norms on the subject of energy frugality and energy performances of building. Demanding an overall energy performance norm with each new building planning application, stimulated the engineers for seek for new measures to reduce to total energy consumption of the building. Over the past years, this energy performance coefficient (EPC) has gotten smaller, from 1.4 in 1996 to 0.4 in 2015 and 0.0 in 2020.

Energy neutrality in a building means that the annual building related energy consumption is compensated by the production of renewable energy by the building itself (Figure 2.3). Energy neutrality does not mean that the building does not consume energy at all. Also user related energy consumption is not included (Jansen, Luscuere, Tenpierik, Geldermans, 2016, P.18) A building is energy neutral when is has an EPC value of almost 0.

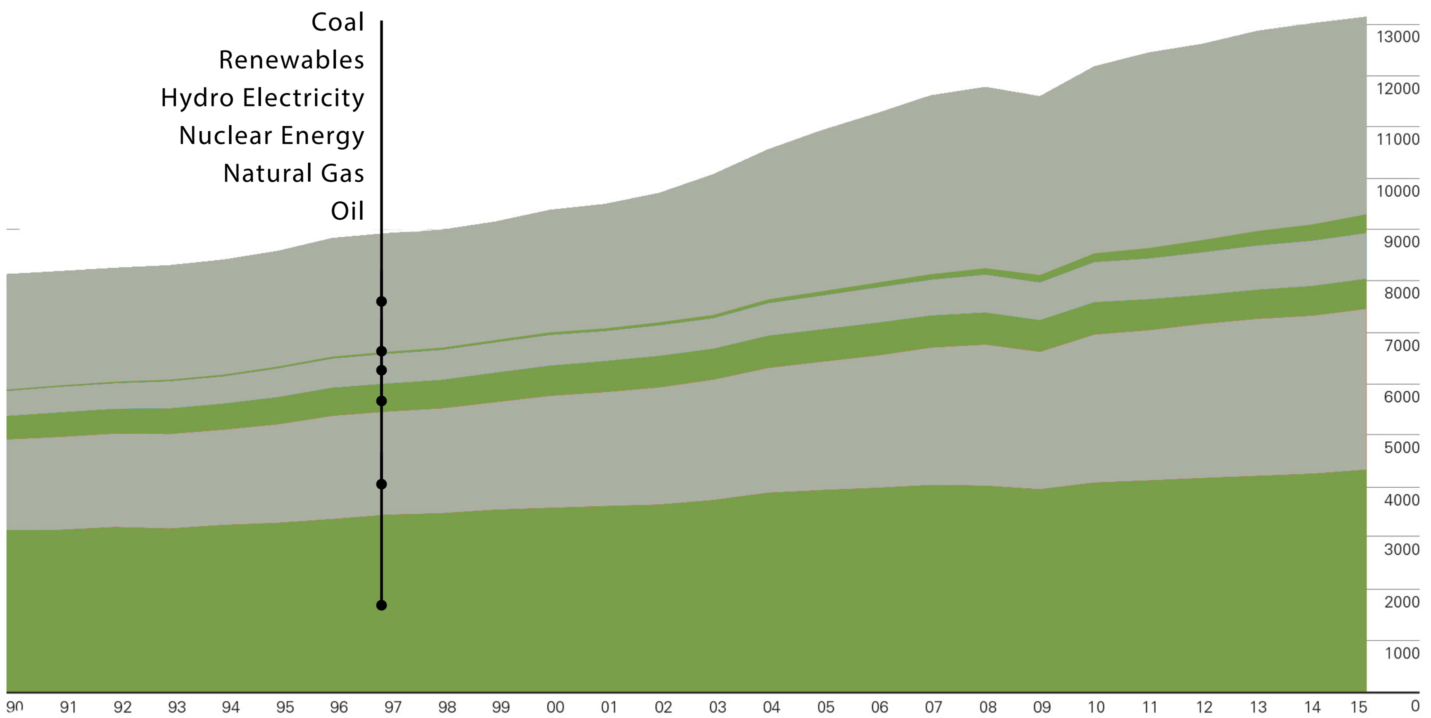


Figure 2.2: Diagram showing the increasing primary energy consumption of the world. Renewable energy production has increased significantly over the past 20 years, but in the absolute sense it is still covers just a fraction of the worlds demand (BP Statistical Review of World Energy 2016, 2016).

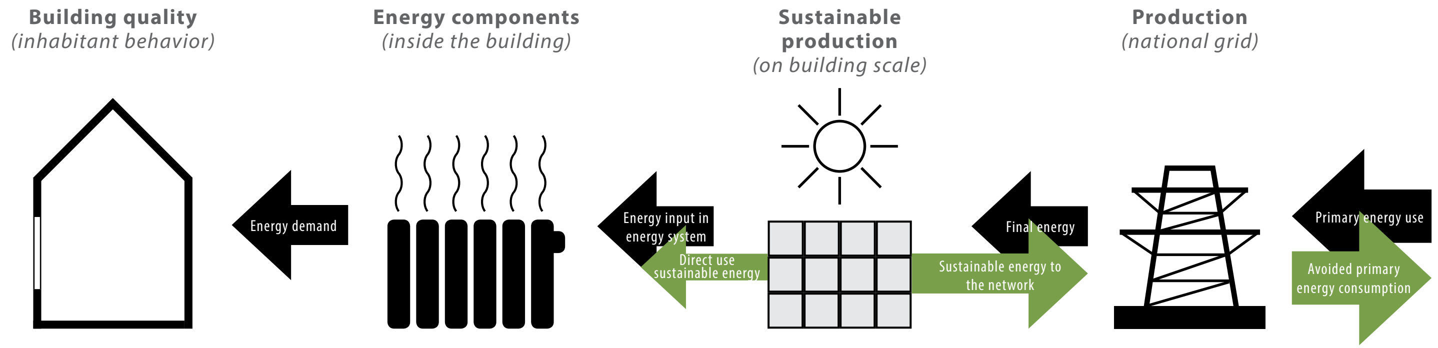


Figure 2.3: Schematic representation of an energy system for an energy neutral house. Annually, the renewable energy returned to the network is equal to the energy taken from it.

The Dutch government has an equal interpretation of energy neutrality and applies to the following assessment criteria for an EPC calculation (Rijksdienst voor Ondernemend Nederland, 2014):

- Energy usage is determined under standard user- and climate conditions;
- <u>Only building related energy is taken into the calculation</u>;
- The generation of energy can both be inside as well as outside the building's plot;
- Renewable energy sources are appreciated;
- The netto energy consumption is determined over a period of one year.

A successive and more optimistic step in energy neutrality would be to include the user related energy in the EPC calculation. Right now, there are already concepts that go beyond 'standard' energy neutrality and are in fact energy-positive. The Dutch *Nul-op-de-Meter* (NoM) concept takes user related energy and operational energy into account. In terms of energy neutrality, buildings that meet the NoM standards actually have a below-zero EPC value (Rijksdienst voor Ondernemend Nederlands, 2014, P. 5).

For a supermarket it will be challenging to meet the NoM standard (meaning EPC <0), but not impossible. The everyday operational processes take up a large part of the energy bill as a the supermarket needs to cool or freeze products. Nevertheless should this be the standard to achieve. What is the value of an energy neutral building if it can only exist with the aid of grey energy for it's operations?

Energy neutrality > fossil free

Circularity is based on the idea of not claiming any natural resources without being able to circulate the same quality and quantity of those resources back to nature. In the CE there is no more destruction of raw materials. Up to this day, the linear economical model has been organized around the consumption of fossil energy. It took a process of millions of years for oil, gas and coals to form and roughly 150-200 years for mankind to use and transform a large part of it into CO_2. It is not realistic to think that we are ever able to replenish the fossil reserves back to the amount it was before mankind based it's whole system on it.

Basically, netto energy neutrality is only achieved when the high demand of energy in winter is compensated by the energy surplus during the summer months. In the Netherlands there are energy programs *(Dutch: salderen)* that facilitate the taking and supplying energy from and to the network. This makes the generation of renewable energy financially attractive for the consumer. For standard houses, with a standard connection to the national grid, this program is interesting to look into. For companies or other large electricity consumers, the program is financially less attractive as other regulations and fees apply.

The problem with this standard-definition energy neutrality is the fact that is still appeals to fossil energy in winter. The surplus renewable energy that a household returns to the network in summer might be sufficient to achieve am annual netto energy consumption of zero, on the other hand does the household still rely on grey energy during the winter period.

This solar intensity controlled electricity taking and returning pattern leads to undesirable demand fluctuations for the national grid. To get independent from fossil energy, we either need to find an effective way to store the surplus energy from summer to later use in winter or we need to find more efficient ways to generate renewable energy during the short days.

The next and final step would be to take investment and embodied energy of building materials into account. Biobased and circular building materials will play a prominent role in the disconnection with fossil energy (and raw materials) It are these materials that allow for fossil free building design, at least without new fossil materials. The age of traditional building material, primarily based on fossil energy is then over.

fossil free > embodied energy compensation

Taking the production and choice of materials into account in order to reduce the energy demand of the building sector has been common knowledge for years now. It is relevant to compare the amount of energy it takes to produce, transport and to dispose/reuse a product with the amount of energy a product can generate or save over the years. For some products and materials it is important to take this *energetic payback time* into consideration. This is the time it takes for a product to compensate for its own energetic investment.

An example is the choice for insulation material. Let's compare the polystyrene PIR with natural sheep wool. PIR performs roughly 50% better than sheep wool, so for the same insulating performance you need 50% less material if you opt PIR above sheep wool. PIR is a form of polymer which means it is based on oil and it requires a lot of thermal energy to produce. Producing sheep wool does not directly take electrical energy nor it needs heat. On the other hand, sheep farms need a lot of land (topsoil) and water. Producing a kg of sheep wool also takes up more time than a kg of PIR. All these points should be taken into account when choosing from an investment energy point of view

Recycling building products and materials, according to the principles of the circular economy, takes up much less energy and less to no raw materials. Again: the smaller the recycling loops are, the more value remains in the materials (page 27). This principle might however not account for materials and products that origin from a linear basis, as they are not intended to be reused. It might still be to costly, difficult or energy consuming to recycle and a producer is economically forced to chose for virgin materials instead.

Where are we now? Where do we want to go? Where does the Lidl wants to go?

Right now, the minimal EPC score is set on 0.4 for new buildings (the 2015 standard). To meet the Europa-wide 20-20-20 targets (see block 2) before the year 2020, it is very likely that the EPC will be brought down even further to 0.0 in 2020. Should this be achieved for all buildings, it basically means that building related energy consumption is history.

Designing a new supermarket with an EPC of 0.0 is hard to achieve, but manageable. The Lidl supermarket in Stein closes in on this energetic equilibrium with an EPC of 0.3[1] and an energy label of A^{++++}.

Designing a new supermarket with an EPC of zero that also includes the operational energy, is already more of a challenge. Lidl claims that the Stein supermarket is only able to be completely self-sustaining during summer days. The 338 PV panels generate an annual surplus of 4498 kWh during the sunny days of the year. This means that during the other months, the supermarket is partly functioning on grey electricity (block 3).

Lidl has started developing the Lidl Zero concept ($1.2). This would mean a supermarket has an EPC of 0.0, including the operational management. In addition to this, the Lidl has started to look at the opportunities of circularity for its supermarkets. Energetically this would mean that fossil fuels are completely abandoned and investment energy would be taken into account.

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[1] *www.rvo.nl/initiatieven/energiezuiniggebouwd/lidl-filiaal*

(2) 20-20-20 in 2020

The core climate objectives that were determined in the 2015 European member stare conference:

- *20% less total energy consumption compared to 1990;*
- *20% less emission of CO2;*
- *20% of the total energy should come from renewable resources.*

These objectives are sub-targets in a larger plan to reduce the environmental impact of the European Union. One umbrella objective is to limit the global temperature rise to only 2^{0}C, compared to the temperature from before the industrialization. The 20% is the European average, the exact value may differ per country.

(source: www.europa-nu.nl)

(3) Lidl Stein in numbers

- *The building delivers 4493 kWh back to the energy network annually;*
- *338 solar panels provide the electricity needed to power the fridges and freezers;*
- *Lidl Stein has an A^{++++} Energy label.*
- *Lidl Stein claims to have an EPC = 0.3*
- *Lidl Stein has an energy performance that is 261% better then the current European law and regulations.*

(source: www.lidl.nl)

2.5 | Precedent studies - Circularity of flows

Overview

Project	Location	Year	Note
Business Park 20|20	Hoofddorp	2010 a.o.	Cradle-2-Cradle business park
Bullit Centre	Seattle	2013	Circular commercial building
Rijkswaterstaat office	Terneuzen	2000	Circularity in practise
City hall	Venlo	2016	Biodiversity, Fossil free was the target
Urban Farmers	The Hague	2015	Urban farming, small scale
Gotham Greens	New York City	2011	Urban farming, medium scale

Each study briefly describes what the project is about. It is mentioned why that project is interesting within the boundaries of this research. Both materialistic aspects as well as energetic aspects of circularity are mentioned.

On page 62 there is seventh case study about an energy storage program with greenhouses in Hoogeland (NL).

2.5.1 | Business park 20-20, Hoofddorp

Precedent studies

Hoofddorp (NL), 2010 a.o.

Braungart & McDonough involved in the master plan.
Renewable energy production: 75%

Located directly South of Amsterdam airport Schiphol, you will find business park 20|20. The park is worlds first full service Cradle-2-Cradle work environment. C2C visionary Michael Braungart himself is closely involved in the design of the park and the buildings. Delta Development Groups is responsible for the development and organization of the park. There are four core values guiding the development of the business park[1]:

1. Design for disassembly. Re-mountable detailing;
2. Productivity and health. Green and ergonomic design to decrease absenteeism;
3. BIM / Material banking. The building as a material depot. Accurate information management is done to ensure the value of the building at the end of its life;
4. Products of service. Service leasing contracts in stead of total ownership to enforce recyclability and efficient product development from the producer.

The initiative for the park was a risky one. There was no experience with the Cradle to Cradle vision on a district scale. The experts came up with a promising plan that up to this day is still in development (Dobbelsteen, 2008).

Working on a neighbourhood or even district scale offers collective opportunities plus a possible interaction with neighbouring flows. Also certain technologies might become feasible when the law of large numbers is applicable. Besides the fact that a large scale offers more technical opportunities, there is also social development occurring when decentralized energy generation is introduced. (Jansen et al., 2016).

energetic circularity

A technology that contributes to the energetic success of park 20|20 is the centralized treatment and reprocessing plant of waste flows. This is where the law of large numbers can make a change. A waste treatment plant on a building scale is financially not feasible and on the city scale it would require a lot of transportations to feed the power plant. A district is the intermediary scale. Transport distances are relatively short and don't require road transport and financial investments are shared by the commercial companies located in the park. In addition to this: being a business park with a lot of vegetation and having a restaurant from which an organic waste flow outflows, means there is a predictable flow of material that feeds the plant.

A selection of the plant's purposes:

- Collection of waste materials that can still be reused
- Treatment of waste water ('Living Machine') digestion of green waste from the buildings and park, production of biogas
- Generation of heat and power from biogas storage of hot and cold in aquifers
- Heat exchange with the shallow underground
- Storage of heat in insulated containers

It has been calculated that the central treatment plant can produce up 53.600 m³ of methane. This would produce 210 MWh electricity and 1132 GJ of heat. Through heat recovery systems, this amount would be sufficient to cover for the district's heat demand. 201 MWh is about 20% of the total electricity consumption (Dobbelsteen, 2008).

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[1] www.park2020.nl

2.5.2 | Bullit centre, Seattle

Precedent studies

Seattle (USA), 2016
Architect: Miller Hull Partnership
Renewable energy production:

The Bullit centre in Seattle is a project in which a lot of existing ideas and technologies come together. There is not one sustainable feature that is not installed somewhere else in the world. The centre shows what can be achieved if technologies are properly combined: approximately 83% more energy efficiency than a typical commercial site in Seattle. The Seattle Bullit centre is one of the Living Building challenge projects.

One noticeable feature is the pendent roof. The overhang is completely fitted with PV-panels. The building extends beyond the borders of its own footprint to increase the PV surface just enough to compensate for the annual energy demand. This points out a problem that a lot of (commercial) buildings deal with: there is not enough space. In the Seattle Bullit centre they solve this problem by extending the roof over the streets, thereby doubling (estimation) the roof surface and putting the facade in the shade. Park 20|20 encounters the same issue. According to Andy van den Dobbelsteen, the waste treatment plant provides about 20% of the electrical demand. This is percentage can be raised with PV panels ans wind turbines up to about 75%. The remaining demand either needs to be met by grey energy or by renewable energy from a different location (2008). Using PV-panels, or wind turbines, goes at the cost of space. Even park 20|20, which is quiet spacious, cannot sustain in on-site renewable energy. Especially high density areas or high buildings depend on off-site renewable energy production.

Energetic circularity in the Bullit center[1]*:*

- *Closed loop geothermal low temperature heating.*
- *Glycol+water mixture form the medium.*
- *Heat pumps boost the temperature up from 11⁰C to 32⁰C.*
- *575 solar panels;*
- *Surplus energy is stored in the city's electrical grid.*
- *Composting toilets that barely use any water. Aerobic digestion converts solid waste to compost.*
- *Water treatment in constructed wetlands. Up to 1800 litres of water can be filtered on a daily basis.*
- *Rainwater collection. The building only uses the amount of water it can collect with surface of it's own footprint.*

technical circularity / sustainability in the Bullit centre:

- *FSC Certified timber framing supports the building above a concrete base.*
- *All wood from within 1000 km, all steel and concrete from within 500 km.*
- *545 metric tons of CO_2 are isolated in the wood.*
- *The building distinguishes itself from other sustainable projects with the exclusion of 350 common toxic chemicals - including PVC, lead, mercury and formaldehyde.*

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[1] *www.bullitcenter.org*

2.5.3 | Rijkswaterstaat office, Terneurzen

Precedent studies

Terneuzen (NL), 2004 > 2017
Architect: opMAAT (Delft)
Renewable energy production: unknown.

Rijkswaterstaat is the department of Waterways and Public Works in the Netherlands. When the building was constructed in 2000, it was according to Greencalc the most sustainable office in the Netherlands. The building was engineered with the principles of circularity.

A lot of the materials in the building are waste materials from Rijkswaterstaat themselves that are being recycled. Old bollards are sawn into a unique facade cladding and will be used in the staircases and interior of the building. Disposed basalt blocks and street pavement is given a second life in and around the building.

What makes this case special is that its circular fundamental idea is being put to the test in 2017. The building needs to make way for an expansion of a adjacent lock and therefore will be dismantled.

New Horizon - Urban Mining is organizing the circular dismantling of the building and delivering the materials to a new building. The owner of the new building saw the opportunity to change their design in such a way that it could directly take in the building elements from the dismantled Rijkswaterstaat building. The rest of the materials will be applied in other projects.

Due the fact that the building is located on a piece of land between two large ship locks, underground infrastructure was limited. This means it was not possible to connect the building to the sewage system and it was forced into on-site water filtration. Two, 90 m^2 on-site constructed wetlands filter the wastewater of the office. The cleaned water is used to flush the toilets (Figure 08). The building is not self-sustainable in it’s water consumption as it is still connected to the network. A septic tank and a grease trap have been added to the circular flow to keep the system working.

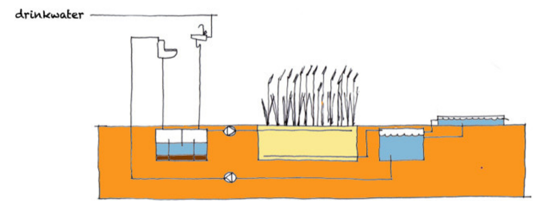

Figure 2.4: water filtration system used in Terneuzen

2.5.4 | City Hall Venlo

Precedent studies

Venlo, 2016

Kraaivanger architects

Renewable energy production: 50-60%

In 2007, the municipality of Venlo decided they wanted their new city hall to reflect the thoughts of C2C. The new building had to be open, transparent and accessible and should proudly refer to the agricultural and logistical culture of Venlo.

Venlo chose to apply another tender procedure then usual[1]: they asked for a vision on the assignment and C2C, instead of a design. The five best visions were invited for a kick-off meeting with Braungart and McDonough and were challenged to translate the C2C principles to a final vision. The design of the project has been awarded to Kraaivanger Architects. Their vision resolved around three important elements: 1) a living green facade that filters the indoor and outdoor air. 2) The use of recyclable materials and 3) The generation of more recyclable energy than the building will use.

energetic

The ultimate goal of the city council is to produce more renewable energy the building uses. All added up, 1000 m² photovoltaic cells and 25 m² of solar collectors cover 50-60% of the total energy demand. The building is disconnected to the gas network and has energy label A⁺.

enhance biodiversity

The North facade of the building is designed as a biological facade with over 100 different plants. 2000 m² of green facade filter the air, contribute to a healthy work environment, enhance work productivity and have a positive impact on the urban heat stress. It is constructed with C2C certified materials by Moster De Winter, a specialist in the field of green roofs and façades.

enhance water quality

Rainwater is collected on the green roofs and stored in an underground storage tank. This water is used in dry periods to irrigated the green facade. Grey water is collected and filtered in a hylofyt filter after which it is used to flush the black water systems. Studies have been conducted to look at the possibilities of a black water filtration system. It was concluded that on this scale, it was not yet profitable. The current water filtration system is anticipated on future: should profitable black water filtration system be developed, the can be integrated in the rest of the system.

The water system and the energy system have been made visible for the users and visitors of the building to stimulate sustainable awareness. Systems have been made suitable for easy upgrading in the future.

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[1] *http://www.c2c-buildings.org/projects/city-hall-venlo/*

2.5.6 | Urban Farmers, The Hague

Precedent studies

The Hague (NL), 2015
Architect: Space & Matter
Renewable energy production: n.a.

In the city of The Hague you can find Europe's largest aquaponic farm. On top of a former Philips factory, a 1200 m^2 greenhouse has been placed and the floor below has been made suitable for a 250 m^2 fish farm. Together they form an efficient symbiotic system for fish and vegetable production in an urban area.

This project does not directly advertise with any circular initiatives. It does show how different functions combined have a smaller environmental footprint than the functions separately, in this case the combination of a vegetable production line and a fish farm. (see *aquaponic farming*). This natural way of food production saves up to 90% of the water usage needed to grow the vegetables.[1]

Production capacity according to Urban Farmers:
1200 m^2 vegetable production surface results in 45 tons of fresh vegetable every year and 250 m^2 fish production surface results in 19 tons of fresh fish every year

Vegetables grown: Cherry tomatoes, Montenegro tomatoes, Haiku tomatoes, Salanova salad, Babyleaf Microgreens-Sprouts, Cucumbers & Aubergines.

Aquaponic farming

Aquaponic farming is a century old method to produce food in a sustainable way. Urban Farmers, the organisation that initiates, organises and facilitates rooftop farming, has combined this method with nowadays technology to produce fish and vegetables.

The waste from the fish are the nutrients for the plant. Waste water filled with potassium, phosphorus and ammonia from the fish's faeces is pumped through the sand bed of the plants. Bacteria in this soil transform these elements into nitrogen, which the plants use to grow. The plants filter the water before it gets pumped back into the fish basin. This short circulation only is not enough to grow fish and plants. The fish still need an external food source and the plants need additional iron, calcium, potassium and magnesium.

Advantages of aquaponic food and fish production[2]:

- Maximum reuse of raw materials and fertiliser;
- Biological cultivation;
- No weeds between the plants that leach the fertilizer away from the plant ;
- Plants can grow faster due to continuous nutrient supply;
- Much lower water usage compared to normal greenhouse vegetable growth and standard fish production.

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[1] www.urbanfarmers.nl ;[2] www.duurzaamdenhaag.nl

2.5.7 | Gotham Greens, USA

Precedent studies

New York City (USA), 2014
Architect: Unknown
Renewable energy production: n.a.

Gotham Greens is a pioneer in the field of urban agriculture. They grow pesticide free products with ecologically sustainable methods and only use renewable electrical energy for their processes.

Gotham Greens has opened three rooftop greenhouses in New York and one in Chicago between 2011 and 2015. The farm in Chicago has been built on top of the Method Products manufacturing plant, which was designed by C2C visionary William McDonough+Partners. This might explain the unique partnership between the urban farming company Gotham Greens and the eco-friendly cleaning products manufacturer Method Products.[1]

Gotham Green's greenhouses:

1. Greenpoint, Brooklyn - 45 tons, 1400 m^2
2. Gowanus, Brooklyn - 91 tons, 1900 m^2
3. Hollis, Queens - unknown, 5500 m^2
4. Pullman, Chicago* - 453 tons*, 7000 m^2

Comparison:
Urban Farmers, The Hague - 45 tons, 1200 m^2.

**Latest, largest and most technological advanced greenhouse by Gotham Greens. Plans to produce 453 tons of food annually*[2]

Gotham Greens claims that 16.000 m^2 of rooftop greenhouses produce yield equivalent to 400.000 m^2 of conventional field farming. The production per acre is about 20-30 times higher compared to field production.[1]

Just like the Urban Farming project in The Hague, water is circulated to minimize the total water consumption and waste water streams are eliminated.

Since the farms are in the middle of urban areas and close to their retailers, transportation miles are brought to a minimum and with that the associated carbon emissions.

Gotham Green's food production relies on natural sunlight and does not use artificial lighting. The greenhouses run completely on renewable electricity. The building is not fossil free as it is appeals to traditional energy sources to meet it's heating demand. Energy demand is kept to a minimum by means of careful greenhouse design and smart building + climate operating systems. On-site renewable energy systems further reduce the energetic footprint.

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[1] www.gothamsgreens.com ; [2] www.cleantechiq.com

2.6 | Conclusions & similarities presedent studies

Materialistic circularity

Park 20|20 and the city hall of Venlo have been built with the ideology of Cradle-2-Cradle. The Rijkswaterstaat office and the Bullit Centre are built as much as possible according to the principles of circularity. In a materialistic sense, it is a thin line between C2C and circularity and in practise both terms are used for the same final purpose: recyclability. All four buildings strive to have as many recycled materials in their structure as possible. The buildings are designed in such a way that demountability and recycling have the upper hand on demolishing after the initial lifespan of the building is over.

Energetic circularity (Fossil free)

None of the buildings reach energetic circularity or have an energy system that is efficient enough to sustain the building over the full year. With energy demand reduction methods and optimising electricity production, the projects manage to compensate for a part of the total annual demand. Park 20|20 can have about 75% of its total electricity demand compensated with renewable on-site energy. The city hall of Venlo has a renewable production ceiling of 50-60%. The Bullit centre in Seattle manages to compensate 100% of its grey electricity consumption with renewable energy.

The Bullit centre, Park 20|20 and the Venlo city hall are dealing with the same problem: available surface. Nowadays, no matter how efficient your energy reduction efforts are or how efficient the renewable production is, in the end it is about having the maximum space available to install PV-systems.

Urban farming

The urban farm in The Hague as well as the ones in the USA heavily intensify their annual food production whilst at the same time keeping the energy demand as low as possible. The farm in The Hague seems to be more of a showcase project, pointing out the opportunities of bringing food production back to the city and re-purposing empty office buildings. Why else would you make the large investment (2.7 million) of building on the roof of a 7 floor building? In the USA, the greenhouses are put on top of low and large supermarkets or warehouses. This lowers the m^2 investment price and scales up the production, making it an economical more feasible projects.

Sustainable water systems

All six projects have water collection or filtration systems. Park 20|20, Rijkswaterstaat Terneuzen and the Venlo City hall collect rainwater and apply constructed wetlands to filter their grey water flows and reuse this again for toilet flushing. The bullit centre in Seattle practically uses no water for toilet flushing because of composting toilets and has a constructed wetland off-site. The urban hydroponic farming project in The Hague minimizes water consumption by enhancing a closed water system through aquaponic. The Gotham Greens farms are also hydroponic.

Circular water systems are another part of the circular economy. Especially in the Netherlands, with an average rainfall of 880 millilitres in 2015, there is a lot of potential to collect the rainwater and apply this in hydroponic farming. However, this subject is outside of the scope of this research.

Energy & Analyses

Part III

3.1 | Towards circularity: 4 mile stones

Roadmap towards circularity

TU Delft research on circularity.
In February 2017, TU Delft professor Andy van den Dobbelsteen and researcher ir. Luuk Graamans started working on a roadmap towards circularity for the Lidl supermarket (§9.6). The transition towards circularity can be segmented into 4 mile stones, see below. In their research, Dobbelsteen and Graamans further elaborated on this roadmap and translated it into concrete actions for the Lidl to execute. The research primarily revolves around energy related circularity, however for this research transport and two different food products were also included.

Roadmap towards energetic circularity
The steps in the roadmap are not necessarily succeeding each other but the order is based on the level of complexity and by that: the sequence of realization. All four steps could be initiated at the same moment. Step 2.5 is an informal addition to the order, to point out a technicality . The roadmap:

1. CO_2 neutrality - *Compensation for CO_2 emission;*
2. Energy neutrality - *Energy demand equals renewable energy generation (on an annual basis);*
    2.5 Energy neutrality > + user related energy!
3. Fossil free - *Total disconnection from fossil based energy;*
4. Circular - *Retrospective compensation for investment energy of building materials*

The roadmap is further elaborated on the following pages. Within the domains of this master research, the roadmap is only regarding the building, user and operational energy.

(1) CO_2 Neutrality

Getting a large organization like Lidl Nederland CO_2 neutral is the least complex achievement of all four. Carbon dioxide neutrality can be obtained by means of compensation without structural changes for the company processes or businesses.

The European Union has initiated a trading system in which CO_2 is given financial value (figure 3.1). The goal of the program is to reduce the CO_2 emission in Europe with 21% compared to the CO_2 level in 2005. At the commencement of the program a CO_2 ceiling was determined: 2039 Mton in 2013. This number must be brought down in the year 2020 to 1777 Mton, which is a reduction of 1.74%/yr. After 2020 the annual reduction is turned up to 2.2%. CO_2 emission is given value by accrediting a certain amount of money to CO_2: 1 ton CO_2 is 1 emission right. Each year, the emission rights are redistributed among the participating companies and for each ton of CO_2 a company emits, 1 emission right has to be given back to the bank. Since the ceiling is getting lower each year, 1 emission right gets more value as well. The idea is that participating companies invest in reducing their own CO_2 footprint, so that they can trade their surplus emission credits with other companies and gain a financial benefit from it (NEA, 2013). The downside of this system is that companies are able to buy of their CO_2 responsibilities.

The moment the Lidl is able to quantify their total annual CO_2 emission, they could participate in the program. The money that is gained by the emission authority, will be invested either in planting trees or in emission reducing research and projects.

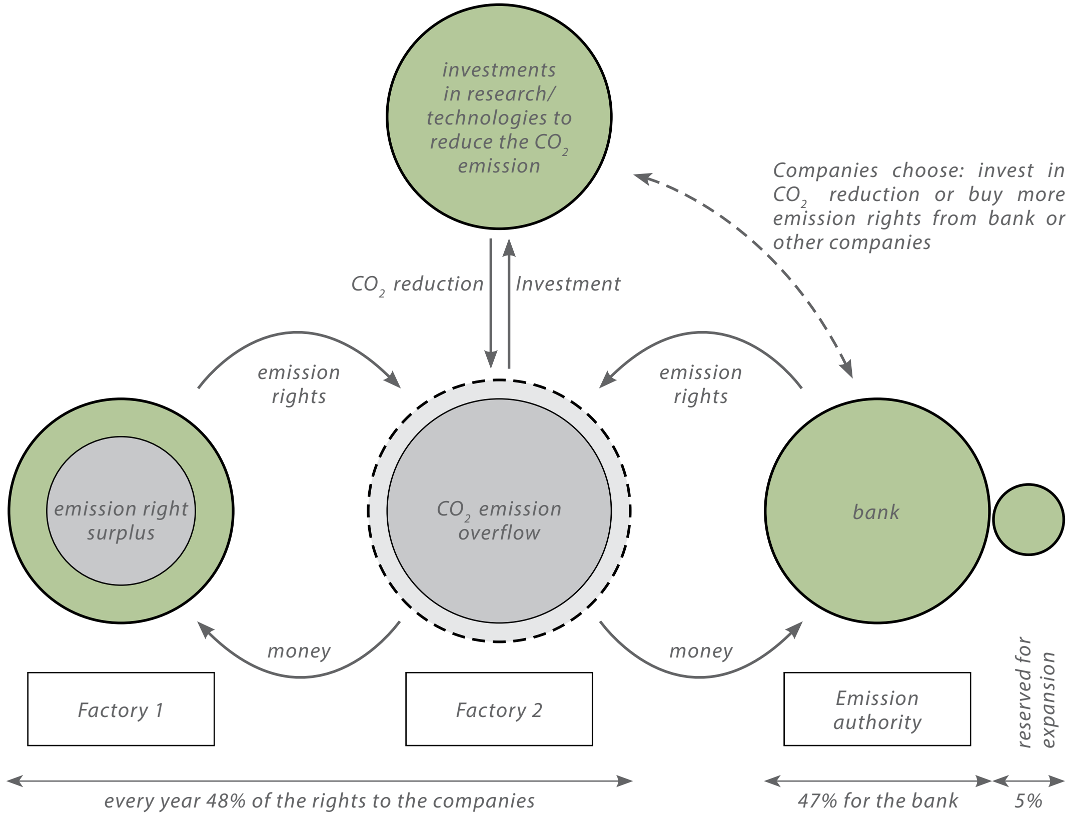

Figure 3.1: Principle of CO_2 compensation and trade

(2) Energy Neutrality

Energy neutrality is, according to the Dutch government (Rijksdienst voor ondernemend Nederland, 2013), compensating the fossil energy that is used from the national network by renewable energy, calculated over 1 year. If energy neutrality is achieved, the EPC of a building is zero. Only the building related energy is taken in the calculation of the EPC and the energy production can take place on site or can be important from where there is space available

In the private sector, this usually comes down to selling the electricity surplus in summer to the network and buying it back during winter. Due to several arrangements from national and local governments, this returning of electricity to the national grid can be financially attractive for the private sector.

A building project does not necessarily have to produce the electricity on-site to be energy neutral. If they choose to only buy guaranteed green electricity from the electricity provider, energy neutrality is also achieved.

Energy neutrality does not per definition equal fossil freedom! By the use of rooftop PV-fields, enough electricity can be generated to cover the demand of a standard house during the summer months. The surplus renewable energy is returned to the network. If the PV installation is large enough, the surplus that is achieved during the summer months is enough to have a netto zero energy use annually. However, the same PV-field does not generate enough power to sustain the building during the winter months. During these periods the building depends on grey, fossil based, energy.

(2.5) Energy Neutrality + user related energy

This point is the same as point 2, but it contains the operational energy and user related energy of a building as well. This concept has been around for years already and it is in the Netherlands commonly known as a *nul-op-de-meter* building (§1.2).

In an conventional household, the division of building related energy and user related energy is about 62% & 38%. In a supermarket this ratio is more in the direction of 61% for user related and operational energy and 39% for building related energy. This makes sense since a supermarket contains cooling+freezing displays, cooling+freezing cells and electrical ovens, see right page.

The fact that the user related energy in a supermarket is about a factor 1.5 higher then the building related energy, is the exact reason why step 2.5 is added to the roadmap. If you can make a standard household energy neutral, you have countered 62% of the actual total energy demand. If a supermarket manages to become energy neutral in the way the Dutch government states, in reality only ~39% of the total annual electricity demand needs to be from renewable energy.

The Lidl zero concept includes user and operational related energy in the definition of *energy neutral*. As roughly 2/3 of the energy demand is user- & operational related (§4.4.2), this concept goes far beyond the current national definition of energy neutrality thus leading to sub-zero EPC values.

Figure 3.2 & 3.3 give a visual representation of the difference between energy neutral and fossil free.

Standard household:
(Source: OTB TU Delft, 2010)

Building related energy:

• Gas	1200m3	38.000MJ
• Electricity	500kWh	1800MJ +
	Total	39.800MJ
		62%

User related energy:

• Gas	450m3	14.000MJ
• Electricity	2900kWh	10.500MJ +
	Total	24.500MJ
		38%

Supermarket
(Source: Meijer, 2009, p.20)

Building related energy in m^2:

• Gas	16m3	500MJ/m^2
• Electricity	278kWh	1002MJ/m^2 +
	Total	1502MJ/m^2
		39%

User related energy

• Gas	~0.03m^3	1MJ/m^2
• Electricity	797kWh	2870MJ/m^2 +
	Total	2371MJ/m^2
		61%

conversion factors
1 m^3 gas = 31,65 MJ
1 kWh electricity = 3,60 MJ
Eff. power plant = 41,4 %

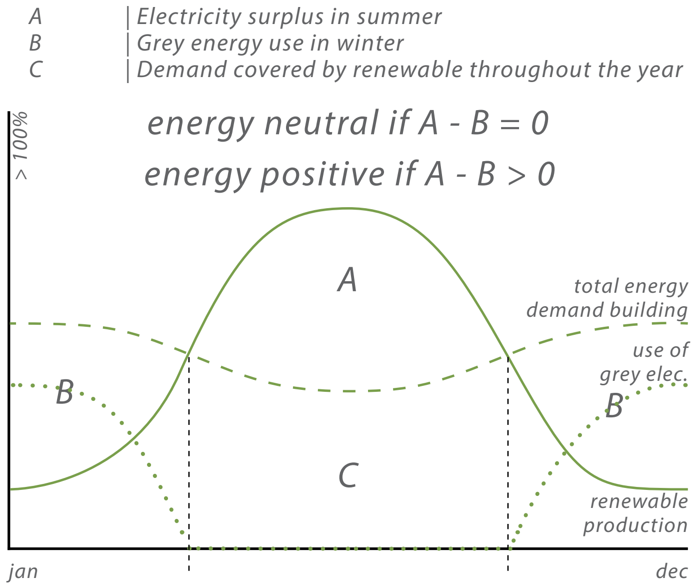

Figure 3.2: Energy neutrality

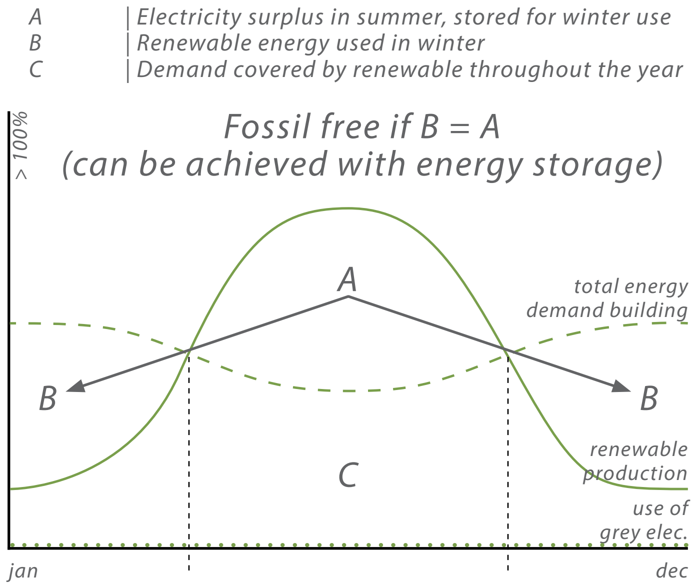

Figure 3.3: Fossil independent

(3) Fossil free

A building that generates on annual basis the same quantity of renewable energy than it uses grey energy from the network, is considered energy neutral. This is not equal to a fossil free building. Even if the generated renewable electricity is more than the consumption of grey energy, the building is only energy positive but still not fossil free. A fossil free building is completely independent from fossil based electricity and disconnected from the national gas network. Only renewable electricity from infinite sources is used for the building, user and operational related energy demand.

Besides the circular ideology that we want to become as independent as possible from earth's resources by gradually shifting to renewable energy, fossil based energy is also very polluting. CO_2 emissions by the industry+energy production are responsible for 60% of the total CO_2 emission in the Netherlands (Compendium voor de leefomgeving - Rijksoverheid, 2017).

To abandon fossil energy completely, there are some general actions that can be taken:

- Far going reduction of the energy demand;
- Enhance energy reuse and stimulate the use of waste energy;
- Increase the efficiency of existing renewable energy production technologies so that they can also approach or even meet the demand in winter;
- Find new ways to generate energy in winter;
- Develop effective ways to store the surplus energy in summer that can later be used for the building during the winter (figure 3.3). Avoid energy 'storage' on the national grid!

(4) (absolute) Energetic circularity

The final step would be becoming circular. It is important to understand that by achieving a full disconnection from fossil based energy, energetic circularity is technically achieved. Energy demand should be fully covered by the generation of renewable electricity while gas based installations are phased out of the building.

In this research, another layer of energetic circularity is added to the roadmap: *absolute energetic circularity*. This concluding milestone focuses on retrospectively taking responsibility for the invested energy in the building materials used for the supermarket. In practise, this is a nearly unquantifiable milestone as it is very hard to exactly determine the embodied energy for a complete building. Until we have a structured and recognized system to determine the amount of energy per kg material and we know exactly how much kg is applied in the building (e.g. by means of BIM), this milestone remains theoretical.

Nevertheless it is important to realize that a lot of energy is already invested preparatory to opening up a new Lidl supermarket. It is not hard to imagine how challenging it would be to make the production building materials energy neutral, let alone fossil free. Extra renewable energy production on-site, could be one way to take a moral, numerical and indirect responsibility for the embodied energy.

The core idea/mindset of *absolute energetic circularity* is to think beyond the demand of the building and over-generate energy for adjacent projects or whole other industries and to apprehend an inter-scale way of thinking.

The roadmap visualised

The graph below shows the roadmap towards energetic circularity, expressed in time and percentages. As mentioned before, the roadmap is not a sequence of steps and the order is based on the level of complexity. Working on reaching each individual target could so to speak be initiated today. Achieving all four targets would take decades. The graph below only covers the building, user and operational related energy. This makes it applicable for both one individual supermarket as well as the whole Lidl company. This is in contrast with the similar graph presented in the research by Dobbelsteen and Graamans, where also transport is included.

Achieving CO_2 neutrality is the least complicated milestone and can be obtained by means of compensation. Energy neutrality is achieved when the (local) surplus production of renewable energy in summer equals the grey energy retrieved from the national grid. Fossil independence applies if a building can operate completely without the aid of fossil based electricity and energy. This also includes a full disconnection from the gas network. From this point onwards, the CO_2 compensation program can be abandoned as CO_2 is no longer emitted due to the energy demand of the supermarket.

In this research, energetic circularity defines the moment when the local electricity production has a certain oversupply to retrospectively compensate for the investment/embodied energy in the building materials. This oversupply not literally needs to be directed to the building product factories, it is about the mathematical compensation.

The energy demand is rising over time due to the rising number of Lidl supermarkets in the Netherlands and due to the fact that gas based installations have to be replaced by electricity based units, hence increasing the total electricity demand.

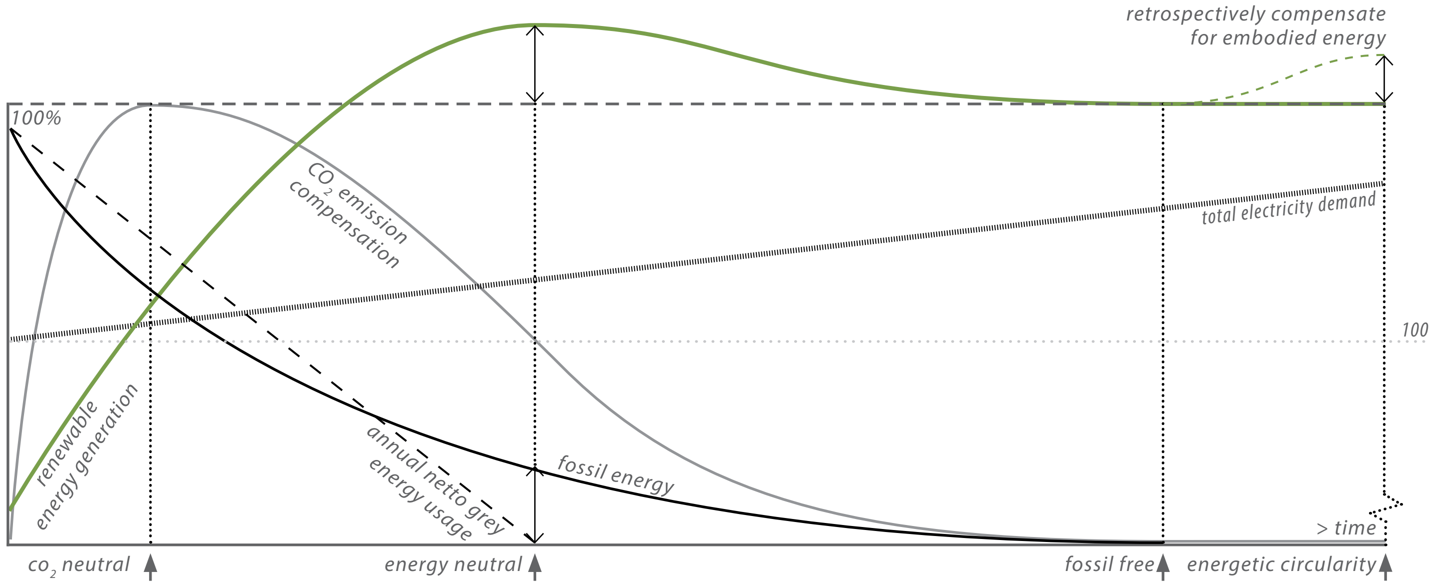

Figure 3.4: Four steps towards energetic circularity visualized. Remember: only building, user and operation related energy is taken into account!

3.2 | Building synergy: the concept

The concept

The principle of this concept is based on the exchange of flows between buildings. Waste flows can be heat & cold but also (waste) water , organic or non-organic waste, CO$_2$ or other gasses, industrial residual material or agricultural material.

Operational processes, user activities or climate systems, everything results in one or more forms of waste flows. Electrical energy can be converted into light, movement, rotation, spring-load, radiation and chemical energy, but the efficiency of this conversion is never 100%. Energy can not appear out of thin air nor it can disappear into nothing, this is Newtons law of conservation of energy. If electrical energy conversion to a different form of energy is not 100%, the rest of the electrical energy has been converted to thermal energy. The best and classic example for this is the traditional light bulb, which only has an efficiency of 5-10%. This is visible as light, the other 90% is converted into invisible but noticeable thermal energy.

On the building scale, the same occurs. A supermarket is kept on a low temperature throughout the year and has 24/7 product cooling. A lot of electrical energy is required to bring the outside temperature down to 4-7^{O}C in the cooling displays or storages, what remains on the other side of the cooling unit is a constant flow of hot air. Surrounding buildings could benefit from this waste heat and reduce their own energy demand.

Energy cascading

Energy cascading is usually seen in the form of heat cascading, where excess heat of one building or industry is used for the heating or processes of the other building. Energy cascading is not limited to one drop and can be repeated as long as the excess flow can benefit a building's climate system.

Centralised high-temperature industrial heat grids are well-known, but the lower-caloric excess heat from buildings as offices, supermarkets and swimming pools are seldom utilised. 'The local exchange of (low-caloric) heat within buildings and between buildings within an urban neighbourhood or district is not very common. Nevertheless,[..], this strategy has great potential' (Dobbelsteen, Wisse, Doepel & Tillie, 2012, p. 9)

Current heat grids work with high caloric heat: temperatures of around 90^{0}C are used to heat buildings to 20^{0}C, an exergy inefficiency. Modern buildings, based on low temperature floor heating, succeed with an incoming temperature of 30-40°C whereas passive houses can even function with a temperature of 25-30°C.

There is a need for an energy grid, that is able to tune, exchange and cascade heat through different scales. Since there is a large diversity in the building physical quality of dwellings and other buildings, a heat grid should be adjusted to this to avoid exergetic inefficiency. Older dwellings, functioning on high temperature heating, should be at the beginning of the cascade, whereas new building should be designed in such a way that they can be at the tail of the cascade.

Example: REAP

Rotterdam Energy Approach & Planning (REAP) is a methodology, set up by a multi-disciplinary research team, that answers to the call of Rotterdam to cut the city's CO$_2$ emissions in half by the year 2025. CO$_2$ reduction in this methodology is realised by minimizing the building physical dependence on fossil energy. The REAP approach takes the following steps (Dobbelsteen, Tillie, Joubert, De Jager & Doepel, 2009):

1. Reduce the initial energy demand by (passive) architectural measures;
2. Make use of waste flows on the building scale;
3. Look at the potentials of using waste energy through multiple scales (building-region-city;
4. Cover the remaining demand with renewable energy.
5. Close the energetic demand with fossil energy.

The REAP methodology is linked to the new stepped strategy, which on its turn is an improvement on the environmental approach *Trias Energetica*. REAP is applicable on all scales: from a single building to a cluster of buildings, a neighbourhood and a district to the city scale. REAP has been applied on the Hart van Zuid district in Rotterdam to see if it was theoretically possible to make an existing district CO$_2$ neutral.

The REAP approach on the scale of the individual building starts with applying the new stepped strategy. First, see how much energy demand reduction can be achieved by reusing waste flows within the walls of the building. Before moving to on-site renewable energy production (3), it is good to explore if the demand for heat or cold might be solved by surrounding buildings with different energy requirements patterns.

Between the building scale and the neighbourhood scale, one could place the cluster scale: different functions under the same roof or directly adjacent to the site. This could be a cluster with a supermarket, greenhouse and one or two additional functions energetically connected.

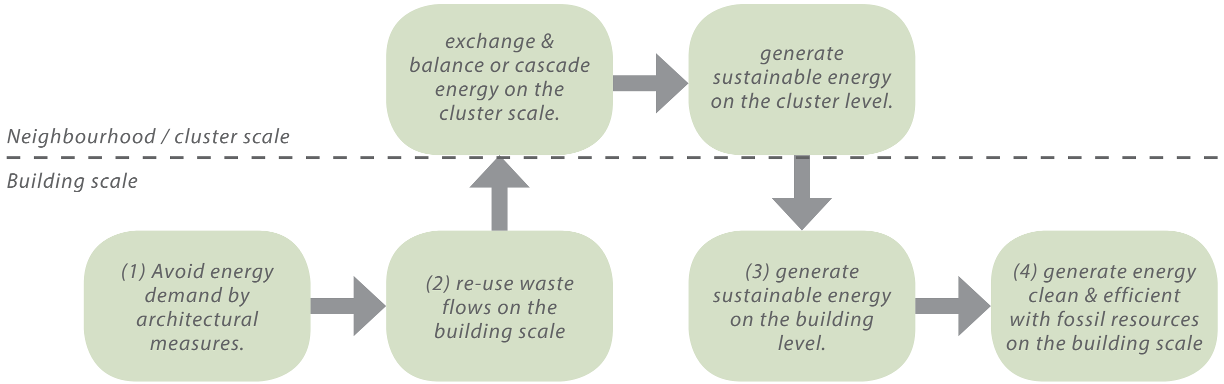

Figure 3.5: Part of the REAP approach (Dobbelsteen et al, 2012)

3.3 | Flows in a Greenhouse

Identifying flows

To design an local energy system that combines a greenhouse function with a supermarket function and reduces the cumulative ecological footprint for both, it is in this phase of the research important to understand the basic elements of greenhouse production.

The urge to produce crops and flowers in glass buildings, arises from the necessity to protect the produce from weather changes and to control the environmental factors for optimal production and quality guarantee. In the colder Northern-European countries we can simulate Mediterranean climates and bring overseas food production to our own Dutch soil.

The downside of modernizing greenhouse technology and using increasingly better insulated glass houses is that an unwanted situation may occur in the form of accumulating moist. If there is no proper balance between moist production by the leaves of the crops and the drainage of this moist, accumulation will happen. Traditional methods to exhaust highly humidified air, like opening windows, opening screens or even using extra heating to dry the air has an insufficient effect and comes at the cost of a lot of energy. In addition to this, the crop growth is disrupted by unwanted changes in the greenhouse climate like temperature fluctuations, downdraught and condensation on the leaves. Where moist problems occur in a greenhouse, diseases and fungus will first emerge and the risk of having to destroy the whole produce increases (Geelen, Voogt, & Van Weel, 2016).

Properly controlling the humidity of the indoor air is one of the key factors of successful greenhouse production. Also, with good control over the humidity, the buildings temperature can be regulated.

According to Van den Engel, Riera Sayol, and Van der Spoel, main issues in greenhouses are the reduction of heating energy, reduction of plant diseases and increasing the CO_2 level to enhance the plant growth (2017). The first two issues are influenced by indoor air humidity. Since outside air humidity is generally lower than inside air humidity (in a Dutch climate), the easiest solution would be to open a window to lower the humidity level, subsequently lowering the risk of fungi and diseases. This would however go at the cost of heat and precious CO_2.

Plant growth is primarily dependent on daylight, temperature and CO_2 levels. Daylight increases the plants metabolism rate and so the production of O_2. A hight metabolism makes a plant vulnerable for drying out. This is countered with rising the humidity, which is achieved by the plant itself due to water evaporation through the leaves. A high temperature is recommended to prevent cold stress on the plants and to prevent condensation on the leaves (moist accumulation). High temperatures are -up to a certain level- not a problem for plants as long as the air humidity remains within desired boundaries. In order to keep the CO_2 levels high, a greenhouse should preferably be a closed system. Dehumidification should therefore take place by other means then opening a window. It is clear that greenhouse food production is a controlled balance between daylight, temperature and humidity.

3.4 | Precedent study: greenhouse energy exchange Hoogezand

Heating + cooling by greenhouses

Hoogeland (Naaldwijk, South-Holland) is the first large neighbourhood in the The Netherlands that is heated and cooled by waste heat from surrounding greenhouses.

The energy system is based on individual heat pumps and two collective 250 meter deep underground heat-cold storages. The heat pumps cover the heat demand for both the tap water and the space heating. The collective heat storage systems have a capacity of $240 m^3$/hr. During summer, the underground storage systems are recharged to carry the neighbourhood over the winter.

To start with: the dwellings have a thick insulation package, CO_2 controlled ventilation systems, HR^{++} glass, low temperature heating and there has been a lot of attention to tightly sealed detailing. All this results in an EPC value of 0.41-0.50, much lower than the current Dutch norm[1]

Greenhouse

The greenhouse (tomato production) used as the energy source is located 1500 meters away from the residential district. It is a 3.4 acre greenhouse system that operates according to the *closed greenhouse* principle. Unlike traditional greenhouses, closed greenhouses are cooled during the warm periods. This is done in a sustainable way by storing the surplus energy in summer in an underground storage that can be extracted again during winter. Also greenhouse cooling is done with the same system. It turned out that this system is so effective, that there is more energy generated then there is used. It was decided to integrate the new district of Hoogeland in this system[2]. The surplus of solar energy is transported out of the building by forced cooling and the water arriving at the Hoogeland storage system has an average temperature of 22°C.

The neighbourhood is planned to have 700 sustainable households and 26.500 m^2 of utility and healthcare buildings and is not connected to the gas network. Because of this unique heat system, an annual CO_2 reduction of 40% is realized for this district[1].

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[1] www.DWA.nl; [2] www.L5.nl

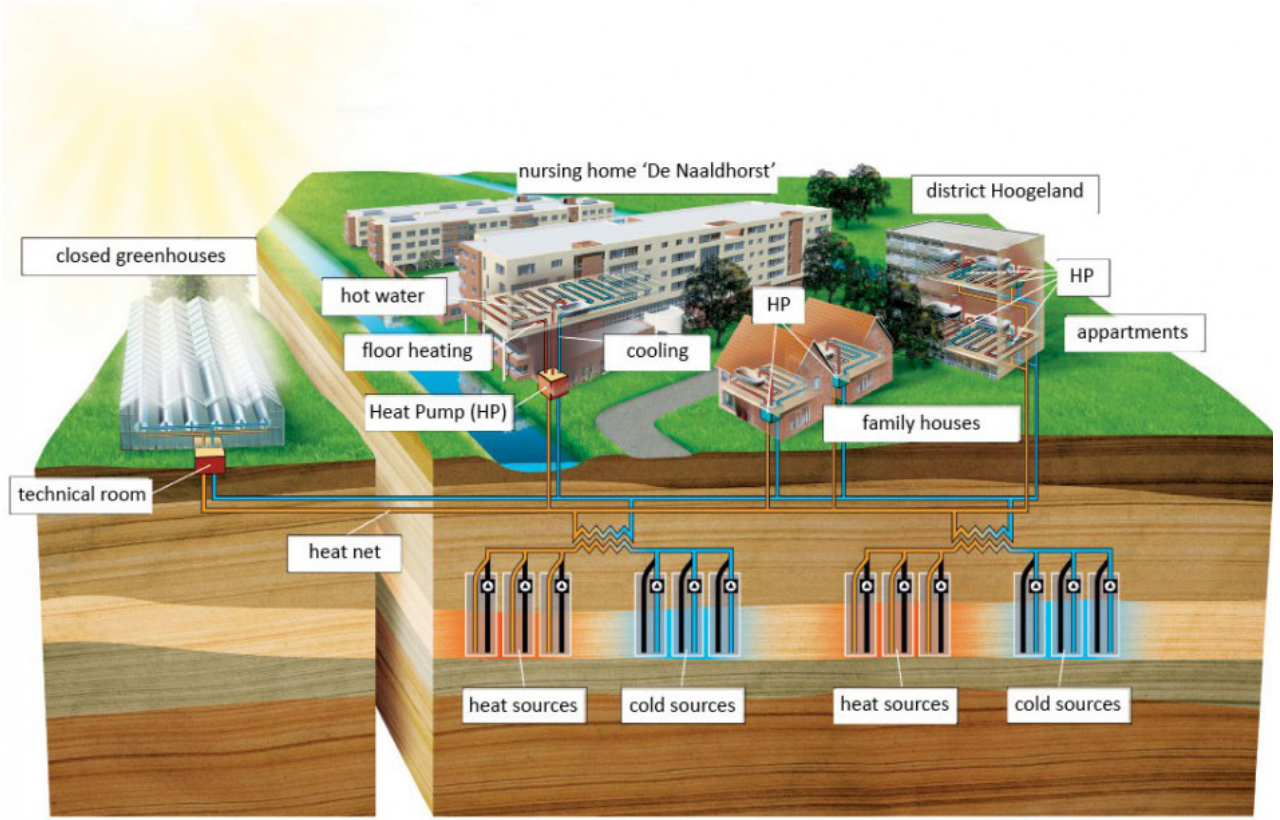


Figure 3.6: Heat & Cold storage system in Hoogeland (x)

Data analysis | Supermarket

Part IV

4.1| Intro

In order to understand to what extend there is room for improvement in the refurbished and modernised supermarket, its future electricity consumption needs to be estimated, see the scheme on the right.

In this chapter, the electricity demand of the present supermarket is first retrieved (1). This allows for later comparison of the difference between the electricity demand in the new and the old energy model.

Second, the total electricity demand of the modern-standard supermarket (Lidl Stein) is determined (2&3) and decomposed into different energy posts (4). Monthly electricity demands of the modern supermarket are expressed into Watt/m^2, this value is later translated to the future refurbished supermarket in Amsterdam so the future electricity consumption can be estimated.

Since we will also know the electricity division of the energy bill (in %) for both supermarkets, the theoretical room for improvement for building energy [kWh] can finally be calculated. This energetic value can then be expressed in theoretical CO_2 emission contained.

For insight purposes, the theoretical PV gain per m^2 is calculated (5). This gives an idea of the ration between supermarket floor surface and required PV surface.

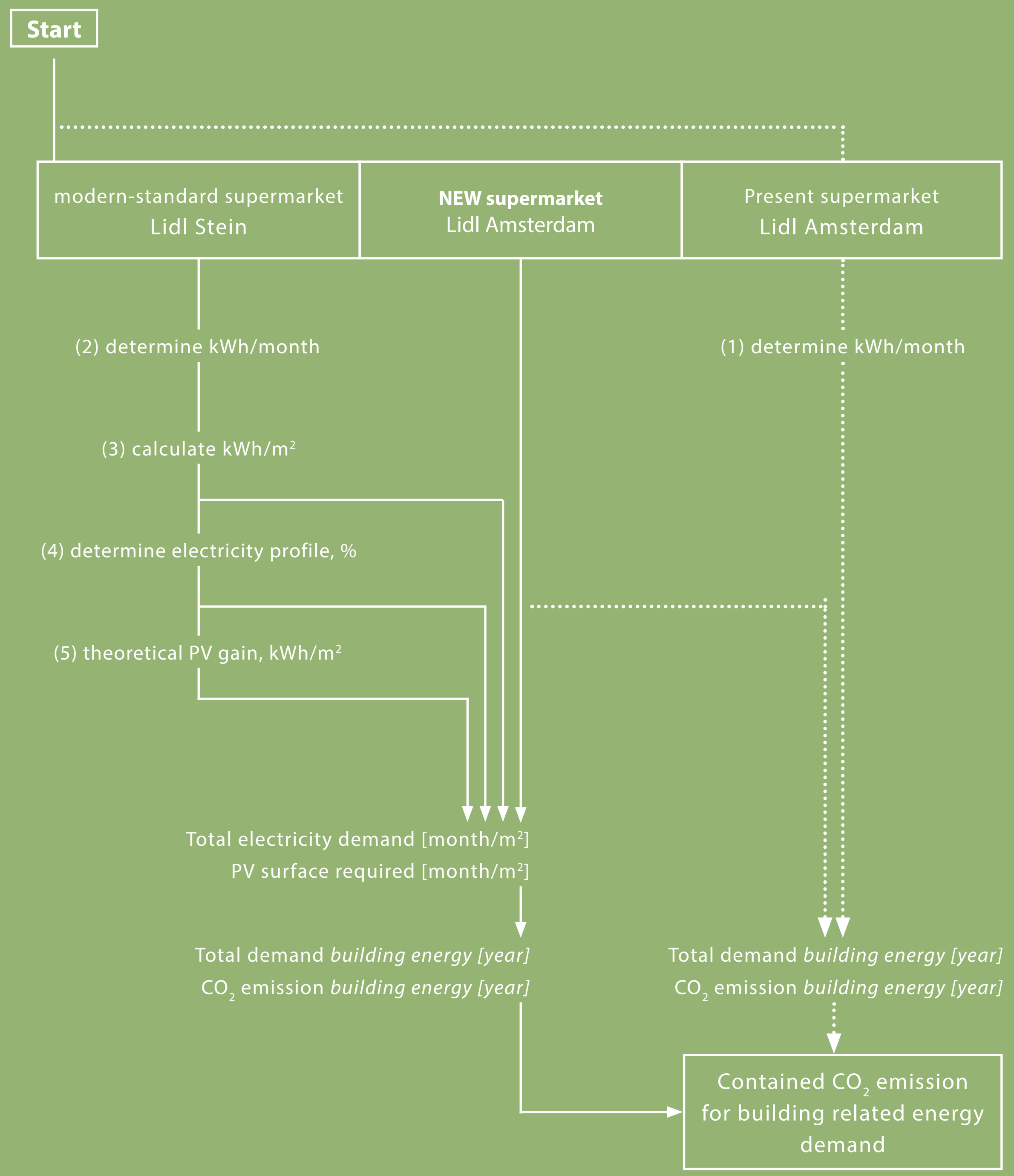
Lidl Amsterdam & Lidl Stein

Lidl Amsterdam - This research revolves around a Lidl supermarket located in Amsterdam: Lidl Helmersbuurt. This supermarket and the direct/adjacent vicinity form the subject of the study. The supermarket is 10 years old and will undergo an expansion plus modernisation in the near future. Currently, any construction plans are put on hold (status on 10-2017).

Lidl Stein - The brand new supermarket in Stein (2014 - Limburg, the Netherlands) is the sustainable supermarket flagship of Lidl Holland and sets the standard for all new future Lidl retail buildings[1]. In this study, this Lidl is also referred to as the *modern-standard* supermarket.

For both the Lidl in Amsterdam and in Stein, electricity data* is available for analysis. Since the supermarket in Stein sets the energetic standard for all new supermarkets in the Netherlands, we can project it's electricity profile on to the new Lidl in Amsterdam and roughly estimate it's electricity consumption. See the scheme on the right page.

**Energy data.*
The calculations and graphs in this chapter are based on energy data that is provided by the Lidl. This data is shared only in support of this research and is not publicly available. If insight in this data is for any reason desired, please contact Lidl Holland.



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[1] www.rvo.nl/actueel/praktijkverhalen/duurzame-discounter-lidl-bespaart-26-op-energieverbruik

4.2 | Fluxes in a supermarket

Identifying flows

A supermarket is a big consumer of energy, a node in transport lines, a transshipment of edible biomass and a centre of activity. Although this research is about the energetic flows in a supermarket: heat, cold and electricity, it is interesting to have a brief peak at the other flows in and out of the building. The following flows can be found in or around a discount supermarket:

- retail (food and non-food)
- customers and employees;
- transport (retail and customer)
- water (hot and cold)
- electrical energy;
- gas;
- fresh air and waste air;
- waste (organic and non-organic);
- thermal energy.

Gas
The Lidl supermarket in Amsterdam is not connected to the gas network. As a matter of fact: the Lidl wants to disconnect all their supermarkets from the gas network by 2018. In practise this includes switching to electrical ovens, subsequently raising the electricity demand.

Ventilation
Minimal air exchange rates for supermarkets vary per source that is addressed but usually a number between 4-10 is found. The Dutch building code states that a supermarket need a minimal ventilation rate of 4 dm^3 per person. The same code also dictates to design the building climate system around an occupancy of 0.05 person/m^2 of 20m^2 per person. The ventilation demand is for the major part covered by the infiltration in the supermarket. Each customers that enters the sliding door brings in a large volume of fresh air. The Lidl calculates with an infiltration rate of 0.625dm^3/s/m^2, or 2.25m^3/m^2/hr. This is practically an exchange rate of 1.

Thermal energy loss due to ventilation and infiltration is included in the determination of the supermarket energy balance, appendix III.

Food
The Lidl sells only about 1500 different types of food and non-food. This is a characteristic of a discount supermarket: a normal supermarket can sell thousands of different types and brands of food (Albert Heijn/ Jumbo). Food, frozen food and fresh food is transported with the same truck. For this, the Lidl utilizes special insulating containers that can keep the food frozen during the transport and a special frozen segment in the truck is no longer required.

4.3 | Lidl Helmersbuurt - The supermarket building

Description

Lidl Helmersbuurt, in this research also called Lidl Amsterdam, is located in the Helmersbuurt, Oud-West residential area of Amsterdam, just outside the outer ring canal of the old city centre.

The supermarket is situated on the ground floor and is for customers accessible though a distinctive long corridor. The building is enclosed on two sides between 5-6 storey high sixties-seventies residential gallery access flats and staircase entrance flats. Part of the surrounding dwelling has influences of the architecture style 'Amsterdamse School' and pre-dates the first world war.

Technical

Administrative

- Lidl supermarket number 423
- Address: 2e Helmerstraat 29, 1054CB, Amsterdam
- Distribution centre: Zwaag (48km)
- Open since 23-5-2007 (10 years)
- Ownership building: rent

Climate

- Water supplier: Waternet
- Gas: not connected
- Airco: KX system
- Boiler: not present
- Electricity supplier: Engie
- Network: Liander

Other

- Total building surface (GFA): ~993m^2
- The current Lidl has a small bake-off section with two ovens;
- Practically no natural daylight enters the building;
- Product cooling & freezing displays on the sales floor are foreseen with glass doors.
- The retail loading entrance and customer entrance are separated;
- The building includes a small office for management and a small pantry for staff, both directly accessed from the sales floor.
- There is one men's and one woman's bathroom. They share the washing bin.
- In the supermarket is one deep freezing cell;
- Further energetic calculations during this study are based on a climatised sales floor area of ~700m^2.

4.3.1| Electricity consumption

Lidl Amsterdam

Total electricity use

Figure 4.1 shows the total electricity use of the present Lidl supermarket in Amsterdam. In 2016, this supermarket consumed 258MWh of electricity in total. The graph points out that the electricity demand is affected by the season. However, this influence is low relative to the total monthly electricity demand. Yet it seems that the colder months require more electricity.

In figure 4.2, the monthly electricity demand has been expressed per square meter (GFS=993m^2). The renewable electricity generated by 1m^2 of PV panel per month has been added as well. This graph points out how much PV surface would in theory be required to meet the electricity demand (ratio total supermarket surface : total PV-panel surface):

- January 1:7
- March 1:2
- May 1:0.8
- July 1:0.9
- September 1:1.5
- November 1:6
- December 1:10

For your information: with 1m^2 of PV-panel is literally meant: 1 meter by 1 meter photovoltaic surface under the optimal angle and orientation and not 1 square meter of PV-system on a flat roof. In practise, you would need about 1.6 square meter of flat roof to place 1 square meter of PV-panel. Rule of thumb: 1 standard market PV-panel of 100x165cm requires ~2.5m^2 of flat roof in order not to be placed in each others shadow.

Electricity production PV-system

Assume a standard market PV panel of 1.65x1.00 meters with a performance of 280 watt peak (Wp):

$$280 / (1.65\text{x}1.00) = 170\text{Wp/m}^2$$

Assume 0.9kWh/Wp for a South facing panel under the optimal angle:

$$0.9 \text{ x } 170 = 0.153\text{kWh/m}^2\text{/FSH}$$

PV electricity production is determined by the amount of *full sun hours* (FSH) in a period. In the Netherlands there are roughly 1000-1100 full sun hours in a year:

$$0{,}153\text{x}1074 = 153\text{kWh/m2/yr}$$

The table below shows the monthly electricity generation per square meter PV panel in 2016:

month	*full sun hrs*	*kWh/m^2*
January	20.9	3.2
February	40.7	6.2
March	80.0	12.2
April	123.7	18.9
May	162.5	24.9
June	145.0	22.2
July	159.1	24.3
August	139.0	21.3
September	103.0	15.8
Oktober	60.0	9.2
November	25.0	3.8
December	16.0	2.4 +
year	1074	153

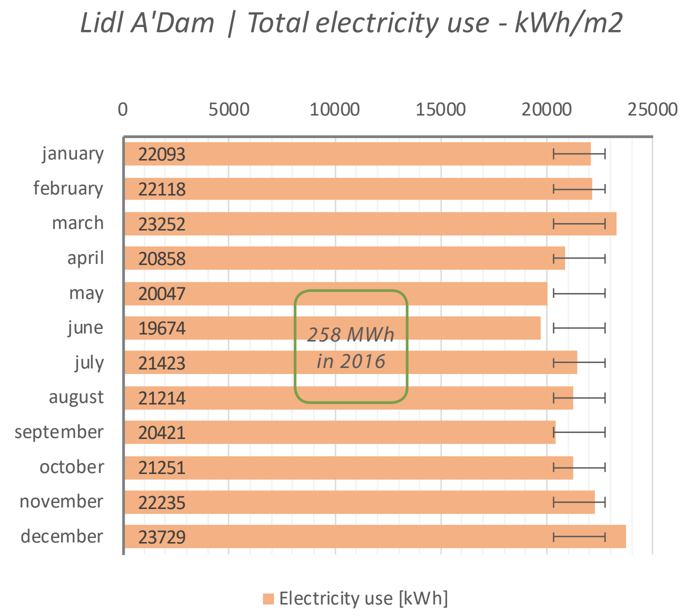

Figure 4.1: Total electricity consumption

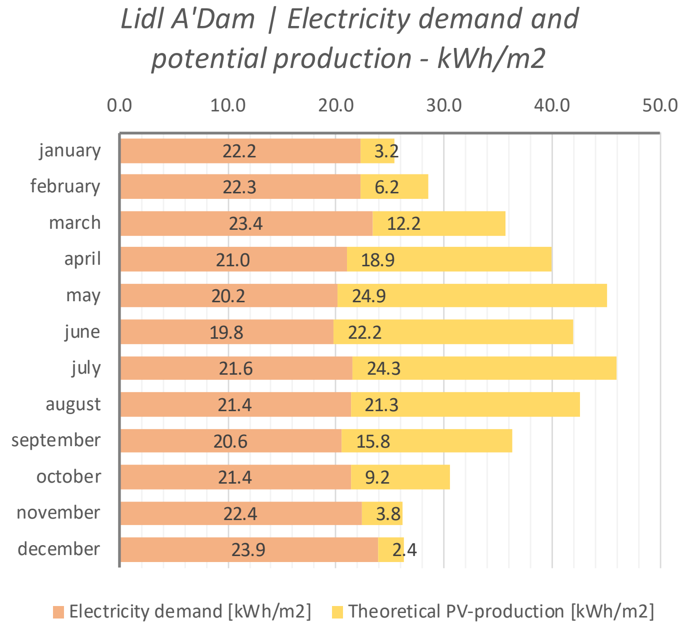

Figure 4.2: Electricity consumption + potential production in kWh/m2

4.4 | Lidl Stein - The supermarket building

Description

The new Lidl supermarket in Stein (Limburg) is the first building in the Netherlands with Energy label A^{++++}. This is the highest possible rating of this label and the supermarket chain has ambitions to achieve this performance as the standard for all future supermarkets. An energy rating this high is achieved by the following measurements (Lidl Nederland, 2015a):

- 338 PV-panels generate electricity. On a sunny day they generated enough for the whole building.
- 100% energy saving LED lights are installed;
- The building is not connected to the gas network;
- Extra high insulation values for the facade;
- HR+++ triple layer insulating windows;
- Motion sensitive lighting system;
- Use of sustainable building materials. All used wood is demonstrable from sustainable sources;
- Charging stations for cars and bikes are available to stimulate electrical transport;
- Rainwater is collected from the roof and the parking lots and is directly infiltrated into the earth underneath the plot.
- According to RVO.nl, this Lidl supermarket has an EPC value of 0.3[1]. The operational processes are not included in this EPC calculation!

This A^{++++} supermarket sets the energetic standard for all future Lidl supermarkets. With this in mind, it is safe to assume that the electricity use kWh/m²/month of this Lidl can be projected on the new supermarket in Amsterdam. This results in an educated estimation of the future electricity use of the supermarket.

This Lidl supermarket has a GFA of 1472m².

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[1] www.rvo.nl/initiatieven/energiezuiniggebouwd/lidl-filiaal

4.4.1| Electricity consumption

Lidl Stein

Total electricity use

Figure 4.3 shows the total electricity use of the Lidl A^{++++} in Stein. In 2016, this supermarket consumed 318 MWh of electricity in total. The graph shows the total monthly electricity demand (red + yellow) and the part of that demand that was covered by locally generated electricity (yellow). To be clear: the total energy use of Lidl Stein is the sum of the yellow and red bar.

Figure 4.4. The total electricity demand per square meter compared to the theoretical electricity production per square meter. Once again: the electricity consumption [kWh/m^2] is the sum of the red and the yellow bar from figure 4.3. The supermarket has a GFA of 1472m^2.

Figure 4.5. On an annual basis, the 338 PV panels on the roof of the building manage to cover 24% of the total electricity demand. The other 76% is grey energy retrieved from the national grid. In the best month, 39% of the total electricity demand is covered by the PV-system (2016 data).

Figure 4.6. The total electricity demand per square meter compared to the theoretical electricity production per square meter.

Quick calculation: assume the whole electricity demand should be covered by the local PV system. The worst month, December with a ratio of 1:7 (figure 4.4), would be normative for the size of the PV-field. The minimal size of the PV-system of this supermarket would be (exclude temporary electricity storage):

7x1472 = 10.304m^2
10.304 / 1.65m^2 = 6250 PV panels
*6250 * 2.5m^2/panel = 15.500m^2 of the PV-field*

This is equals 3 soccer fields to guarantee enough solar energy production throughout the whole year. Generally, there is no space for 3 soccer field in the urban environment!

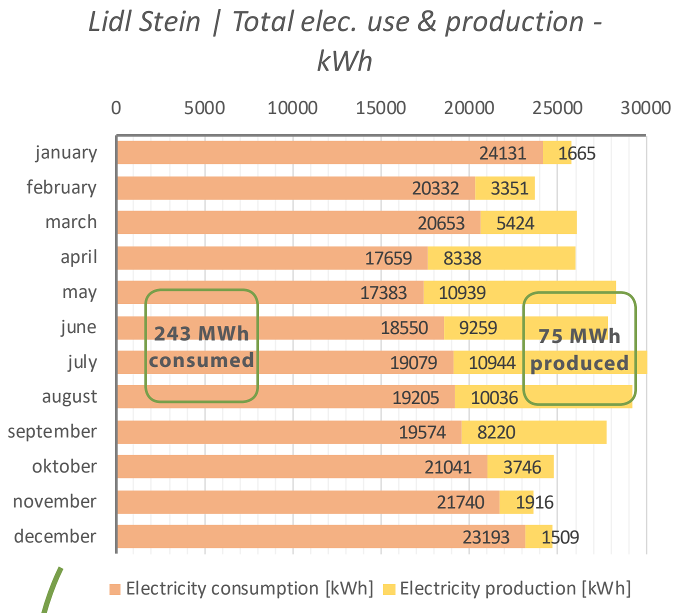


Figure 4.3

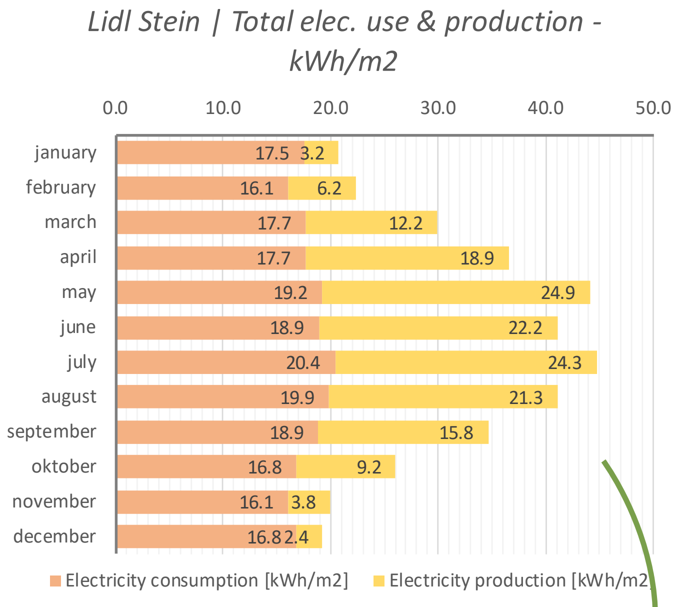


Figure 4.4

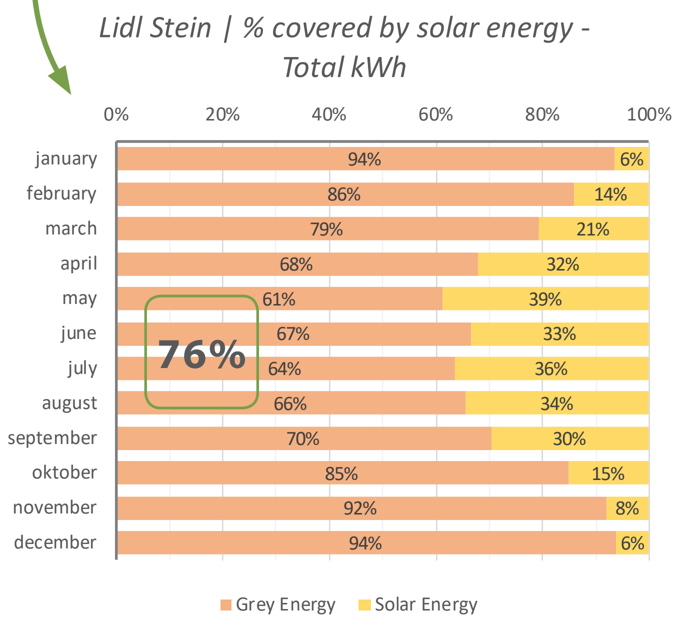


Figure 4.5

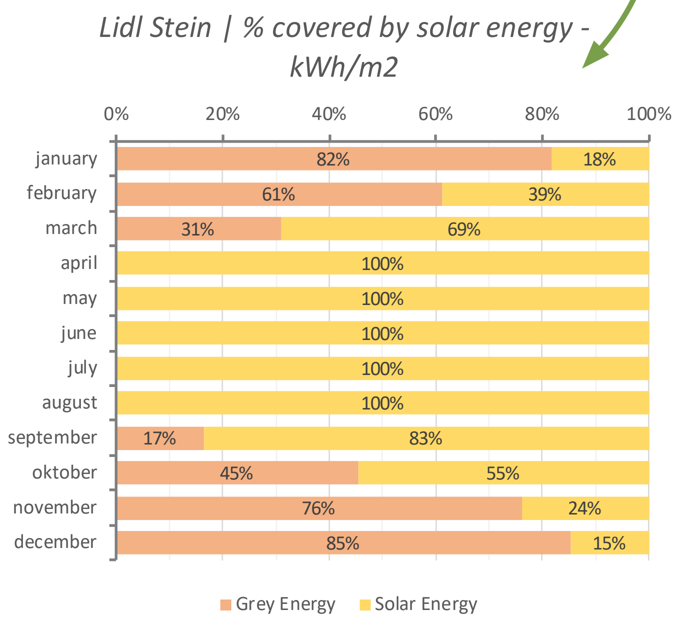


Figure 4.6

4.4.2 | Electricity distribution

Lidl Stein

Decomposing the energy bill

The total electricity demand of a supermarket is usually decomposed in the following energy posts:

1. Product cooling (cooling & freezing displays/cells);
2. Lighting system;
3. Product preparation (electrical ovens);
4. Building climatising (cooling of the sales floor);
5. Rest.

Through various calculations and assumptions, the different posts can be determined. This is elaborated in Appendix I. The values that have been defined in this study are compared and validated to values from other research (Appendix I - figure A.1.5). See the circle diagram in figure 4.7.

In figure 4.8, the circle diagram on the right and the graph in figure 4.4 are combined with each other. The different percentages from the circle diagram are projected on the energy demand per square meter of the Lidl in Stein. The bright yellow bar points out the theoretical electricity production per m².

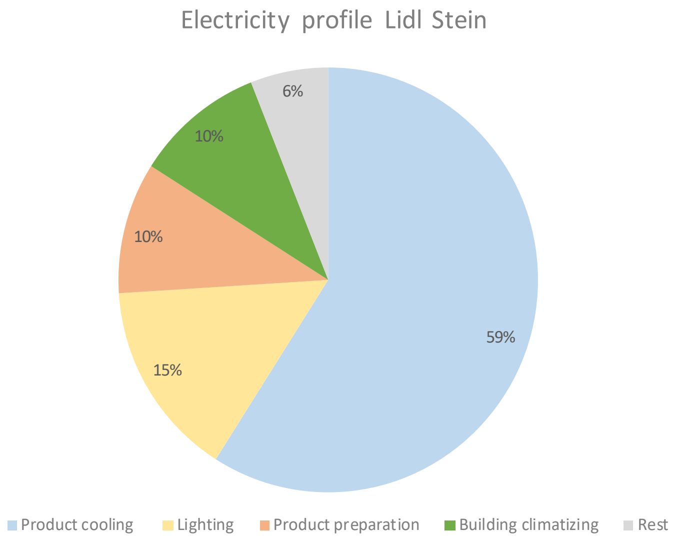


Figure 4.7: Distribution of the energy demand

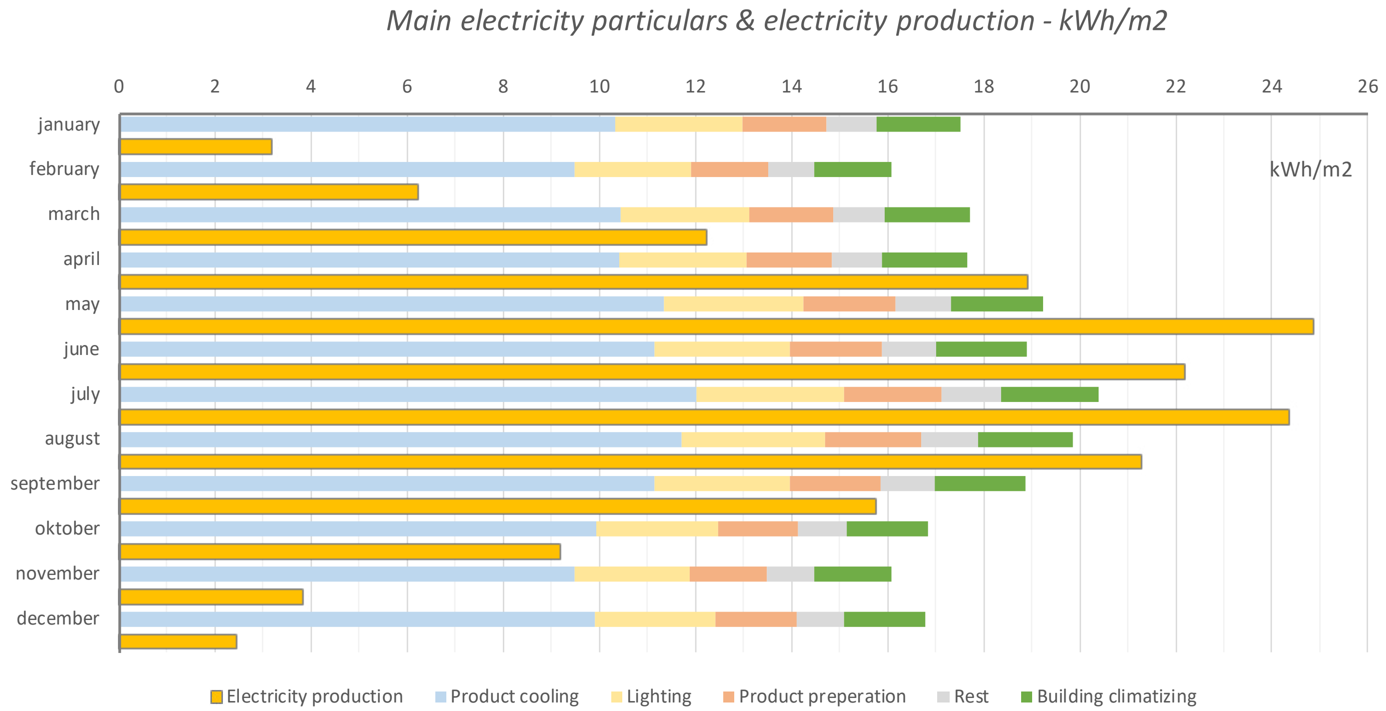


Figure 4.8: Distribution projected on the monthly energy demand [kWhh/m2]. Monthly total solar energy is included [kWh/m2]

4.4.3 | 24hr electricity demand curve

Lidl Stein

Description

Figure 4.9
This graph visualises the electricity demand over the course of 24 hours. The electricity data that was provided by the Lidl performed a measurement every 15 minutes. Electricity consumption of each first day of the month are taken and averaged to obtain a representable graph. For clarification purposes, 15 minute values added up to each other to obtain an hourly electricity demand.

The green curve shows how the energy demand proceeds during the day. There is a clear demand peak in the early morning, when all the ovens are turned on to bake-off the morning fresh bread. The second demand peak can be seen around 13:00. This peak can either be explained by the sun altitude or because it is a busy moment on the day: energy balances further in this research prove the substantial effect of customer occupancy on the cooling demand. When the supermarket closes at 20:00, the energy demand rapidly reduces until the supermarket is in *standby mode* during the night.

Figure 4.10.
This graph is an approximation of the electricity demand and the graph is for indicative purposes only. For exact values, please remain with figure 4.9.

The electricity distribution from figure 4.7 is projected on the daily energy profile.

Obviously, *lighting* only applies for working hours [06:00-22:00].

Product preparation is not applicable from the evening till the early morning [18:00-06:00]. Product preparation electricity demand shall mainly be caused by the electrical ovens in the supermarket. The use of these ovens roughly relates to the expected number of customers in the hours that follow. This explains why this energy post is some moments higher than other hours. We assume that after 18:00, no more bread is baked-off and the ovens are shut down.

Building climatising will show a peak demand in the hours before and just after opening the store as the climate system starts up for the day.

Product cooling and *rest* are equally distributed over the day.

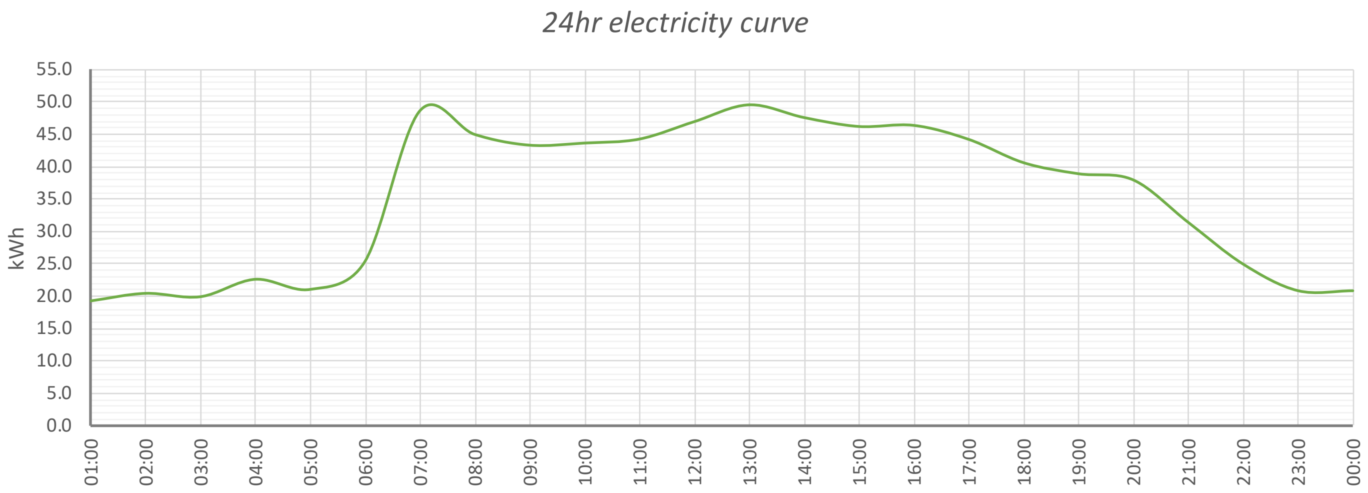


Figure 4.9: Proceeding of the electricity demand throughout the day

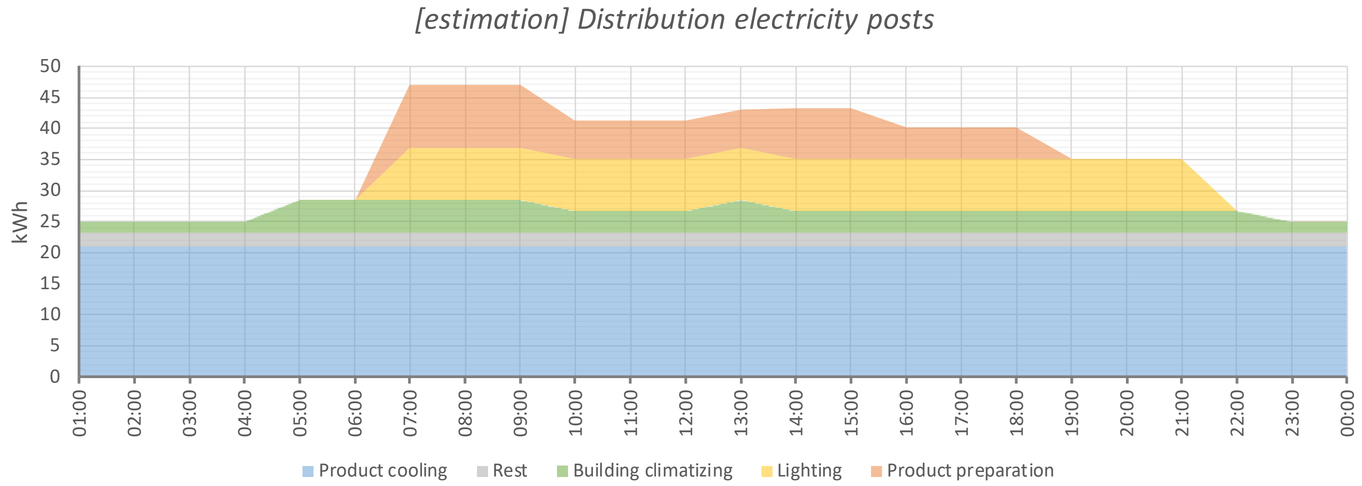


Figure 4.10: Assumption of the electricity distribution on a daily base.

4.5 | Comparing Lidl Stein & Lidl Amsterdam

Total electricity use & kWh/m2

Figure 4.11 shows a significant difference between the old and the new modern supermarket.

The figure also points out that during April, May, June, July and August, 1 m² of supermarket requires 1 or less m² of PV-panel. This was also already found in Figure 3.6.

Comparability
Even though the Lidl in Amsterdam will get an energetic performance that is comparable with the existing Lidl in Stein, this comparison is only up to a certain level. There are still contextual differences and the buildings do not have similar designs, for example:

- Geographic location. Lidl Amsterdam is in the centre of a large city and is most likely affected by the urban heat island effect. The Lidl in Stein is located in a more rural area, close to a body of water and open fields.
- Lidl Stein is free-standing. The Lidl in Amsterdam is for the major part enveloped by the adjacent structures. In Amsterdam their is practically no influence by the wind nor direct sunlight.
- Even though the Lidl in Amsterdam will undergo a complete (energetic) refurbishment and modernisation, large elements of the existing construction will very likely be reused, like for example the existing roof. We can assume that even after the renovation, the insulating properties of the facade of the buildings are different.

The differences mentioned above are not taken into calculation, but it is good to understand there is still a level of uncertainty when comparing the two buildings.

comparing electricity data
Lidl Amsterdam - present supermarket

- Total annual electricity demand = 258 MWh
- GFA supermarket = 993 m²
- Electricity demand per m² = 260 kWh

Lidl Stein - Standard supermarket

- Total annual electricity demand = 318 Mwh
  compared to Lidl Amsterdam = *+23%*
- GFA supermarket = 1472 m²
- Electricity demand per m² = 165 kWh
  compared to Lidl Amsterdam = *-37%*

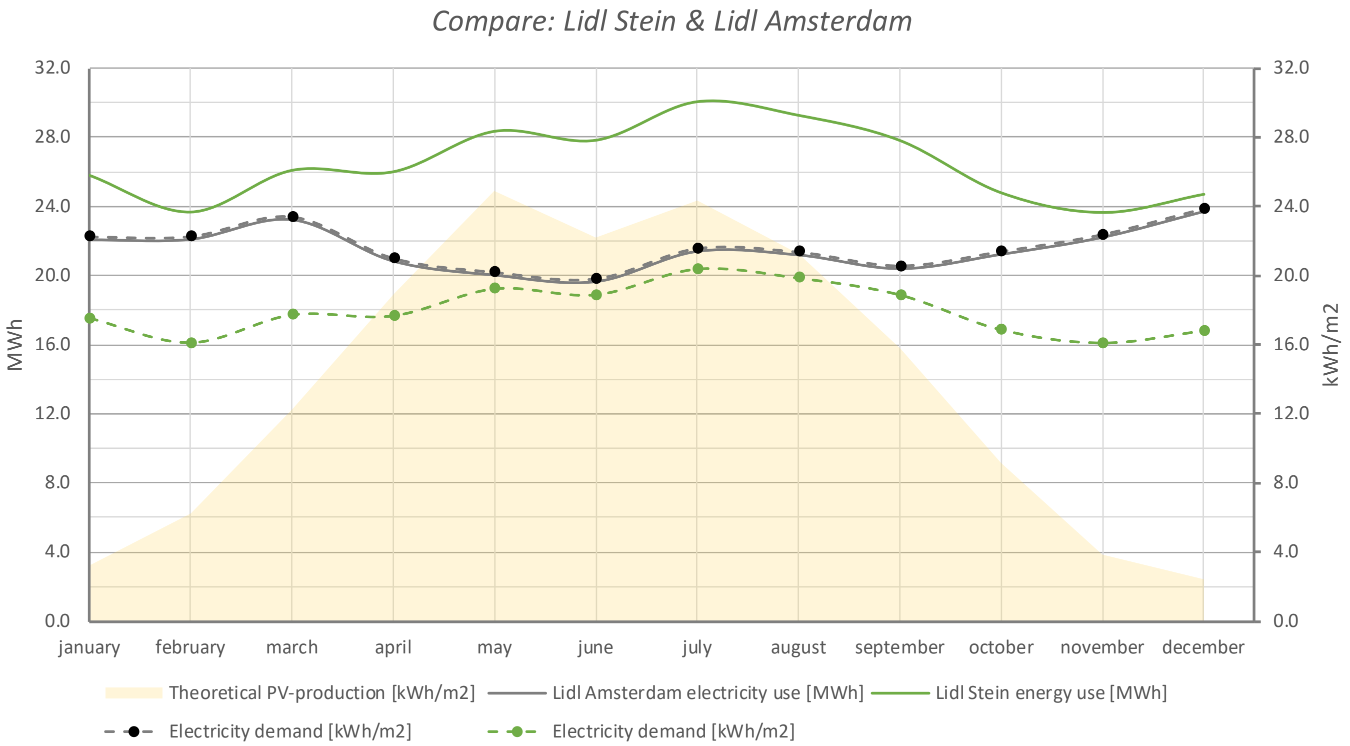


Figure 4.11: Comparing the electricity demand [kWh/m2 & total kWh] of the present Lidl in Amsterdam and Lidl Stein. Side note: the total GFA of the supermarket in Amsterdam is roughly 1000m². This coincidental round number makes the total MWh curve and the kWh/m² curve overlap each other.

4.6 | Analysis conclusion: room for improvement > building energy

Building energy

Through the energy data analysis of the modern-standard Lidl supermarket in Stein, the electricity profile for the new Lidl in Amsterdam can be defined. Through different calculations (appendix I) it is possible to determine the demand distribution. We find that the building related energy takes up ~10% of the total energy bill.

Within the domain of this research, it is only possible to alleviate the *building related* electricity post. With broad interpretation, *lighting* can also be classified as building related energy, however this remains outside of the scope of this study.

We can apply the kWh/m^2/month from the Lidl in Stein to the future supermarket in Amsterdam. Since the expansion plans for this new Lidl have been put on hold, we assume that the supermarket will not expand but it will only undergo a modernisation. According to the construction plans the current Lidl has a gross floor area of 993m^2.

If we project the energy profile (figure 4.7) on the annual electricity consumption of the current Lidl in Amsterdam, we find that the building nowadays consumes ~26 MWh electricity for its climate systems.

If we project the profile on the estimated annual electricity consumption of the new Lidl in Amsterdam, we find that the future building will use ~21 MWh of electricity for its cooling system (figure 4.12 & 4.13).

Potential CO_2 contained - first calculations

Present supermarket

Total electricity use: 258MWh
10% = 25800kWh, used for building energy
25.800kWhf = 66.154kWhp (x 2.5, n=40%)
66.154kWhp = 34.797kg CO_2 emission

New supermarket (before inclusion in the energy grid)

Total electricity use: 214MWh
10% = 21400 kWh, used for building energy
21.400 kWhf = 53.500kWhp
53.500 kWhp = 28.141kg CO_2 emission

If the complete *building energy* is nullified, 28 tons of CO_2 emission is contained each year. Relative to the present supermarket, about 35 tons of CO_2 is contained.

Calculations later in this research show how much the electricity demand is actually reduced after inclusion in the new energy model and how much CO_2 emission can theoretically be contained by this.

Estimated electricity demand new Lidl in Amsterdam.

The graph in figure 4.13 shows the estimated electricity demand for the new supermarket in Amsterdam.

This energy system designed in this study has only influence on 10% of the total energy bill: the building related energy. For calculation purposes we assume that this 10% is fully utilised by the building's cooling system and no other installations.

This electricity post is isolated from the rest in figure 4.12. Any interventions designed in this study that influence the supermarket's cooling demand have direct consequence to the electricity demand. Figure 4.12 is returning later in this research to point out the direct electricity use reduction when the supermarket is included in the new energy system.

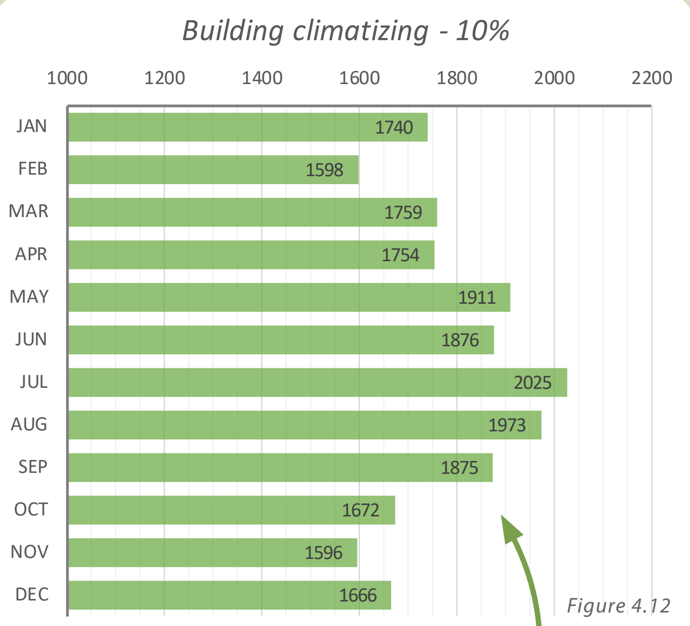


Figure 4.12

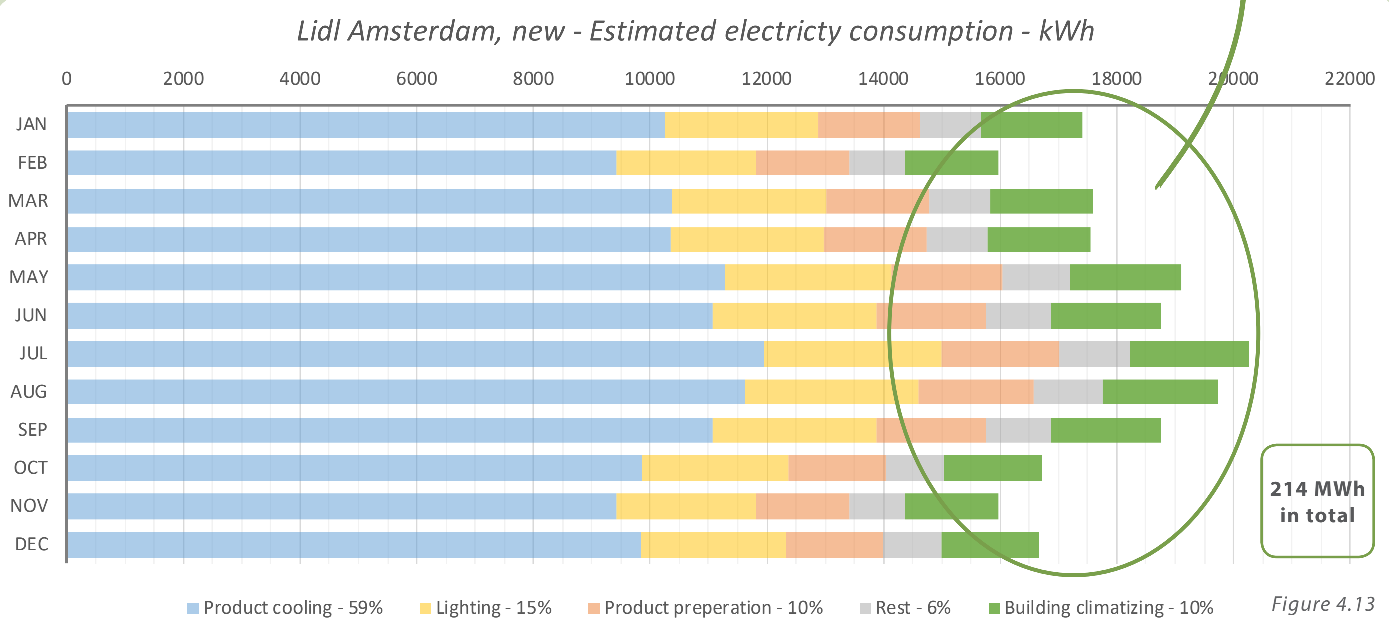
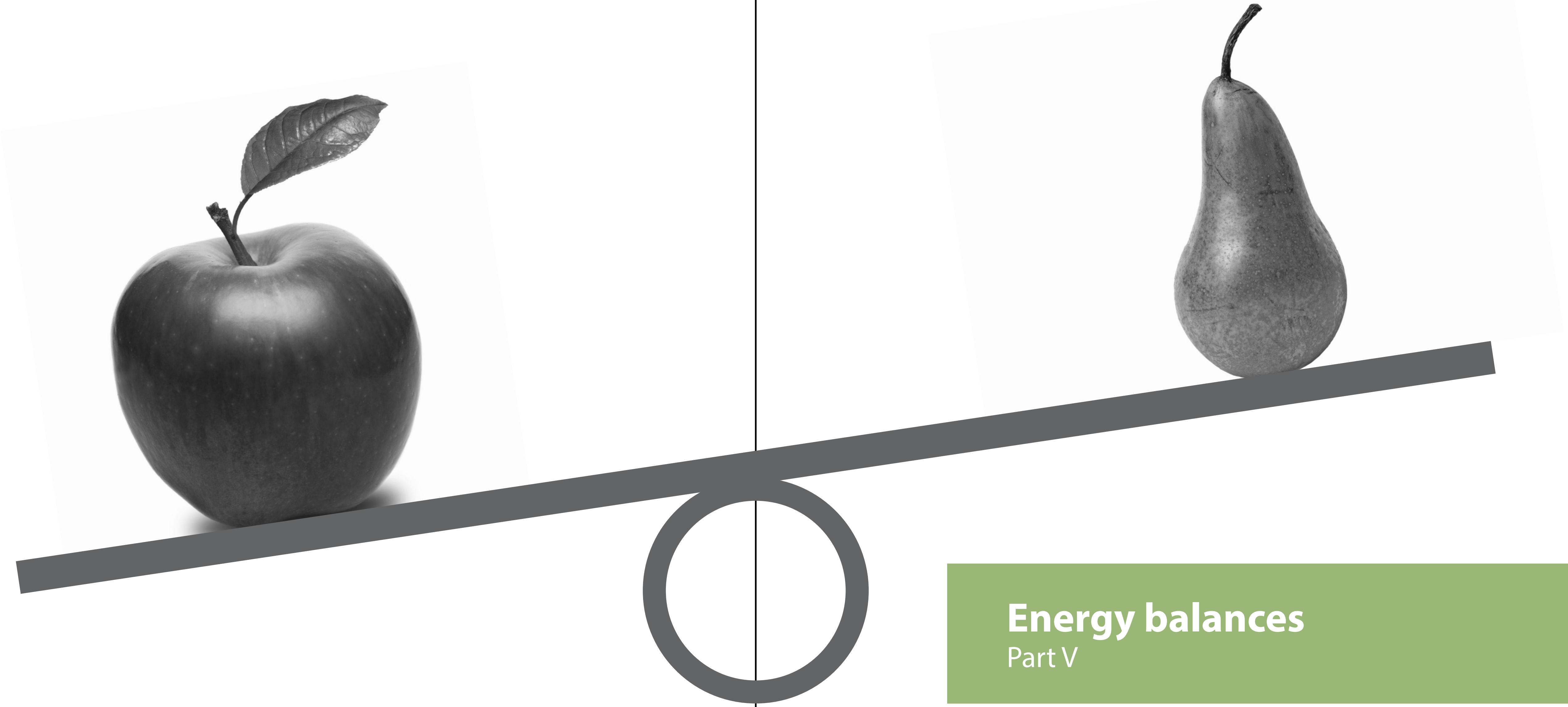


Figure 4.13



Energy balances

Part V

5.1 | Intro

This research explores the opportunities of energetically connecting a greenhouse, a supermarket and dwelling together. From an energetic point of view, a greenhouse is a complicated system in which a lot of thermal energy can be collected. On the other hand does maintaining a stable indoor climate require a lot of energy.

This study is not about improving the yield production, greenhouse capacity or production efficiency in a greenhouse. However, bringing farming into the heart of the city is an large economical investment. Any investors would like to see the payback time reduced as much as possible an this is only achieved by maximising the production. This chapter starts with a concise literature study on the best possible environment for Tomato production.

Energy balances
To find out where and when there is a heat demand or a heat surplus for all three of the functions, energy balances are made. The first greenhouse energy balances will be based on the climate parameters found in the literature survey. After this, an energy balance for the supermarket is made. For the dwelling will only be the heating demand taken into account. These numbers are derived from online research.

24hr and monthly / seasonal energy profiles
To get a complete insight on the energy balance of the system, both only monthly and daily balances are made. Climate data for one day of each season is collected and together with the greenhouse parameters and specifications put into an energy profile. These 24hr profiles are meant for insight and understanding and have an indicative function. Further energetic calculations in this study are not based on these profiles.

Climate data

Climate data used in establishing the energy balances has been retrieved from the following sources:

- Average monthly temperatures:
  Climate consultant - Amsterdam weather station;
- Average monthly solar intensities:
  Climate consultant - Amsterdam weather station;
- Hourly temperatures for 24hr profiles:
  Climate consultant - Amsterdam weather station;
- Average hourly solar intensities, direct sun:
  Retrieved from TU Delft data: BK Wiki, diagram give average hourly solar intensity for all 4 seasons.
- Average hourly solar intensity, diffuse sun:
  Retrieved from TU Delft data: BK Wiki.

| Index chapter V

Greenhouse

Supermarket

Dwelling

1) http://www.meteomoes.be/paginas/tabellen.php , 2) http://wiki.bk.tudelft.nl/bk-wiki/Zonnestralingsintensiteit

5.2.1| Production Technology

Greenhouse

Traditional and modern greenhouse production: open vs closed

Maintaining an stable energy balance and greenhouse climate throughout the year to optimize the greenhouse production is a complicated task. It used to be the experience and sense of the farmer that determined the annual yield. Nowadays it has been acknowledged that a good understanding of physics and using it to your benefit can optimize the production rate of a greenhouse. Many studies on the optimisation of the indoor climate for all kinds of crops have been performed in the past and are still happening. One of the more essential conclusions drawn from this research is that a closed greenhouse system has both a higher production rate as well as an improved energy efficiency compared to the traditional open greenhouses.

The main difference between an open and a closed greenhouse is the permanent closure of the ventilation windows. Cooling is no longer done by natural ventilation but by other means, for example an HVAC system. Heat does not get lost to the environment but the surplus solar energy is stored and later used when needed. Better energy efficiency is the result of carefully dealing with the energy flows in a closed greenhouse. Closing the windows also means that precious CO_2, essential for the growing process of the plant, can be accumulated in the glass building (Geelen et al, 2016).

A succeeding improvement after opting for a closed greenhouse is the hydroponic farming technology, a production methodology in which soil is no longer needed.

Hydroponic farming

The standard method of food production all over the world is in soil. In temperate climates like in the Netherlands, the annual freezing of the ground top layer makes sure that any pathogens built up over the course of the season are neutralized. This way the same earth can be used over and over again without any major interventions or investments of the farmer. Crop rotation should be applied to prevent soil depletion.

In a closed greenhouse system, a warm climate can be maintained throughout the year, ensuring continuous crop life cycles to boost up the production per square meter. A major problem are the soil-borne diseases that built up and reach excessive levels after periods of uninterrupted production due to the absence of crop rotations or winter soil freezing. Because of environmental and health restrictions, there is not yet a soil fumigant available that can be applied in the intense production environment of a closed greenhouse (Jensen, 1981).

To avoid soil contaminations there has been a lot of interest and development in the hydroponic technology. The advantages of hydroponic farming in closed greenhouse systems include (Jensen, 1981):

- high-density maximum crop yield;
- indifference to ambient temperature;
- efficient use of water and fertilizer;
- minimal use of land area;
- avoiding soil-borne contaminations and by that the costly procedure of soil sterilization.
- a more reliable and easier control on the temperature of the medium and the root temperature

The principle disadvantages of hydroponic farming relative to open field growing are:

- High investment costs;
- High and costly energy inputs;
- High degree of management skills required for successful production.

Because of its significantly higher costs, successful farming with hydroponics in a closed system are limited to crops of high economic value (Jensen, 1981). Annual yields from hydroponic production are between 5.5 and 20 times larger than those of open field agriculture (Graamans, 2015).

In his research, Luuk Graamans (2015) gives a brief and clear overview on several different methods of hydroponic farming. Three methods are worth considering for application in Amsterdam:

- deep flow technique;
- nutrient film technique;
- aeroponic farming.

Point of measurement is what the influence of a specific technology could have on the interior climate of the greenhouse.

Technologies: DFT, NFT & Aeroponic farming.

Deep flow technique (DFT)

DFT & NFT are two medium free systems of production. It features a flow of nutrient solution inside growing channels or basins that contain the root system of the plants. The DFT technique features seedlings planted in a number of floating plastic rafts, with the roots of the crop suspended in the nutrient solution. As there is less nutrient circulation, DFT relies on the introduction of oxidant along the full length of the channel or around the basin.

Advantages

- (General) Space use efficiency/harvest manageability. The floating rafts allow for a mobile production element. The basins filled with nutrient solution serve as near-frictionless conveyor belts that can facilitate planting and harvest.
- (Energy) This technique allows for the control of root temperatures, either by heating the nutrient solutions or cooling the solutions in order to reduce bolting.
- (Energy) The DFT system can maintain a more constant temperature in the nutrient solution than other techniques, due to the larger volume.

Disadvantages

- (General) This technique can only support a limited amount of produce varieties, due to the mobility and maximum buoyancy of the rafts.
- (Energy) Where the large body of nutrient may in winter contribute in maintaining a stable indoor climate and high temperature, in summer the DFT system may counter work the cooling of the greenhouse system.

Nutrient film technique (NFT)
The nutrient film technique relies on a thin layer of nutrient solution on the base of a nutrient channel rather than on a deep layer of water. The solution is pumped up and due to gravity the water slowly flows down though the PVC channel back into the storage tank. Here the composition of the nutrient is continuously monitored and alterations in pH and temperature are made or fertilizer is replenished before recirculation. Graamans (2015) lists the following advantages and disadvantages for NFT (a selection):

Advantages
- (Energy) The NFT system requires significantly less total nutrient solution than other systems. It is therefore easier to heat the solution during winter months, to obtain optimal temperatures for root growth and to cool it during hot summers in arid or tropical regions. Reduced volumes also facilitate the treatment of the nutrient solution for disease control.
- (General) This technique is inherently able to induce aero root formation.

Disadvantages
- Space use efficiency/harvest manageability - The NFT system features stationary production beds. The space is used less efficiently, as a significant amount of space has to be reserved for seeding and harvest.
- Energy use - It is difficult to maintain a constant temperature in the nutrient solution, due to its relatively small volume, constant movement and relatively large surface area for heat exchange.

Aeroponic farming
Aeroponic farming is based on, as the name insinuates, a mist of water that is sprayed over the root system of a plant. The plants are suspended in mid-air and the roots are enclosed in a spraying box where no light can get in to prevent algae from developing in the system. Periodically, a mist is forced through the roots, keeping them moist. This system uses less water then the NFT sytem and much less water then DFT system. This technology is deemed to be as versatile and responsive as the NFT system, but also more complex and harder to maintain.

Advantages:
- Efficient water use;
- Space efficient if spraying chambers are stacked

Disadvantages:
- Less space efficient as the DFT technology, as the production beds are stationary and space needs to be reserved for harvesting;
- Stacked aeroponic production beds result in uneven growth due to varieties in light intensity on the inclined crops.

Conclusion

To ensure a sustainable and closed energy system and to maximize the annual produce yield, a closed greenhouse system is essential. This is even more recommended in projects where space is scarce and the greenhouse is relatively small compared to standard open field farming. To prevent the accumulation of soil borne diseases, avoid expensive soil decontamination procedures and increase the production rate per square meter even further, hydroponic farming is an interesting farming technique.

DFT, NFT or Aeroponic farming?
As mentioned, the choice of production technique has influence on the indoor greenhouse climate. The choice of technique needs to be in line with the mindset of this research: energy efficient urban farming. This means that the chosen production method has a positive or no effect on the total energy system. At the same time it should be kept in mind that only crop species with high economical value for the retailer are desired.

Keeping this in mind, the NFT system is most suitable for a rooftop greenhouse in the city centre of Amsterdam for the following reasons:

- The NFT system allows for a high variety of crop species, including the heavier ones. With NFT, there is no weight limitation due to the limited buoyancy of the floating production platforms seen in DFT.
- To enlarge the production yield, the nutrient solution is brought up to temperature before reaching the root system. DFT involves a large volume of warm water. During the colder months, this volume acts as a welcome thermal buffer and storage to keep the temperature in the system within the desired values. However, during the summer months this same volume makes it more difficult to control the indoor air temperature. The Nutrient Film Technology uses only a thin layer of water in the nutrition gutters and much less water in the total system, which means it is much easier to adjust and has less influence on the greenhouse indoor air temperature. This is a desired feature during the hot summer months;
- Due to the large volume of water, the DFT methods is much heavier then the NFT or the aeroponic method. This makes it less suitable to be applied on the rooftop of an existing residential city block.
- The impact of aeroponic farming on the greenhouse indoor climate is just like NFT, also much less compared to DFT. However, aeroponic farming is more complex to maintain and less predictable then NFT.

Considering the advantages and disadvantages of the 3 production techniques in relation to the influence on the greenhouse climate plus the desired suitability to heavier and economically valued crops, the Nutrient Film Technique is the suitable production method for this project.

5.2.2 | Optimal climate tomatoes production

Greenhouse

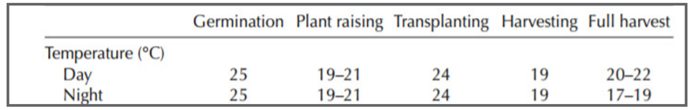
Temperature

The indoor climate properties: temperature, relative humidity and CO_2 concentration, are key factors for the production of Tomatoes.

Online research quickly learns that the recommended optimum temperature for crop growth or the minimum-maximum temperature range varies a lot depending on the addressed source. According to Peet and Welles (2005), the optimum growing temperature for tomatoes differs for each of the growing phases of the tomato, see Figure 4.1.

According to the Ontario Ministery of Agriculture, Food and Rural Affairs (OMAFRA), the generally recommended temperature for tomatoes is in the range of 18.5 - 26.5 degrees Celsius. Going above this range results in a reduced fruit set, having the plants grow in an environment that is colder then 18.5 degrees increases the risk of misshaped fruit. Should the indoor temperature get below 10 degrees Celsius, the fruit set will be poor[1]. The OMARFA recommendation is in line with the value mentioned by Peet and Welles (figure 5.1)

Conclusion: for the energy calculations in this research we hold on to the temperature range of 18.5^{0}C - 26.5^{0}C.



	Germination	Plant raising	Transplanting	Harvesting	Full harvest
Temperature (°C)					
Day	25	19–21	24	19	20–22
Night	25	19–21	24	19	17–19

Figure 5.1: Temperature recommendations for tomatoes crops (adapted from Peet & Welles)

Root Temperature

Raising or lowering the temperature in the root zone of the crops contributes in increasing the production yield of a greenhouse. An increased root temperature in a hydroponic system results in higher values for specific leaf area, leaf area ratio and leaf weight ratio at final harvest. In addition to this will cooling of the nutrient solution in NFT systems during the summer months improve crop quality and reduce the risk of fungal infections (Graamans, 2015).

For each plant, a different root temperature is recommended. Just like the air temperature in a greenhouse, the optimal root temperature is also different depending on the life cycle status of the growing tomato plant. During the first 4 weeks of the germination phase, the recommended temperature range is 25-30 degrees Celsius. After week 4, a temperature between 20-25 degrees Celsius results in optimum growth. (Bugbee & White, 1984)

This number is backed up by the research of Tindall, Mills & Radcliffe (1990). According to them the root and shoot dry weight, rate of shoot growth, plant height, and water use peaks at 25 °C.

The root temperature will be controlled by heating up or cooling down the nutrition solution that seeps through the root system.

Conclusion: the temperature in root zone of the produce will be kept around 25^{0}C throughout the year.

CO_2

Temperature determines the speed of the plant development while daily light integral and CO2 concentration affect photosynthesis and biomass production. Nederhoff concludes that raising the CO2 concentration from the current ambient level of approximately 400PPM up to 1000 PPM increases photosynthesis of tomato by approximately 30%' (1994).

In a traditional greenhouse that relies on natural ventilation for cooling, CO_2 is lost every time the windows are opened. This brings the CO_2 concentration back to the ambient concentration of around 400ppm.

In closed greenhouse systems there are 3 general ways to control or increase the CO_2 concentration:

1. External CO_2 source. Particular heavy industries have CO_2 as a waste product. This pure CO_2 is pumped towards the greenhouses;
2. Internal CO_2 source. A cogeneration installation is used by many greenhouses (Dutch: WKK). This climate installation produces both heat and electricity by burning fossil fuel. The CO_2 that is emitted by the machine is pumped into the greenhouse;
3. At night, when photosyntheses is not happing due to the absence of light, plants emit the CO_2 they have assimilated during the day. Netto, plants produce more O_2 than CO_2.

Conclusion: optimal tomato production happens at a CO_2 concentration of 1000PPM.

Relative humidity

According to Bakker (1991) , the relative humidity of the greenhouse air should be between 65% and 75%. This range is optimal for growth, flowering, fruit set, and fruit growth of tomato plants. It should be mentioned that the exact effect of RH on the tomato plants is complicated and is depending on many other factors as well.

Plant photosynthesis decreases due to stomata closure at very high temperatures and low relative humidity. Below an RH of 30% , tomato plants still grow but not optimally. Low RH values in combination with lasting high temperatures accelerates the propagation of harmful insects. On the other hand, long lasting RH higher than 85% in combination with high temperatures above 30°C are critical for fruit set, because pollen clump together and pollination is hindered. In addition to this, high RH favours the propagation of fungal leaf diseases. (Swartz, Thompson & Kläring, 2014)

Hézard, Sasidharan, Poughon & Dussap conclude that 'High humidity enhances stomatal aperture and photosynthetic rate by decreasing water evaporation rate and transpiration, which increases photosynthetic efficiency' (2012, p. 16). A RH in the range of 70%-80% is often considered ideally for most plants species. (Hézard et al, 2012).

Controlling the relative humidity in a semi-closed greenhouse is a challenging task but one of great importance and with significant effects on the annual yield and cooling capacity. Conclusion: Tomatoes thrive best in an environment with a relative humidity that revolves around 75%.

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[1] *http://www.omafra.gov.on.ca/english/crops/facts/info_tomtemp.htm*

5.2.3 | Conventional greenhouse climate control

Greenhouse

Closed system > semi closed system

Maintaining an indoor temperature of 18.5°C-26.5°C in a temperate climate like the Netherlands requires a lot of cooling and heating power. The average dry bulb temperature in the Netherlands is ranges between ~4°C in February to ~17°C in July and August. This means that if the direct and diffuse solar load are left out of the balance, there is a heating demand throughout the year. In practise the greenhouse will start heating up the moment the sun starts shining, even in cloudy weather.

In this paragraph the conventional ways of greenhouse climate control are discussed. It is pointed out that a completely closed greenhouse system is not possible/ sustainable and that a semi-closed system would be a better choice.

Cooling

If the outgoing energy fluxes are smaller then the sum of the incoming fluxes plus the internal heat fluxes, the temperature in the greenhouse will increase. This is acceptable until the upper limit of 26.5°C is reached. After this set point, the cooling is activated. Extracting the surplus thermal energy from the space is an energy demanding challenge in climatising the greenhouse.

In figure 5.2, three common temperature curves are drawn. These curves roughly represent the indoor greenhouse temperature of the 4 seasons.

Summer

The lower temperature limit of 18.5°C is relatively high in a Dutch climate. The outside dry bulb temperature usually drops below this value a few hours after the sun has set. The greenhouse heating system remains active throughout the larger part of the night and morning.

Winter

In Winter the heating system is turned on for most of the day. Only if the sun is at it's highest altitude, the temperature in the greenhouse rises slightly and the pressure on the system lowers temporarily.

Spring / Autumn

Regarding global horizontal irradiance, Spring and Autumn are comparable with each other. Outside dry bulb temperature is on average lower compared to the summer situation but warm peaks will occur and temporary high summer temperatures are not uncommon. During these 'transition months' between summer and winter, both a cooling demand and a heating demand is recognizable in the energy balances.

The temperature can be guarded by means of:

1. Mechanical ventilation [sensible energy based]. Bringing the temperature down by adding air that is of a lower temperature (sensible heat difference). In a closed system this would mean the air is conditioned in an mechanical cooling system;
2. Evaporative cooling [latent energy based] In a greenhouse this can occur by three methods: (1) Dehumidifying the indoor air, this creates more room for the crops to evaporate their water and humidify the air on a natural way. Humid air can take up large quantities of energy by turning sensible heat into latent heat.; (2) Artificially increasing the RH of the cooled and treated air, this can be achieved by means of a fan-pad system. This way the plants will evaporate less water and use their energy for photosynthesis. (3) Evaporative cooling. Literally spraying a mist of water through the greenhouse. Small water droplets will take up the sensible energy if phase changing occurs (liquid > gas state);
3. Floor cooling [based on radiation + convection]: bringing down the temperature of the mass in the building helps in mitigating temperature fluctuations and lowers the indoor temperature. This technique is more effective for heating ;
4. Shading/reflection systems. Significantly lowers the solar load on the greenhouse surface.
5. Natural ventilation. This is a last resort ventilation method, only applied if the demand on the regular cooling system extends beyond the cooling capacity. Hence, this greenhouse is a semi-closed type and not fully closed.

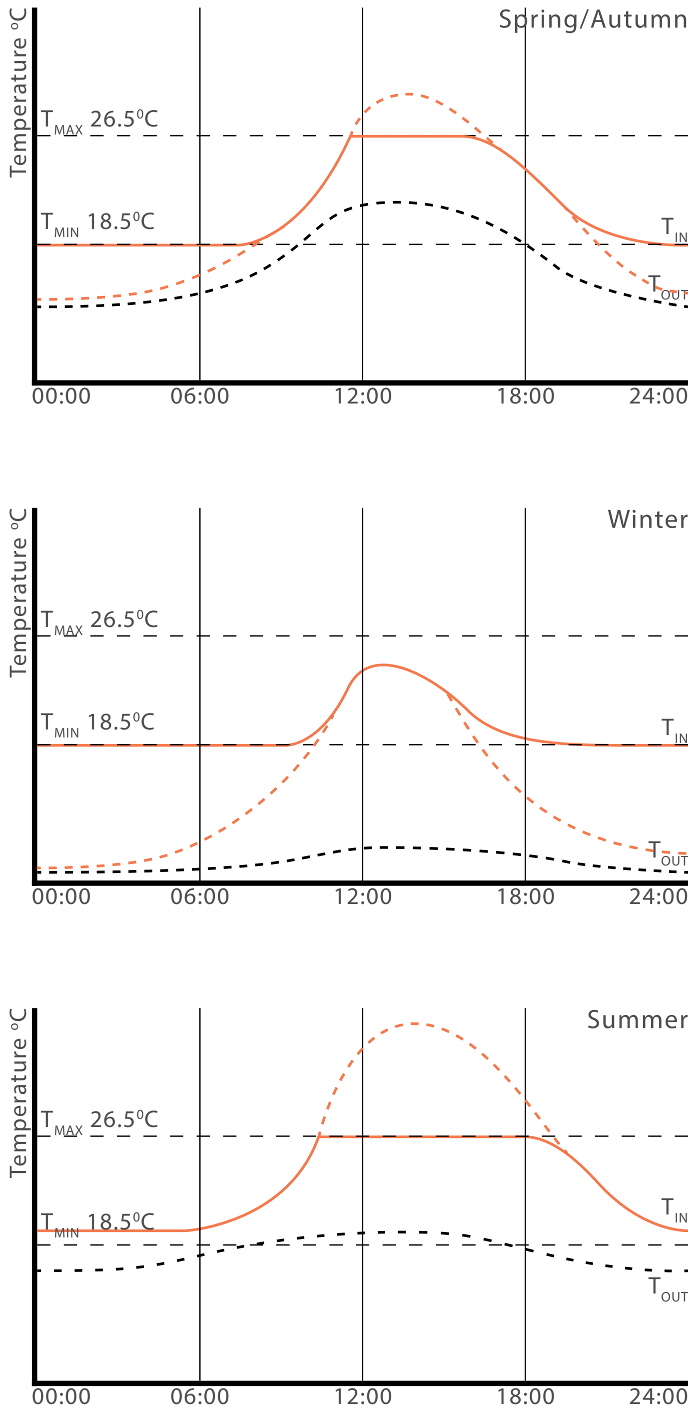

Figure 5.2: GH temperature profiles, four seasons.

Heating

If the outgoing energy fluxes are larger then the sum of the incoming fluxes plus the internal heat fluxes, the temperature in the greenhouse will drop. This is acceptable until the lower limit of 18.5°C is reached. Below this set point, the heating is activated.

Conventional methods of greenhouse heating are:
1. Low temperature floor heating [based on radiation + convection]. Warm water is pumped though the mass of the floor, thereby charging the mass with thermal energy.
2. Ventilation [based on sensible energy]. Greenhouse air is circulated through a HVAC system, where the temperature is increased.

Prevention
Better than mechanically bringing up the temperature is of course preventing heat from escaping the greenhouse. Some general methods are (Geelen et al, 2016):
- Insulation. A slight increases of the U-value of the glazing conserves a lot of energy.
- Mitigate radiation. With screens, curtains or glass coatings, long wave outwards radiation can be lowered;
- Decrease the crop evaporation. This reduces the ventilation demand (not immediately applicable in a closed greenhouse system).

Heating installations are traditionally ignited by fossil fuels. Greenhouses often opt for cogeneration installations (WKO), as both the demand for heat and the demand for electricity is high.

Relative Humidity, CO_2 and lighting

Relative Humidity
The optimum level of the RH for the growth of tomatoes is 75%. There is no further elaboration on the RH in this research. Chapter 7.4.7 goes deeper into the theory of adiabatic cooling.

CO_2 concentration
The CO_2 concentration improves the tomato growth best if the values revolve around 1000PPM. The world wide average concentration shows values of around 380-400ppm. Daily concentrations depend on the factors like the geographical location, weather and climate, wind speed, time of day and day of the week (due to commuter activity) and season. In inner cities and industrial areas, the concentration can increase to 700PPM[1].

Conventional closed greenhouses artificially increase the CO_2 concentration by pumping the exhaust fumes of the cogeneration installation into the production space. Investing fossil fuel to increase the indoor CO_2 concentration is of course completely opposite to the general though of this research, which is about decreasing the dependence on fossil energy and mitigating the CO_2 emission.

The semi-closed greenhouses that are constructed on top of the Amsterdam city block have no access to industrial waste CO_2. Perhaps there is industrial activity in the vicinity of Amsterdam that can deliver pure CO_2 as a waste product, but it is economically infeasible to invest in the infrastructure required to transport the CO_2 to the inner city location. Opportunities might be found in above-ground transport of liquefied CO_2 in containers, but that goes beyond the scope of this research.

Extracting CO_2 from the Lidl & the Apartments
The CO_2 demand can't be covered by the nearby industry and burning fossil fuel is no longer an option in the new energy system. A third CO_2 source could be the adjacent Lidl supermarket. These indoor concentrations do generally not show absurd high values but concentrations of ~1000PPM[1] can be reached during busy supermarket hours if a lot of customers are doing their groceries. Directly exchanging air during peak hours could benefit the greenhouse CO_2 concentration. Of course the question arises if the investment in the required infrastructure would really pay back in increased tomato yield.

The least complicated and cheapest accessible source of CO_2 would be to directly exchange outside air with indoor air. Not just mitigating cooling peaks, but also supplementing the CO_2 reserves with city air would be a trigger to open up the windows periodically.

Lighting
Having proper control over the light intensity on the leaves means you have control over the photosynthetic activity and thereby the growth of the plant and the fruits. Done the right way, this leads to another increase of the annual yield. However, in this research is opted for the sustainable solution and shall the plants only be illuminated by natural daylight. Artificial lighting is only turned on in the early morning and late afternoon to make work possible for the caretakers.

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[1] *http://www.buroepn.nl/ventilatie/co2-en-het-vergaderruimte-effect*

5.2.4 | Conclusion and design

Greenhouse

Greenhouse climatic properties and parameters for optimal tomato production

An overview:

- The greenhouse will be a semi-closed system. Only at peak cooling moments natural ventilation will be applied.
- Hydroponic farming is apprehended. The production technique will be according to the Nutrient Film Technology (NFT). This system has the least impact on the indoor climate and it takes less energy to adjust the root zone temperature since the total nutrient solution is much less;
- The temperature of the greenhouse will remain between 18.5^0C and 26.5^0C.
- The temperature in the crop root zone will be kept on 25^0C;
- The RH of the greenhouse should be maintained around 75%;
- The CO_2 concentration should be increased to 1000ppm. However this might not always be possible without the presence of a CO_2 source.
- There is no additional night-time lighting in this greenhouse. This is both for sustainable reasons as contextual reasons.

The energy balance of the greenhouse is based on the temperature range of 18.5°C-26.5°C.

Greenhouse construction

Building properties:

- For economic feasibility, the greenhouse should produce crops of high economical value. In practise this means that high-grade crops shall be produced, which require higher greenhouse temperatures. Double glazing reduces the energy lost to the exterior by roughly 50% compared to single pane glazing. In the calculation a U-value of 2.7 is used. The g-value is set on 60% (0.6).
- Facade structures like mullions, trusses, braces or irrigation channels are not taken into account.
- The greenhouse has an average height of 3.0 meters. The facade orienting to the South-West and South-East are 3.5 meters high. The North facing façades are 2.5 meters. This give the roof an inclination of approx. 5°.
- The building has a 66^0 orientation from the North, following the orientation of the existing residential structure underneath.
- For the benefit of this energetic research it is assumed that the substructure is constructively able to support a rooftop greenhouse;
- The illustration on the right page (figure 5.3) shows the greenhouse in plan (not to scale).
- The greenhouse floor is constructed from concrete to allow for floor cooling and heating.

Rationality and functionality is a the foundation of the greenhouse architectural design. The greenhouse is located in a the dense residential environment in the city centre of Amsterdam. All the regulations, laws, city visions and zoning plans which limit this plan in actual execution are for this research disregarded.

Further elaboration on the greenhouse plan can be found in § 7.2.4.

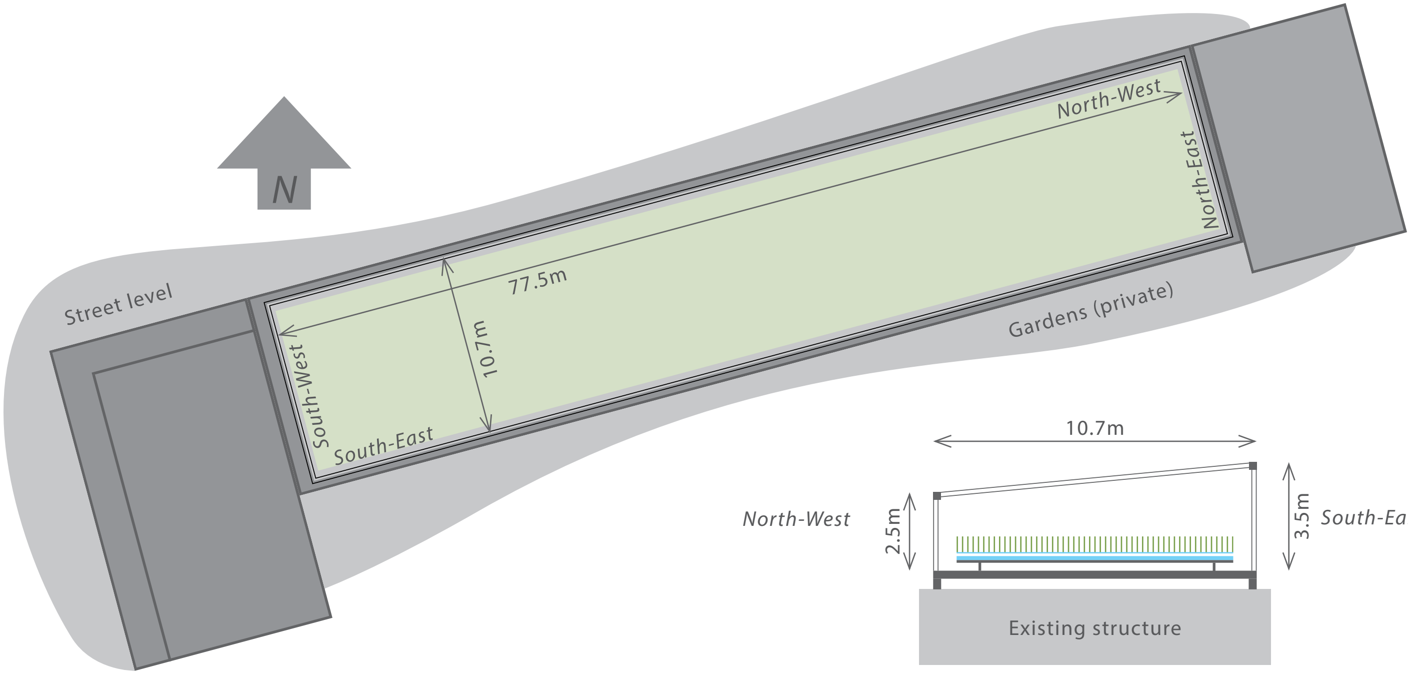


Figure 5.3: Sketch of greenhouse A (greenhouse B is similar). Calculations are based on this layout

5.2.5 | Energy balance semi-closed greenhouse

Greenhouse

Energy fluxes in a semi-closed greenhouse

According to equation 5.1, the greenhouse energy balances can be determined.

For indicative purposes, the daily energy balances are calculated and shown in §5.2.6.

In §5.2.7, the monthly energy balances are calculated and shown. The final design for the energy system is based on values found in this monthly energy balance.

Each energy flux is further explained in appendix II.

Energy balance

The energy balance in the greenhouse is represented by the following equation:

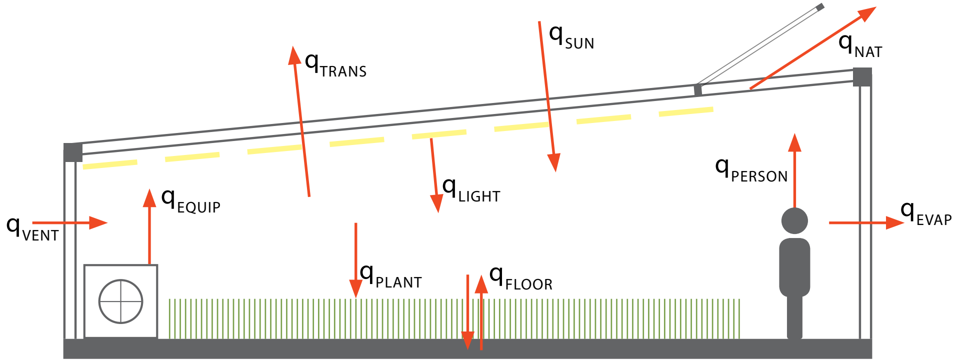
$$q_{LIGHT} + q_{PERSON} + q_{EQUIP} + q_{SUN} + q_{TRANS} + q_{COOL} + q_{HEAT} = 0 \qquad [5.1]$$

where

q_{LIGHT}	Represents the interior heat load by the lighting system;
q_{PERSON}	Represents the interior heat load emitted by the greenhouse caretakers / farmers;
q_{EQUIP}	Interior heat gain by operational equipment;
q_{SUN}	Solar heat gain. This flux covers both the direct solar heat gain as the diffuse solar heat gain* (Global horizontal irradiance);
q_{TRANS}	Heat transfer through the facade, floor and roof construction based on the temperature difference between the interior and exterior;
q_{COOL}	Represents the surplus heat extracted from the greenhouse by means of a cooling system. In the greenhouse, this can be either through floor cooling (q_{FLOOR}), by evaporative cooling (q_{EVAP}) or by natural ventilation (q_{NAT});
q_{HEAT}	The energy balance is closed by q_{HEAT} during colder periods. Heating is achieved by floor heating (q_{FLOOR}) and ventilation (q_{VENT}).

Figure 5.4 gives an overview of the energy flows in the supermarket. In appendix II, each energy flux is elaborated and calculated. The energy balances in the next two paragraphs are based on these calculations.

**In the 24hr energy balances, the GHI is split up in two seperate posts: q_{SUN_DIR} & q_{SUN_DIFF}, or direct solar gain and diffuse solar gain.*



$$q_{LIGHT} + q_{PERSON} + q_{EQUIP} + q_{SUN} + q_{TRANS} + q_{PLANT} + q_{HEATING} \,/\, q_{COOLING} = 0 \qquad [5.1]$$

Figure 5.4: Fluxes in the greenhouse

5.2.6 | 24hr energy profiles

Greenhouse

Energy balance - 24hr profiles

For each of the four seasons, a 24hour energy balance is made (figure 5.5-5.8). These 24hr profiles are meant for insight and understanding and have only an indicative function. Further energetic calculations in this research are not based on the values found in these 24hr balances, but are derived from the monthly energy balance, found on page 109.

The 24hr balances show how the heating or cooling demand develops during the day.

Notices:

- The range of the y-axis varies per season;
- Direct and diffuse solar intensity [W/m²] are retrieved from TU Delft data (BK-Wiki information page);
- The balances represent that following days: 26 June, 23 March, 21 September & 19 December.
- Outside dry bulb temperatures are taken from Climate Consultant software (location Amsterdam) on the before mentioned dates.

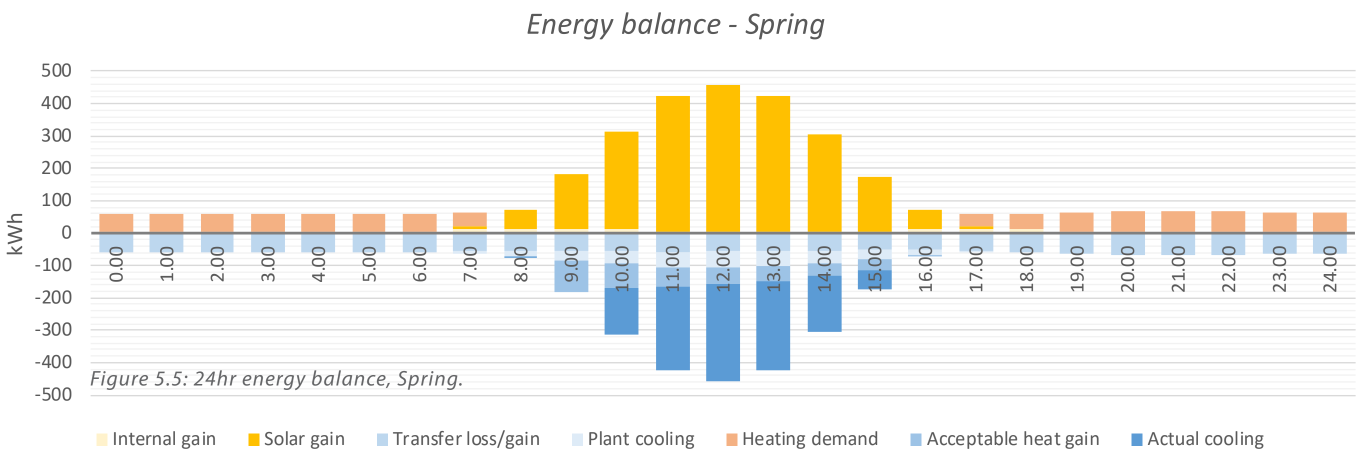


Figure 5.5: 24hr energy balance, Spring.

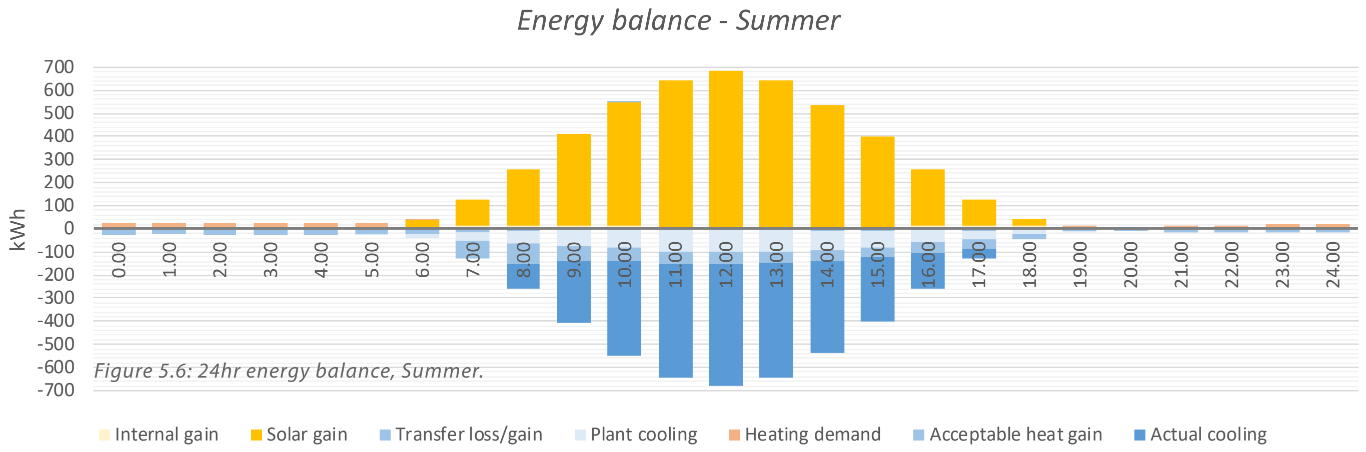


Figure 5.6: 24hr energy balance, Summer.

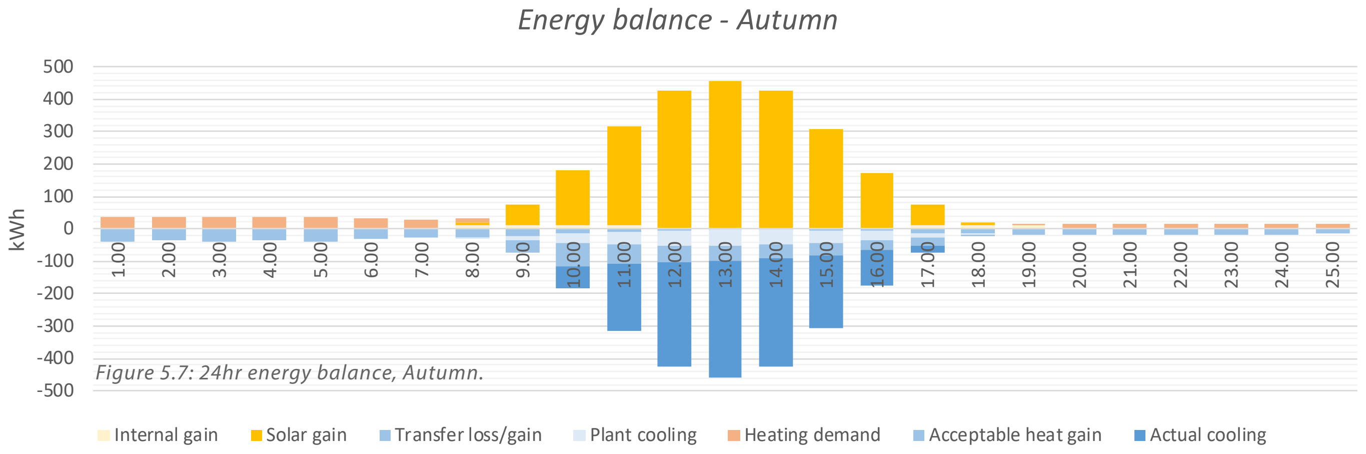


Figure 5.7: 24hr energy balance, Autumn.

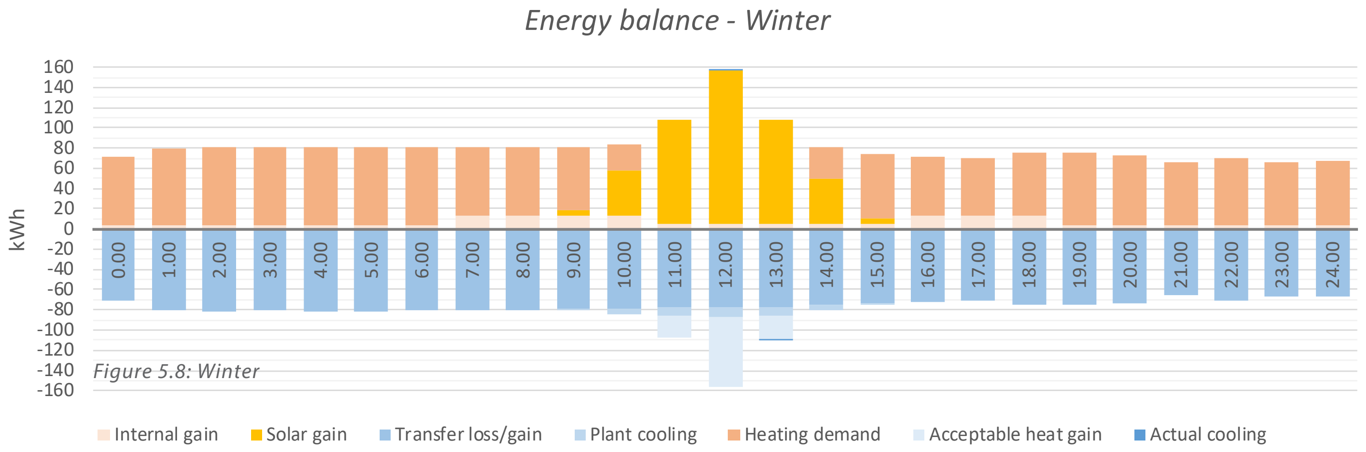


Figure 5.8: Winter

5.2.7 | 12month energy balance

Greenhouse

Annual energy balance

The energy balance in figure 5.9 is based on equation 5.1. In appendix III, all energy fluxes are elaborated.

The indoor temperature range (18.5°C-26.5°C) in the greenhouse is narrow and relatively high for a temperate sea-climate like in the Netherlands. That is why the energy balance indicates a heating and cooling requirement in almost all of the months. Only in November, December and January no cooling is imperative.

In perspective with energy fluxes like the solar gain, transmission loss and cooling demand, transmission gain and internal heat gain are zero respectively neglectable.

In figure 5.10, the monthly heating and cooling demand are isolated.
On an annual basis we find:

- Cooling demand = 1374 MWh
- Heating demand = 600 MWh
- Energy surplus = 774 MWH

The numbers are based on 2 rooftop greenhouses on their maximum possible dimensions. The indoor temperature range = 17.5°C - 26.5°C.

Balance not in balance

If you look closely at the energy balance in figure 5.9, you can see that the monthly positive energy fluxes and the negative fluxes do not even each other out. This has one very good reason:

Over the course of 24 hours -one day and night cycle- there is a heating demand and a cooling demand. The period of cooling can be considered short but intense and the period of heating is usually the rest of the 24 hours. This pattern is clearly visible in the 24hr balances of the previous page. The transition period in which not heating nor cooling is required, usually lasts no longer then one or two hours since the indoor greenhouse temperature is strongly affected by the ambient temperature. If you would compare the daily total cooling demand with the total heating demand, on a netto basis there is a surplus of energy, making it look like there is no heating demand at all. Only in winter this is the other way around: the total heating demand surpasses the total cooling demand.

With this in mind, the annual energy balance is calculated. Heating demand and cooling demand are considered separate from each other and both added to the balance.

In practise, the heating demand equals the transmission loss since the minimal indoor temperature is 18.5°C and the highest monthly average T_{OUT}= 17.1°C. Based only on the temperature difference between inside and outside, there is an outgoing heat flux all year around.

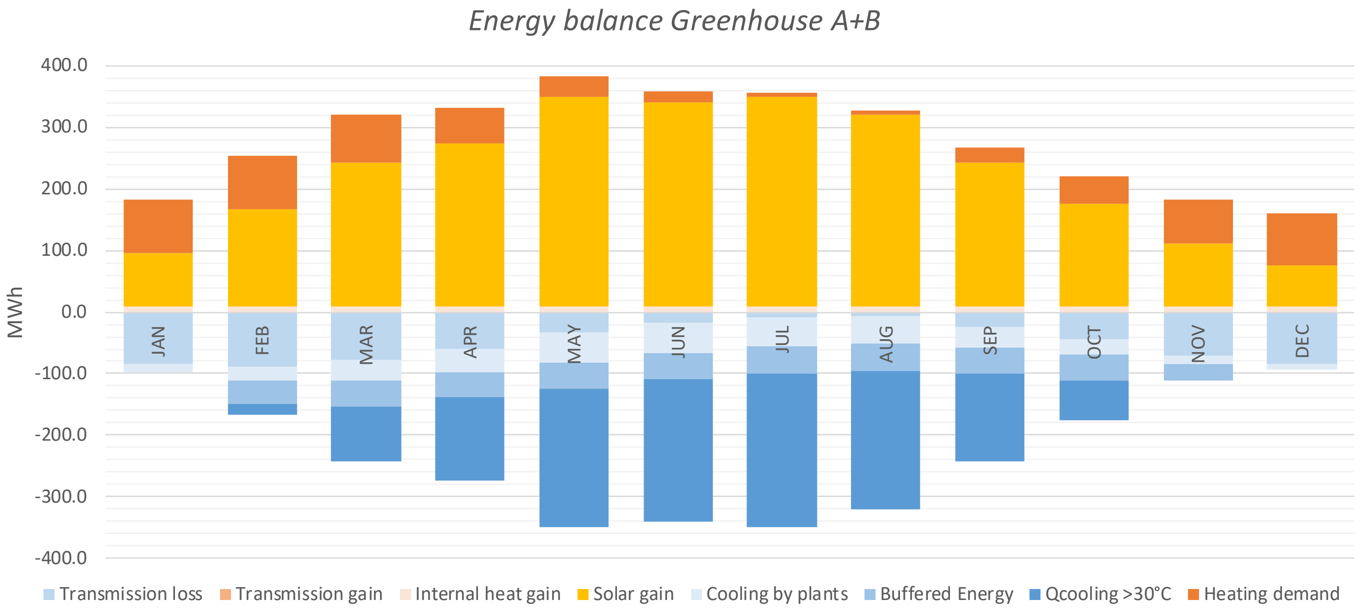


Figure 5.9: Greenhouse energy balance

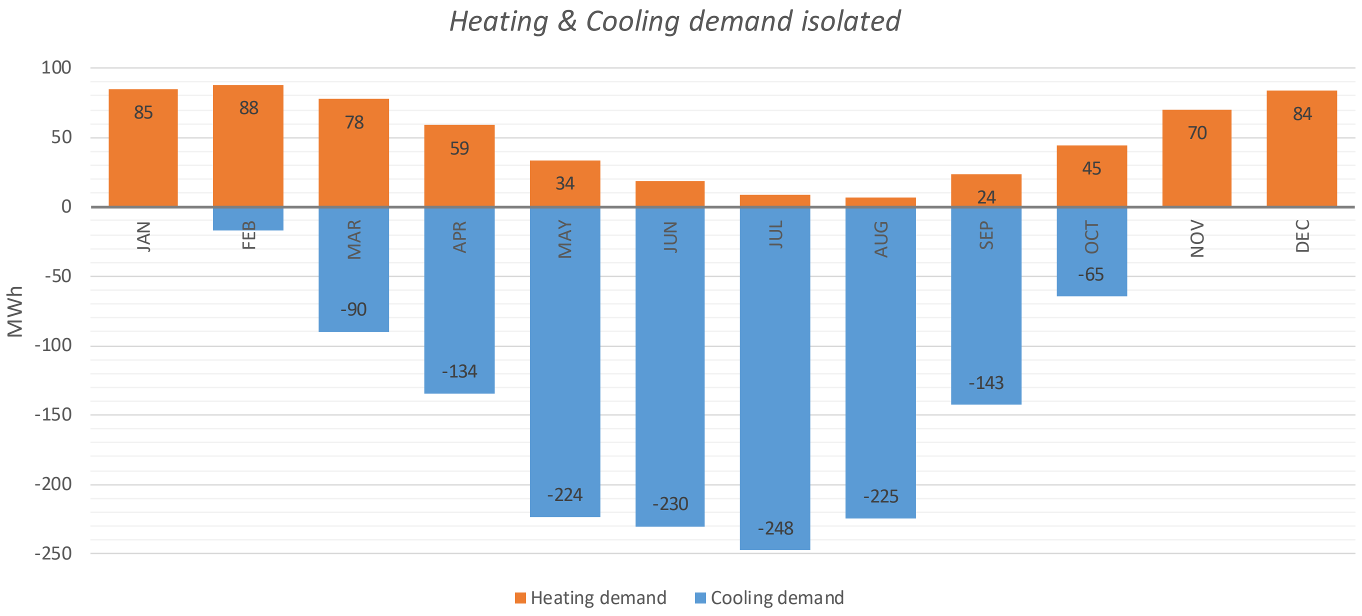


Figure 5.10: Greenhouse monthly heating & cooling demand, isolated from the total energy balance.

5.3.1 | Energy balance

Supermarket

Overview of the energy flows in the supermarket

Lidl Helmersbuurt in Amsterdam has been build in 2007 and is scheduled to be renovated within the near future.

There are thorough plans to scale up the size of the supermarket significantly and modernize it to today's shopping standards. In this update, the main entrance of would also be brought towards the other side of the city block, meaning it would be accessible from the Nassaukade, a busy street surrounding the centre of Amsterdam. At the moment, the overhaul plans of this Lidl have been put on hold and the ambitions plans have not been elaborated any further then a preliminary design. As it looks now, the Lidl will still get an overhaul but will remain within it's present footprint. This floor plan (figure 5.12), is apprehended for the energetic calculations in this research.

The following points apply:

- The supermarket is not connected to the gas network (as mentioned on the Lidl sustainability targets);
- There are 2-3 ovens present in the new supermarket;
- There is no natural daylight present and because of that there is no solar load, q_{SUN} can be omitted.
- For the calculations, it is assumed that the supermarket is open from 08:00-20:00, every day of the week;
- Mechanical ventilation is present;
- Applied infiltration rate is as declared by Lidl;
- Where the supermarket's construction is directly connected to an adjacent construction, a T_{OUT} of 15^{0}C is applied, independent from the current season.

Energy fluxes

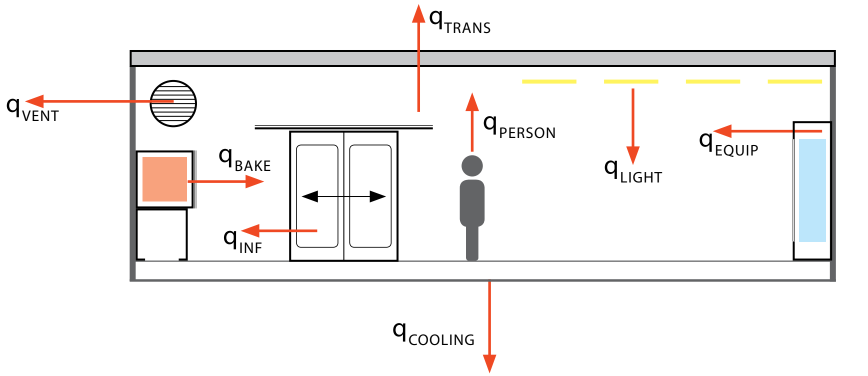
The energy balance in the supermarket is represented by the following equation:

$$q_{LIGHT}+q_{PERSON}+q_{EQUIP}+q_{BAKE}+q_{TRANS}+q_{INF}+q_{VENT}+q_{COOL}=0 \qquad [5.2]$$

where

q_{LIGHT}	Represents the interior heat load by the lighting system;
q_{PERSON}	Represents the interior heat load emitted by the customers and staff;
q_{EQUIP}	Interior heat gain by operational equipment and thermal energy emitted by the product cooling machines;
q_{BAKE}	Heat gain by the bake-off section;
q_{TRANS}	Heat transfer through the facade, floor and roof construction based on the temperature difference between the interior and exterior;
q_{INF}	Cooling load by the air infiltration due to door openings;
q_{VENT}	Represents the heat exhausted by the ventilation system;
q_{COOL}	Represents the surplus heat extracted from the greenhouse by means of a cooling system, this can be either through floor cooling (q_{FLOOR}) or by HVAC system (q_{HVAC}).

Figure 5.11 gives an overview of the energy flows in the supermarket. In appendix III, each energy flux is elaborated and calculated. The energy balances in §5.3.2 & §5.3.3 are based on equation 5.2.



$$q_{LIGHT} + q_{PERSON} + q_{EQUIP} + q_{BAKE} + q_{TRANS} + q_{INF} + q_{VENT} + q_{COOL} = 0 \qquad [5.2]$$

Figure 5.11: Fluxes in the supermarket

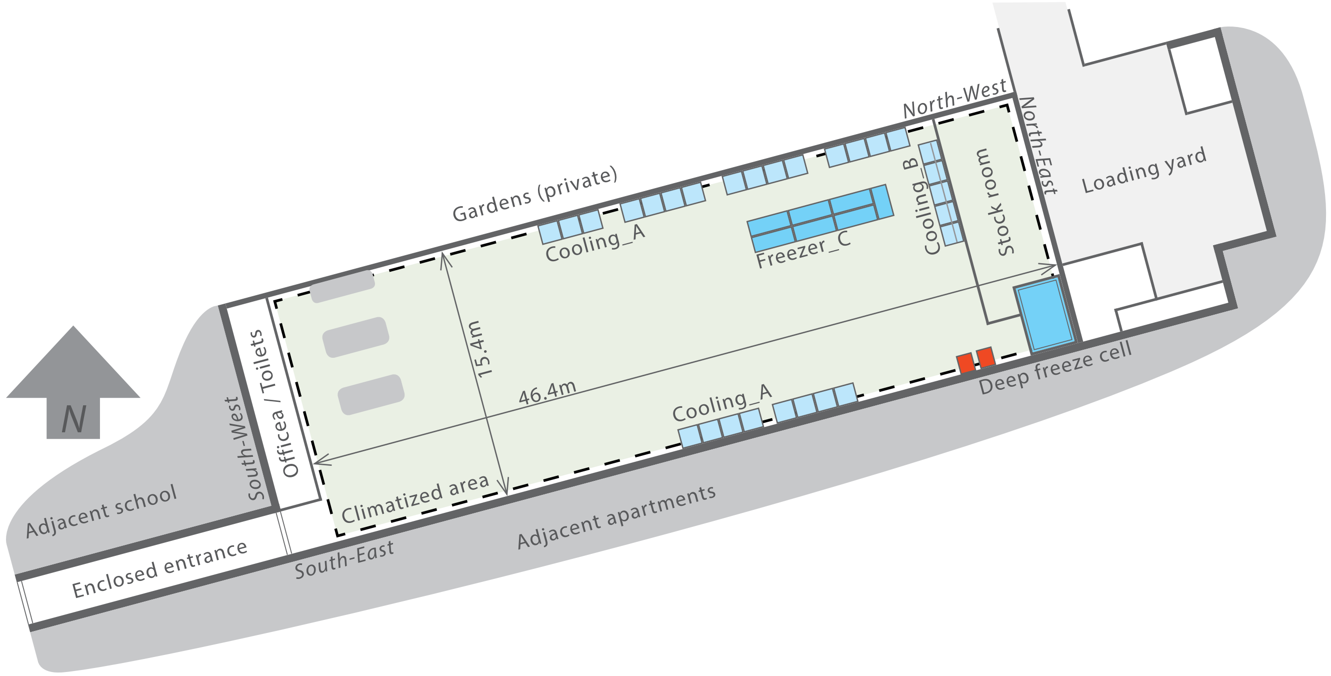


Figure 5.12: Plan of the supermarket. Energetic calculations are based on the dimensions in the illustration.

5.3.2 | 24hr energy balance

Supermarket

Heating / Cooling

The last energy flux to bring the energy balance to zero is the q_{HEAT} or q_{COOL}. After calculating all the other fluxes and bringing them into equation 5.2, we can conclude there is a cooling demand 24/7, every day of the year. This cooling demand is strongly affected by the season, internal activity and customer presence.

The supermarket has no mentionable windows in the exterior wall, so no sunlight makes it into the building. Added to this is the fact that the supermarket is always located in the shadow of the much higher adjacent apartment building, no direct sunlight warms up the roof of the building, only diffuse sunlight might have some effect. If we also include the fact that the roof of the supermarket is well insulate, it makes more sense to completely leave out the solar heat gain. For these reasons, q_{SUN} is not included in equation 5.2.

Unlike the 24hr energy balances of the greenhouse combination, the supermarket energy balances are accurate and not merely for indicative purposes.

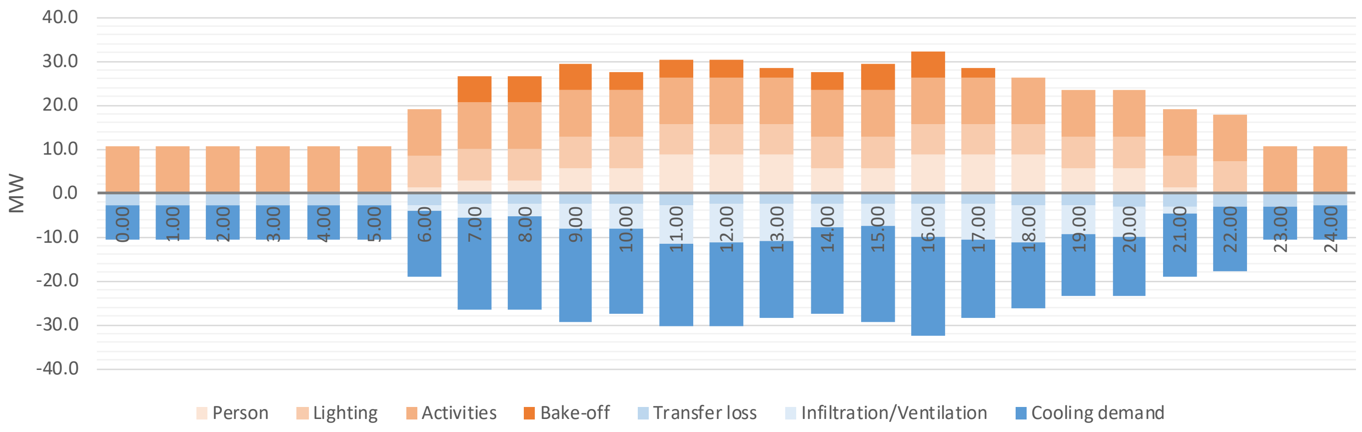


Figure 5.13: March

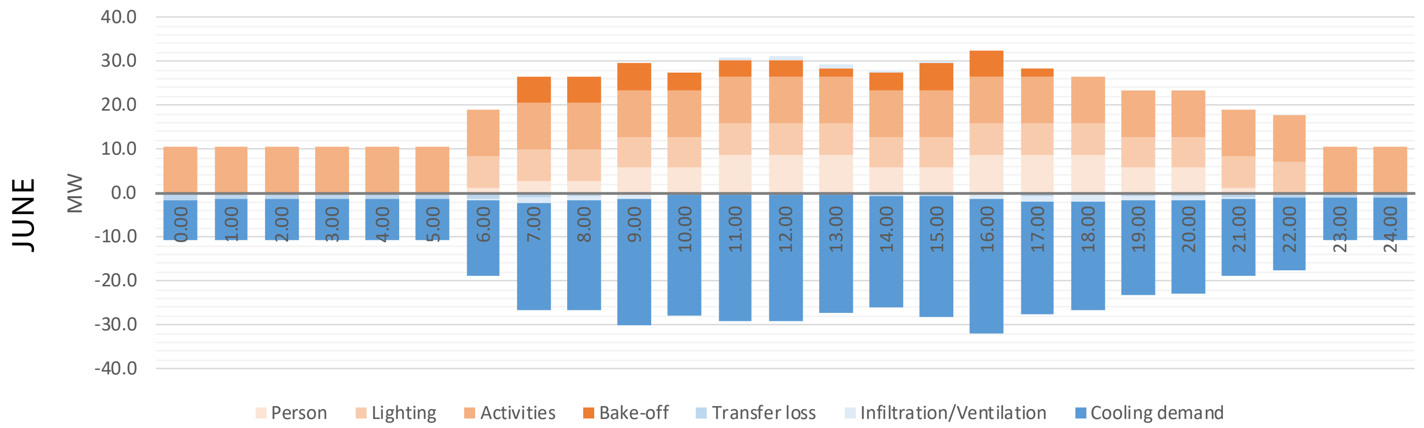


Figure 5.14: June

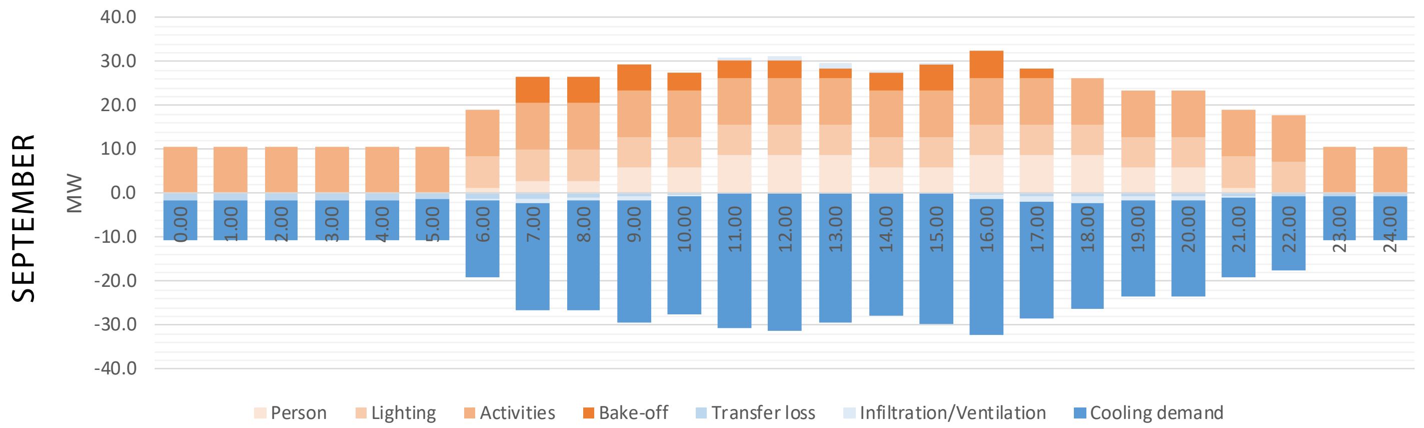


Figure 5.15: September

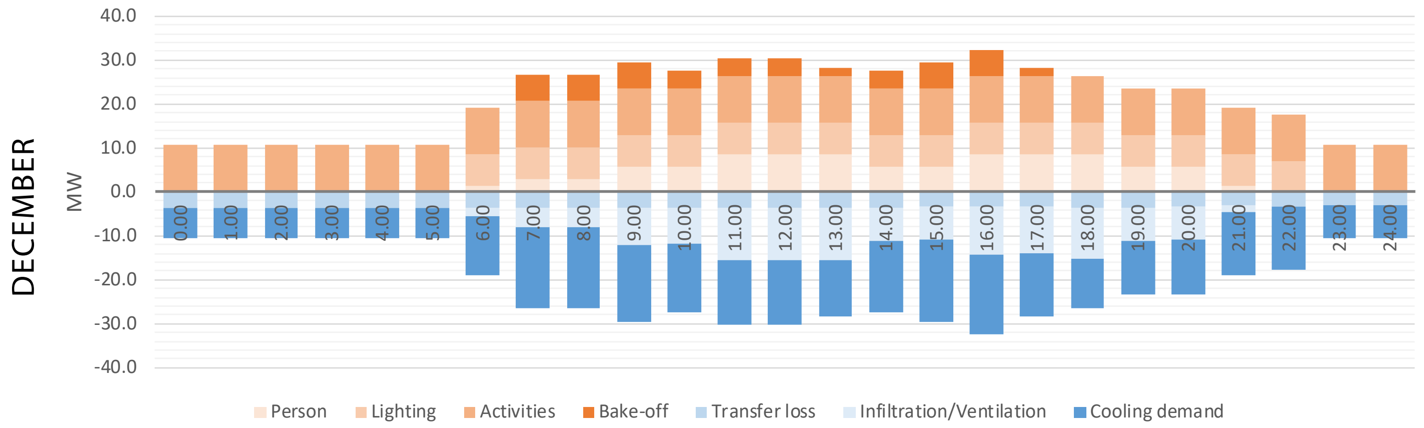


Figure 5.16: December

5.3.3 | 12 month energy balance

Supermarket

Stable environment

The annual energy balance shows a stable environment in which the internal heat gain of roughly 15 MWh is compensated by the cooling system. The average monthly outside dry bulb temperature curve is resembled in the energy balance by the transmission loss energy flux.

In figure 5.18, the monthly cooling demand is isolated from the total energy balance. On an annual basis we find a cooling demand of 136MWh.

The number is based on a supermarket sales area (the conditioned area) of 15.4 m x 46 m and a constant indoor air temperature of 19°C.

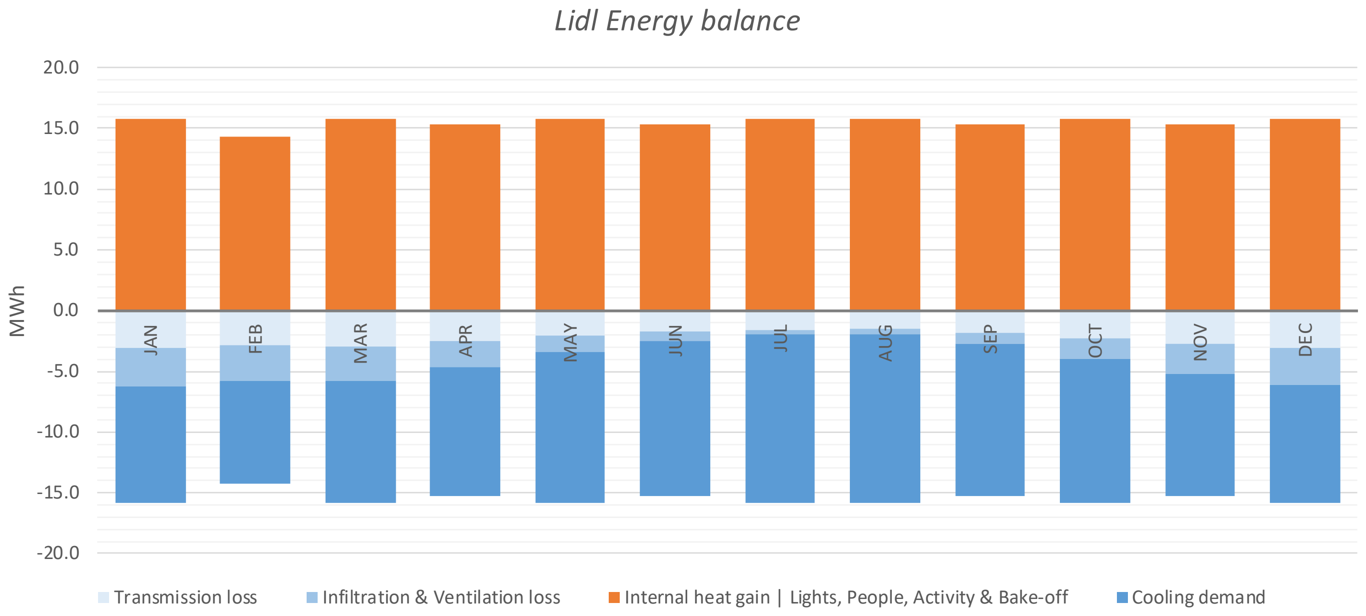


Figure 5.17: Energy balance supermarket

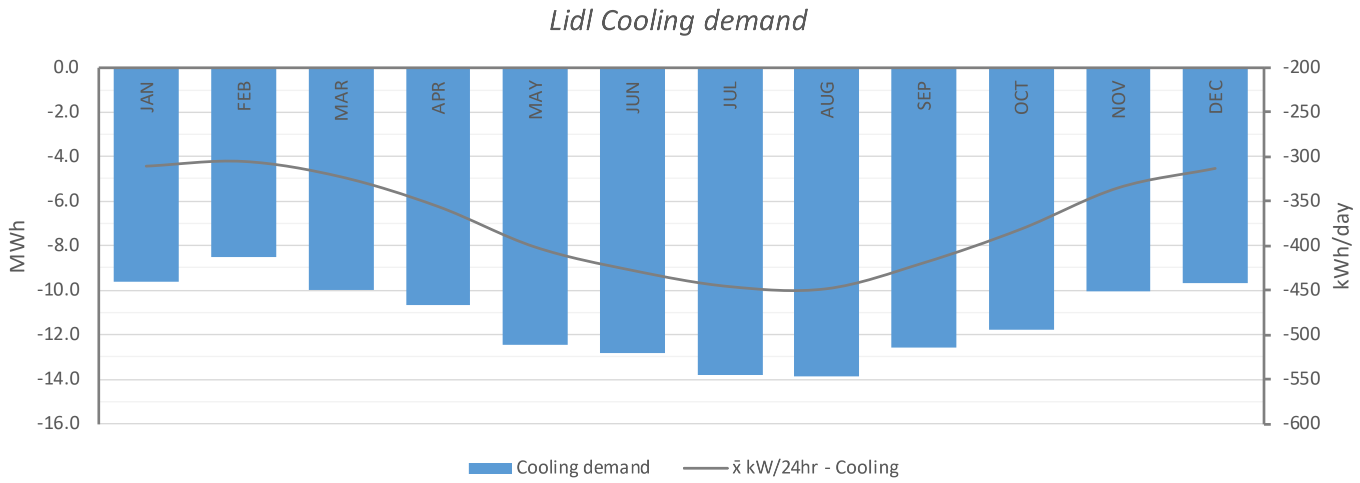


Figure 5.18: Monthly cooling demand of the Lidl supermarket [MWh & ~kWh/day].

5.4 | Dwelling heating demand

Typology and gas demand

Two residential buildings have been identified from the city block that show most potential to be integrated in a local energy grid (also see chapter 7.2.1). Together these buildings offer place for 124 households.

Residential buildings especially the older ones, do not require cooling in summer. People can just open up one or two windows opposing each other to start a draft. In other words: the buildings rely on natural ventilation for their cooling.

According to the research of Schepers, Naber, Rooijers & Leguijt (2015), a household living in an old typology house on an inner-city location have a gas demand of 583m^3 for space heating and 231m^3 for the heating of domestic water (cooking/shower etc). The monthly gas use is converted to kWh put brought into a graph.

Total gas use
The total annual gas use of one household is 814 m^3. The average gas use of a small apartment/flat in the Netherlands is between 800-1200 m^3 per year, the exact value depends on the source that is addressed. Putting it in perspective with the Dutch average range, a total gas use of 814 m^3 is not unusual or impossible, but it is on the lower side. With this in mind, it is important to understand that these old type of houses should be refurbished to meet modern building standards (e.g. HR^+ glazing). If this is not the case, the gas demand would most likely be much higher then 814 m^3.

Heating demand

Figure 5.19 gives an indication on how the heating demand proceeds during the course of 24hr. The Figure is just for insight and understanding of the heat demand from the dwelling. No further calculations are based on the graph.

Figure 5.20 shows the heat demand of the two apartment buildings (124 households). Seasonal influence is clearly visible. Heat demand for domestic hot water is not affected by the outside climate. Further calculations in the research are based on the value from this graph.

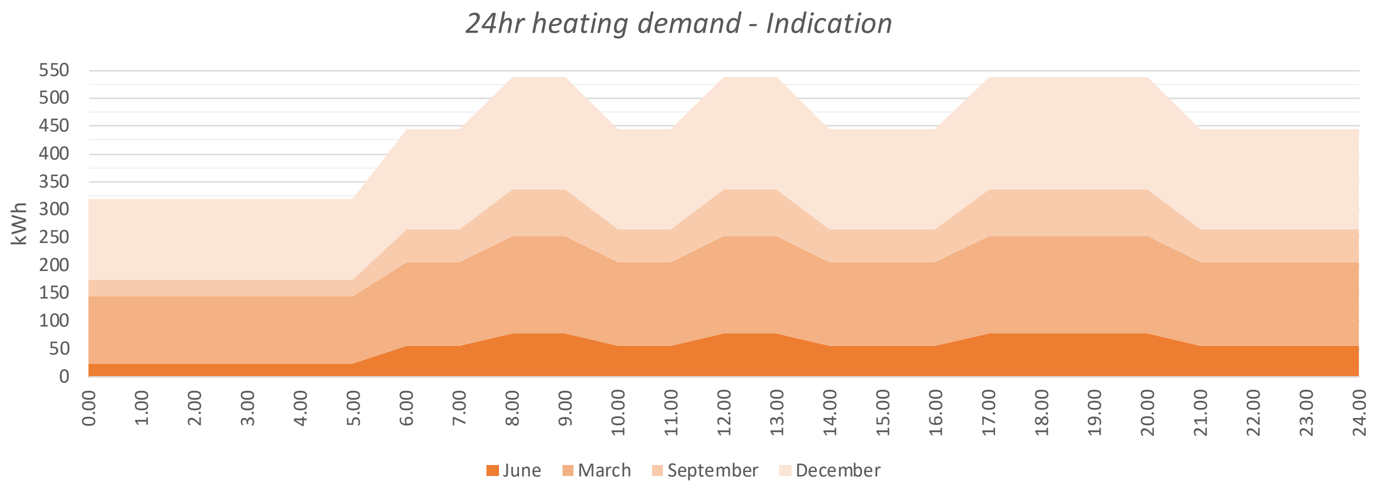


Figure 5.19: Proceeding of the hot water demand for 124 households (indicative!).

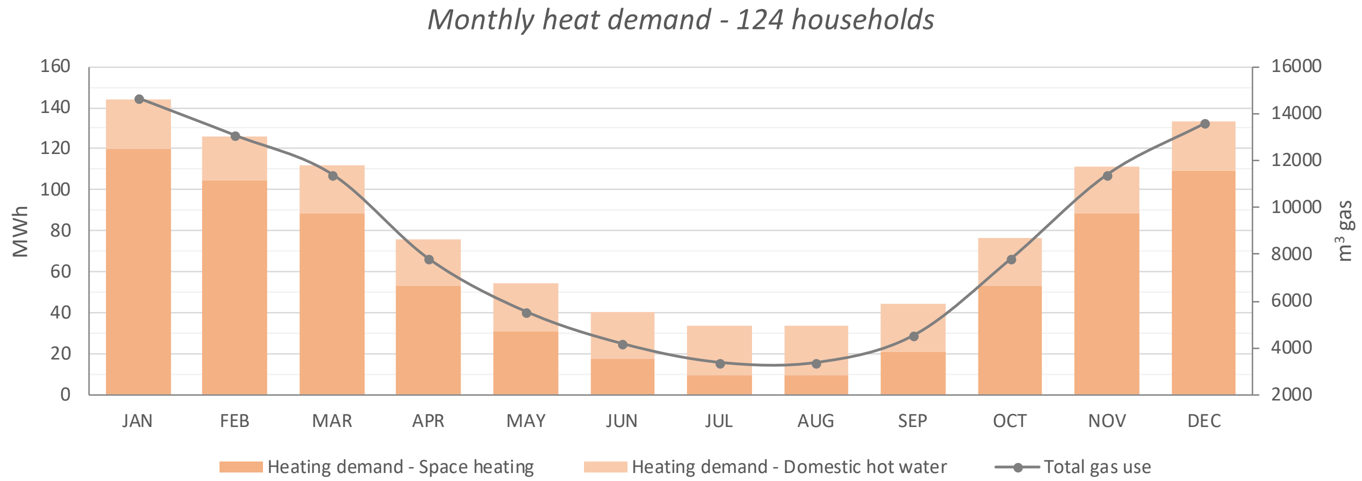


Figure 5.20: Annual heating demand (space heating & heat for domestic hot water) + gas use.

5.5 | Sustainability check

Reality check

Maintaining an environment that is fully optimised for the maximum production of tomatoes, requires a lot of cooling and heating energy in a country like the Netherlands. The average ambient temperature in July and August in the Netherlands fluctuates between 17-18°C, slightly lower than the minimum temperature (18.5°C) in the greenhouse. The energy balance reflects this by showing a heat demand in these warm months.

CO_2 on 1000 PPM?
Its inner city location and the small scale of the greenhouse make it infeasible to connect with an external CO_2 source from the nearby industry. Artificial CO_2 generation by burning fossil fuel (by means of a cogenerator / boiler installation) is no longer desired in the new energy system as a total disconnection from fossil energy is persuaded. It seems that there is no way for this greenhouse to increase the CO_2 concentration to meet the desired 1000PPM. The best option would be to periodically open up windows and let in the CO_2 rich city air. This air shows values of ~700 PPM, which is already much better then the global average of 400 PPM. Once again, a semi-closed greenhouse system does not appear to be the best solution for this specific context.

New indoor climate

To make this relatively expensive farming system feasible, vegetables/crops of high economical value are desirable (e.g. tomatoes) and a maximum production capacity should be persuaded. This is best possible if the greenhouse's indoor climate offers the best possible growing conditions. Maintaining this high demanding and sensitive climate requires professional maintenance, expertise and knowledge. Besides this, one could ask the question why such an expensive and demanding greenhouse system should be realized on such a small scale in the first place? From an economical perspective, this type of greenhouse farming would guarantee more financial security if the greenhouse would be scaled up. From a sustainable and energetic point of view it makes much more sense to widen the indoor temperature range to lower the pressure on both the cooling and the heating system. Expending from 18.5°C-26.5°C to 15°C-30°C reduces the heating+cooling demand by 38% and 11% (figure 5.21,5.22 & 5.23) This subsequently leads to a mitigation of the electricity demand by the heat pumps. A less intensive climate will go at the costs of crop yield. Also, more simple/ accommodating crops would be a better option now. This would also make the whole greenhouse more easily accessible in a social sense and the possibility to add the farm to the local social environment opens up.

For the establishment of the initial energy system, the greenhouse temperature range is set on 15°C-30°C. CO_2 and RH values become of subsidiary importance now that the greenhouse will rely more on opening up the windows for CO_2 replenishing and peak cooling. See the research design thought on the right page.

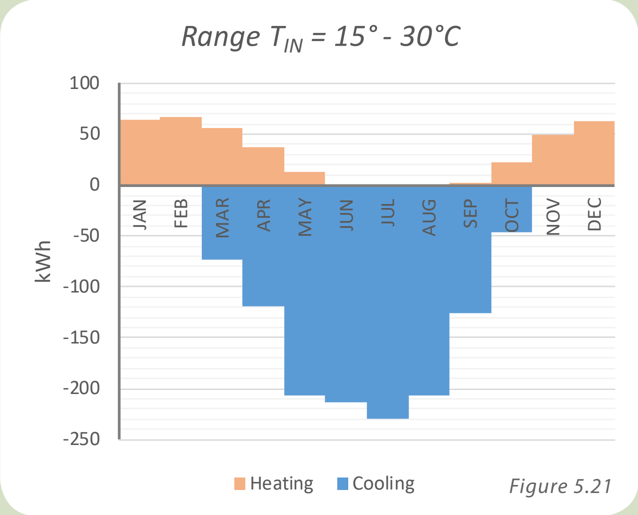


Figure 5.21

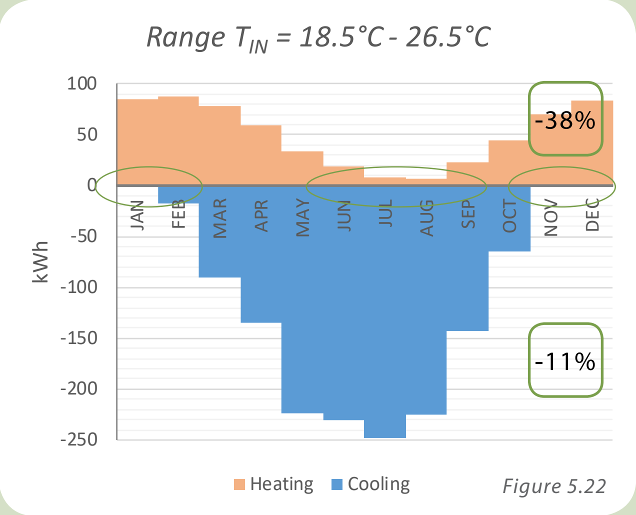


Figure 5.22

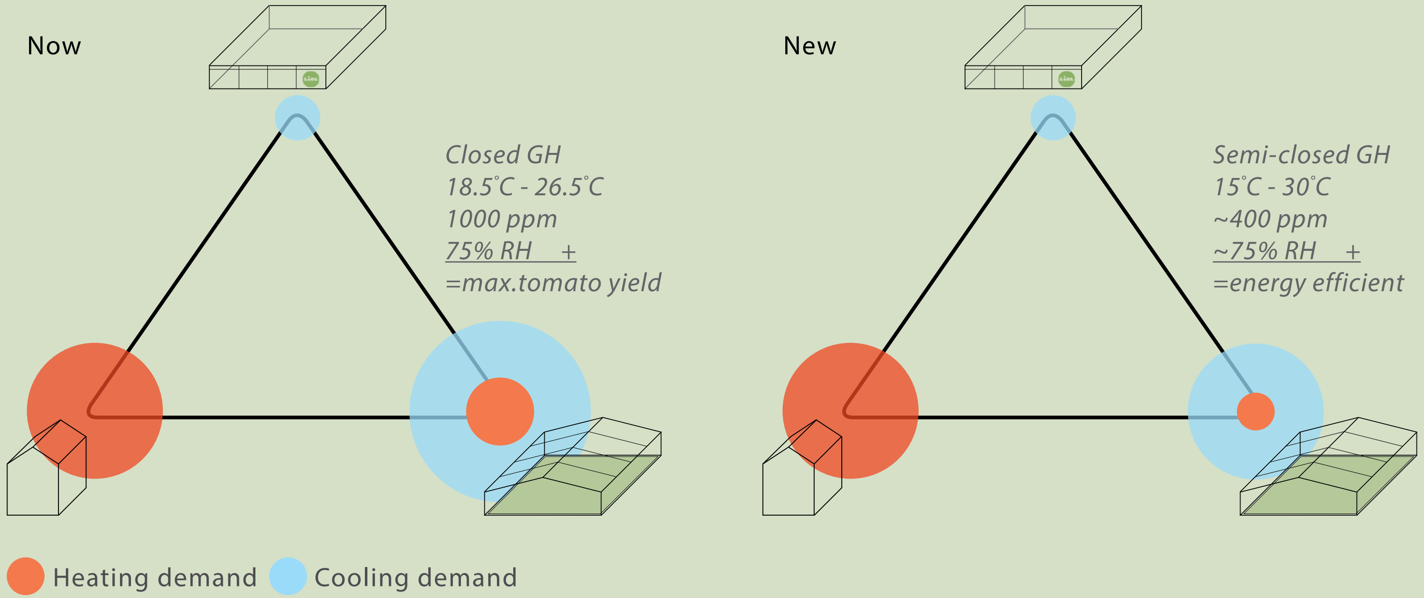


Figure 5.23: Two systems: now & new. Now T_{IN} greenhouse = 18.5°C-26.5°C & New T_{IN} greenhouse = 15°C-30°C. Also CO_2 1000ppm > 400ppm.

Dwelling heat demand and Supermarket heat surplus

=

Capacity of the system and determines the Greenhouse indoor climate

Digital Simulations

Part VI

6.1 | Purpose of the simulation

DesignBuilder software

The plant's influence on the indoor greenhouse environment varies with each growing phase the plant is going through. Plants react on the amount of sunlight that is getting through the glazing. Plants also react to the relative humidity, the CO_2 concentration, the indoor greenhouse day & night temperature, artificial lighting and to many other parameters the farmer wishes to adjust. In short: the dynamic effect of plants on the indoor climate is mostly affected by something that is just as changeable: the weather.

It is complicated to make an accurate and reliable simulation of an active greenhouse without proper expertise and the right software. That is why digital simulations in this research are not used as a design tool, but merely to check if hand calculated balances show general similarities with digitally generated graphs.

DesignBuilder (DB) is used in this research. The DB software offers many options and parameters to design a climate system and with the internal modelling tool is possible to quickly set up buildings with basic geometry. Another advantage of DB is that it doesn't require expert level knowledge on building systems to operate the software and evaluate the outcomes. However, for reliable greenhouse simulations the software is not intended.

For accurate and reliable digital simulations of active greenhouses, the Greenhouse Technology group in collaboration with the University of Wageningen (Netherlands) has developed a special digital simulation tool: KASPRO. This software is not used in this research.

Purpose of the simulations

Like mentioned, computer simulations in this research are not used as a design tool. Design decisions are not based on any simulation outcome. It is within the time period of this research not possible to have the computer outcomes match the results of the hand calculations.

However, the hand calculated heating and cooling demand throughout the year can be compared to the digital values. In this research DB simulations are used to check the influence of expanding the indoor temperature range in the greenhouse. It are not the exact values that matter, it is the general behaviour of the graph on these parameter changes that is looked at.

Additionally. DB is later in this researched used to determine the electrical demand of the lighting system under a specific 500 lux minimum and with a certain lighting schedule.

6.2 | The digital model

Parameters / construction / climate / energy

The simulations run in DesignBuilder are based on Greenhouse B: 107 x 8m.

The DB model is set up according to the following parameters:

Parameters that are underlined are changed between the closed greenhouse and semi-closed greenhouse simulation.

General / location
The location template has been set on Amsterdam AP Schiphol (Schiphol Airport). This location template matches the geographical location of the city block.

The site orientation has been set to 66° to match the location's urban planning.

The model for the greenhouse has been simplified to one climatic zone, without internal structural elements. The model consists of a stretched out rectangular box, with a roof inclination of ~7°. The dimensions are 800(X), 10700 (Y) and 250-350 (Z). Figure 6.1 & 6.2.
Construction - Materials

- The outer wall of the greenhouse are represented by 120mm thick concrete walls. Walls are glazed for 90% (horizontal strip). The remaining 10% resembles the facade structure that would be present in the actual greenhouse.
- The roof is simulated by a 120 mm thick sandwich panel. The roof is then glazed for 100%. However, horizontal and vertical dividers are manually added to the roof surface to resemble actual roof structure.
- The floor in the model is resembled by a 150 mm thick concrete floor slab. This floor is set to adiabatic to cancel out any heat fluxes incoming and outgoing heat fluxes with the substructure.

Openings
All openings in the greenhouse walls and roof are glazed with standard double glazing (clear glass, 6-13-6, U=2.7)

Interior climate
In accordance with the production requirements mentioned in paragraph 5.2.2, the margin for temperature was set between 18.5°C-26.5°C for the first simulation and 15°C-30°C for the second simulation.

In accordance with the production requirements in §5.2.2, the indoor Relative Humidity is set on 69%-75% for the first simulation and 50%-90% for the second simulation.

The HVAC system (Fan coil unit - 4pipe - air cooled chiller) is considered to be responsible for heating, cooling and (de)humidifying to unify the results.

Natural ventilation is turned off in the first simulation.
In the second simulation, natural ventilation is turned on.

Auxiliary energy is set on 0.75 W/m^2 (On 24/7). This results in a total electricity demand of ~5500kWh/year.

Energetic fluxes

- Heat gain by equipment is simulated by checking the *miscellaneous box* under the activity tab. Q_{EQUIP} is simulated with a 24/7 value of 5 W/m^2.
- Heat gain by the lighting system is simulated by checking the *general lighting* box under the Lighting tab. A heat gain of 10 W/m^2 is applicable during the hours the light are switched on. For this, a separate lighting schedule is made. The target luminance is set on 500 lux.
- Heat gain by people activity is simulated by assuming that there are 4 people working in the greenhouse (=0.005 person / m^2) during greenhouse working hours (Monday-Sunday, 07:00-19:00). A separate working schedule has been made in DB. Metabolic activity is set on 'machine work - light', which resembles 216 W/person.

Miscellaneous:

- Holidays do not apply and is therefore checked off (activity tab);
- Computers, Office equipment and catering are checked off (activity tab);
- There is no local electricity generation;
- It is assume there is no air infiltration. This box has therefore been unchecked (construction tab)

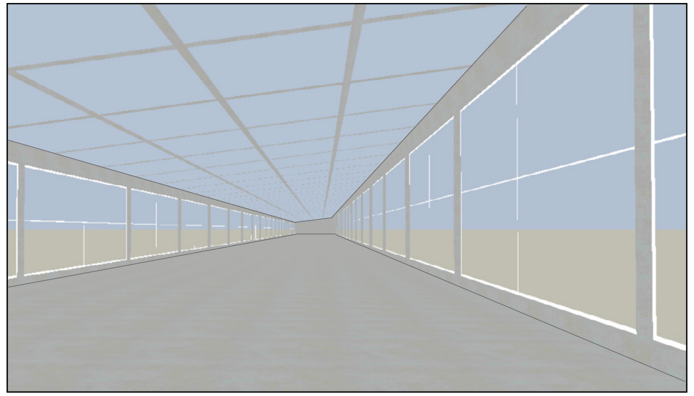


Figure 6.1: Interior view of the greenhouse (from DB).

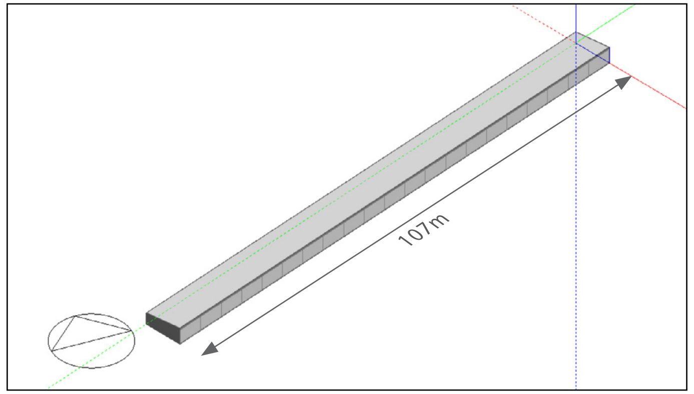


Figure 6.2: Model of the greenhouse in DB.

6.3 | Simulation 1, closed greenhouse

18.5°C - 26.5°C

In the first simulation of the greenhouse, the indoor temperature is kept with the strict limits of 18.5°C and 26.5°C, the optimum temperature range for tomato production.

As expected, the there is a minor heating demand that reaches deep into May. A narrow temperature rang (figure 6.4) results in an increased cooling and heating demand, figure 6.3 & 6.5.

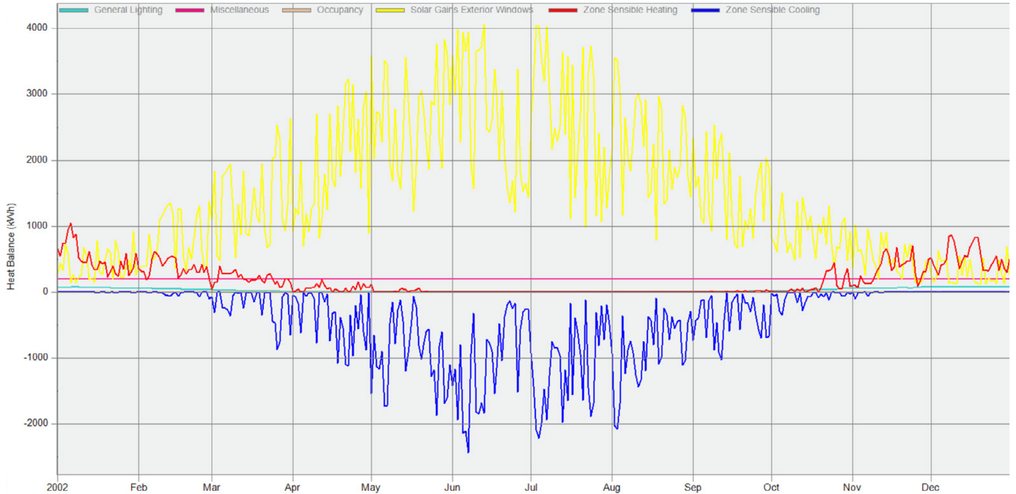


Figure 6.3: Simulation 1, T_{IN} = 18.5-26.5°C. Thermal energy fluxes

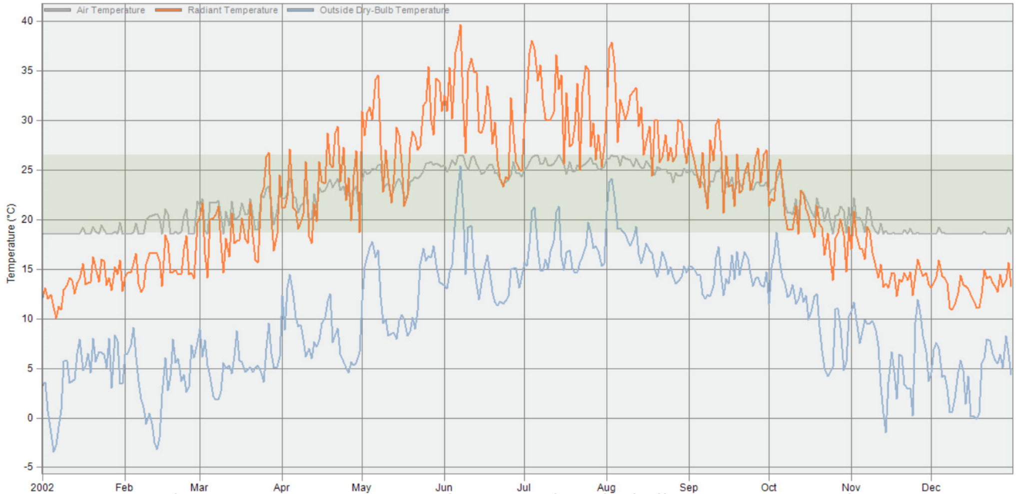


Figure 6.4: Simulation 1, T_{IN} = 18.5-26.5°C. Indoor T, Outdoor dry bulb temperature & radiant temperature

6.4 | Simulation 2, semi-closed greenhouse

15°C - 30°C

In the second simulation, the greenhouse indoor temperature is eased down to the range 15°C-30°C. This leads to mitigated heating and cooling demands.

Both hand calculations as the simulations show a reduction in cooling demand and heating demand. The reduction are however no analogous with each other: the cooling demand is reduced with 49% and the heating demand with 19% in the simulation. The hand calculations show a reduction of 38% and 11% for the heating and cooling for the greenhouses. A discrepancy was expected, however not this large.

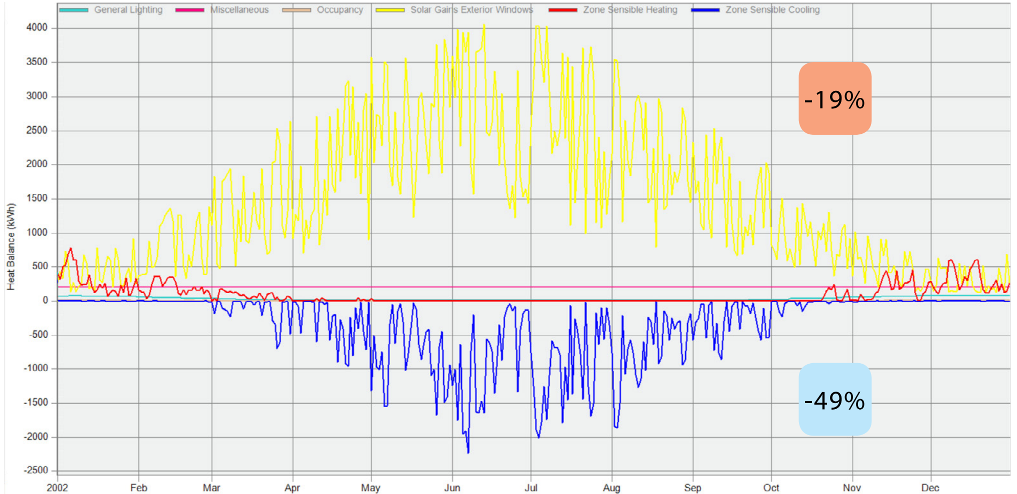


Figure 6.5: Simulation 1, T_{IN} = 15-30°C. Thermal energy fluxes

If we look at the proceeding of the curve throughout the year, there is a resemblance with the hand calculated monthly energy balance. It shows, as expected, very low to zero heating demand in the months April - September and very low to zero cooling demand in November-March. Figure 6.6 shows how the temperature fluctuates between 15°C and 30°C and how the ambient temperature is mostly underneath that range.

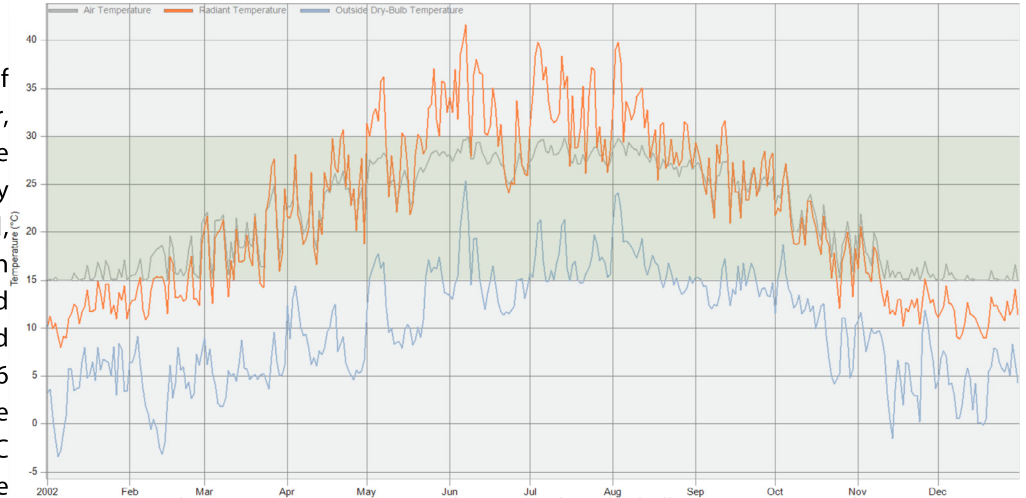


Figure 6.6: Simulation 1, T_{IN} = 18.5-26.5°C. Indoor T, Outdoor dry bulb temperature & radiant temperature

Concepts Elaboration

Part VII

7.1 | Intro

Designing the energy system

This chapter elaborates on the design of the new energy model. The first part discusses the general idea behind the concept: it briefly describes the involved components, the energy triangle that is formed between the greenhouse, supermarket and the dwelling. It discusses the necessity of energy storage and how Nutrient Film Technology tomato production is applied in this greenhouse so that an estimation of the number of plants can be made (§7.2.1 to §7.2.4).

Before elaborating on how energetic synergy can be facilitated between several components, the heating/cooling demand of the system at maximum capacity is given (§7.3). This is visualised again afterwards, so that the impact of the component synergy becomes visible (§7.5). This system energy overview is used as the starting point to balance out the total heating and cooling demand. For this, two alternatives are proposed.

The last part of the chapter describes the conclusive design for the local energy grid. The two energy models, summer and winter, are represented in schematic overviews (§7.9). The last paragraph of the chapter covers the PV-system that is added to the local energy grid (§7.10).

The energy grid is designed according to the following design thought:

dwelling heat demand and supermarket heat surplus
-determines-
capacity of the system and the greenhouse indoor
climate

| Index

Chapter VI: Concept elaboration

Concept elaboration

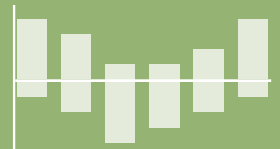
System elements & connections

Final design energy model

In appendix VI, an additional supermarket cooling method based on a free cold source is explained. This method is not included in the final energy model and just serves an inspirational purpose.

Design methodology of the energy model

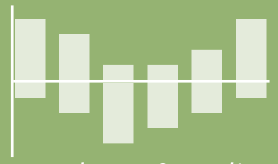
Step 1 | Quantify heating/cooling (H/C) demand of the system at maximum capacity
Greenhouse A & B (78.8x10.8m & 107x8m), apartment building A & B (44hh & 77hh) and the Lidl supermarket



heat- & cooling demand

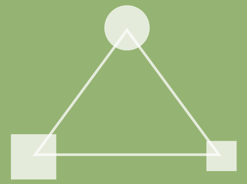
Step 2 | Have components work together + disconnect from gas: energetic synergy
This contains: Lidl <> Greenhouse exhange, Lidl heat recovery, Thermal buffer, heat pumps & adiabatic cooling

component synergy reduces the demands

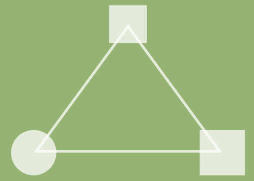


results in new heat- & cooling demand

Step 3 | Balancing the H/C demand for the energy storage: change components / change climate parameters
Vary components and parameters to find most sustainable solution | 2 options

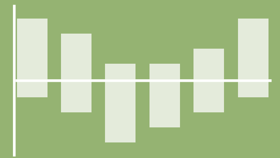


Option A

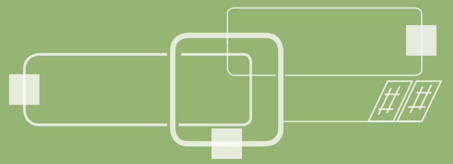


Option B

Final step | Final energy system
One of the options translated into an energy system + include renewable energy production



final heat- & cooling demand for the balanced system



design for energy grid (summer, winter)

7.2.1 | Urban context

concept elaboration

The city block - Helmersbuurt, Amsterdam

The city block is part of an early 20th century expansion plan of the city of Amsterdam and has a high residential density. Although the city development plans of this block date back to the years around 1900, not all buildings in the block are from the same period.

The existing Lidl is located in the courtyard between the residential buildings and will not move during the refurbishment. In the building block is no free plot of land available to build a greenhouse and the courtyard would be to much in the shade. Therefore we have to raise the food production above street level and on top of the roofs of the apartment buildings.

The suitability of a roof for constructing an urban greenhouse on top is decided based on two criteria:

1. It must be a flat roof;
2. The roof should have an efficiently shaped plan.

Based on these two points, two roofs are identified that are theoretical suitable: greenhouse A & B.

Suitable residential buildings are selected based on two criteria:

1. The building should not be of mentionable architectural/historical value and with that preventing any kind of technical intervention;
2. The building should be preferably be large and based on a serial construction method, making any technical improvements easier to execute and making it easier and more efficient to connect the houses with each other and the system.

Based on these two points, apartment block A & B have been identified.

Components included in the new energy model

Apartment block A:
Gallery apartment complex (1965) - Residential building, 77 apartments over 5 floors. Floor 1&2 are maisonettes.

Apartment block B
Staircase access apartment complex (1928) - Mixed residential + commercial functions on the ground floor. There are 49 households in this building on the top 4 floors. Built in the Amsterdam School architectural style

Greenhouse A - The North greenhouse
On top of apartment block A is place to built greenhouse A. The maximum gross floor area of the greenhouse is 10.8x78.8 meters.

Greenhouse B - The South greenhouse
Op top of apartment building B is space to build the second urban greenhouse. The gross floor area of the farm would be maximum 8x107 meters.

Lidl
The Lidl will remain on its current footprint and any future refurbishments will only include the interior + installations and the entrance portal.

Support functions
There is a third suitable roof surface on the city block. It is is to small for a rooftop greenhouse but it can be used to house the support functions to the urban farm or for other functions.

The remaining rooftops in this city block have to irregular shapes or are to small for a greenhouse. These roofs are suitable however for a PV system, see §7.10.

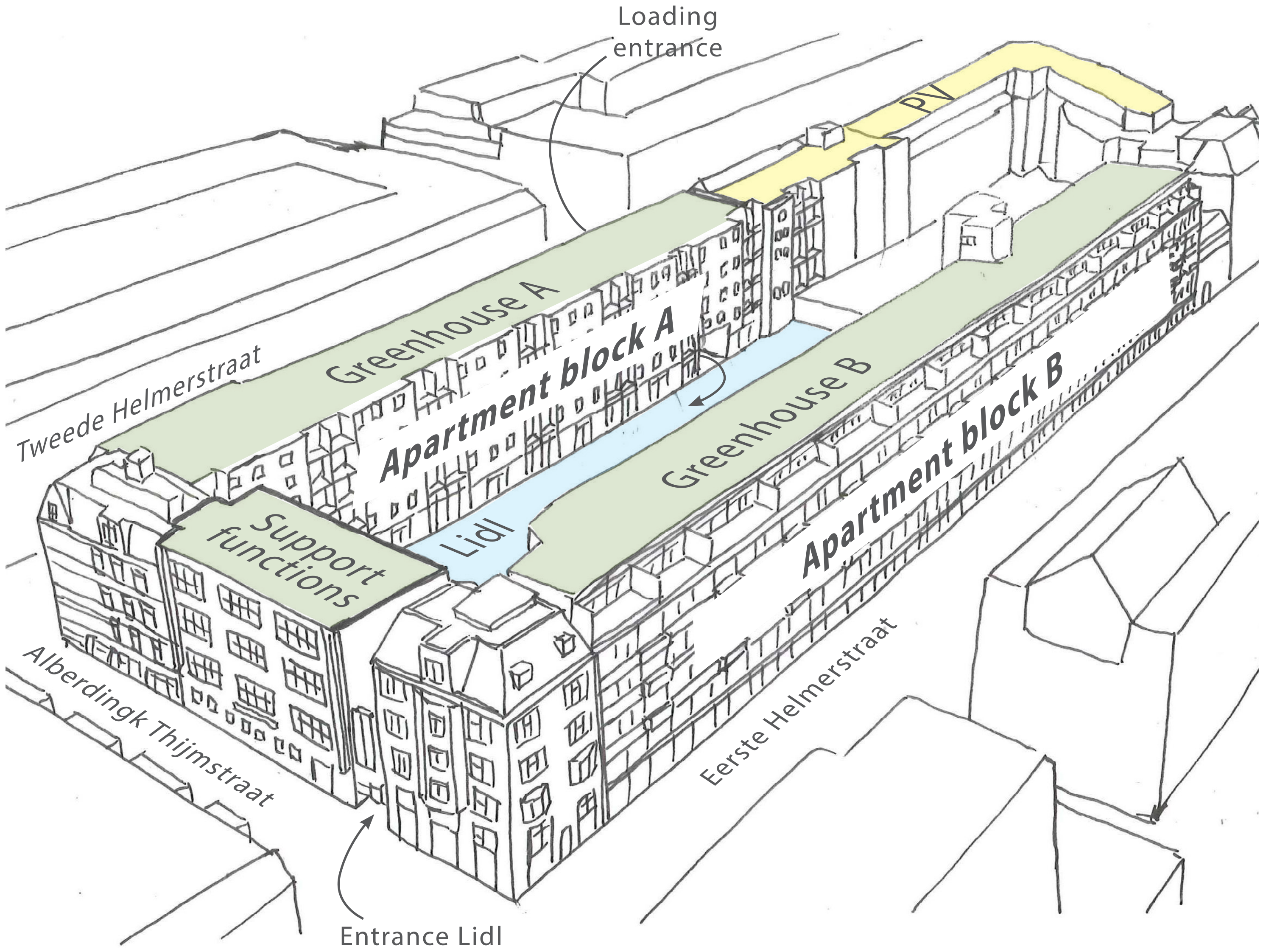


Figure 7.1: The city block and the included components: Apartment block A & B, Greenhouse A & B and the Lidl Supermarket

7.2.2 | The energetic triangle

concept elaboration

The triangle

Three different functions are connected with each other:

- Semi-closed urban rooftop greenhouse(s);
- Residential buildings, year-round climatised by high temperature heating (no cooling, no ventilation);
- A mid-sized supermarket with a year-round cooling demand.

These three functions together form the triangle (figure 7.2) that represents the energy system which is established in this research.

The supermarket has a steady indoor climate that revolves around an average indoor temperature of 21°C. Throughout the year, there is a constant cold demand to compensate for the waste heat emitted by the cooling units. Product cooling in this supermarket is done by individual cooling units and not with a centralized system (§7.4.6).

The greenhouses have a heating demand mainly during the winter months and a cooling demand mainly during the summer months. These glass structures form the energetic motor of the system and will act as large and functional solar collectors.

The heating system of the *residential buildings* rely on high caloric heat. Waste heat streams therefore need to be upgraded with a heat pump. The large annual heat surplus of the greenhouses feed the demand of the houses.

Figure 7.3 sketches the flows of energy in the local grid.

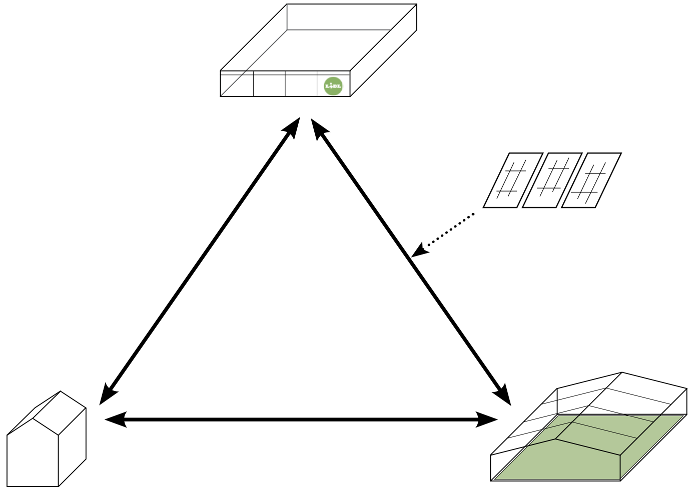


Figure 7.2: The energy triangle

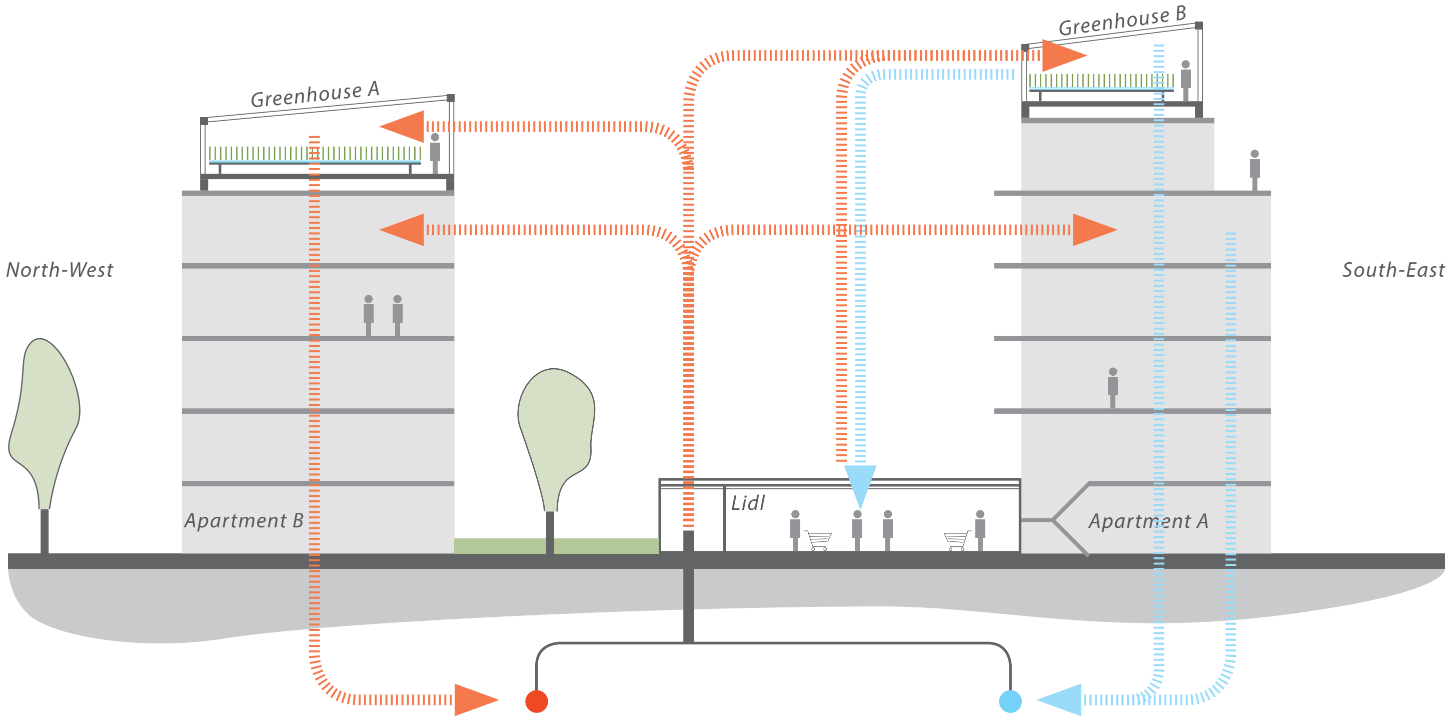


Figure 7.3: More visual representation of the energetic triangle. Underground energy storage added to the system.

7.2.3| Energy storage

concept elaboration

The principle of energy storage

In order to set up the greenhouse energy balance, the temperature range in this research has been established on 15°-30°C. If the sum of negative and positive energy fluxes is below zero, the temperature in the greenhouse decreases and below 15°C heating is activated. If the energy balance is positive, the indoor temperature rises up to the set point of 30°C. Above 30°C, heat extraction should be activated (cooling). The greenhouse energy balance and simulations point out that the heat demand is primarily in the months October-March (6months) and an energy surplus is available from April-September (6months).

Greenhouse agriculture has a mismatch in demand and supply of thermal heat on a large scale and on two time periods:

- Short term mismatch: day & night;
- Long term mismatch: summer & winter.

To overcome this mismatch, extracted thermal energy should be stored for later use, figure 7.4. In this paragraph, both short term energy storage as long term storage are explained.

Daily

Thermal storage or heat accumulation is storing thermal energy in a medium for later use. Preferably this medium is a material with a high specific heat capacity. A classic example are heavy construction materials like concrete: during the day solar energy thermally charges the concrete surface so it can emit this heat during the night. This mitigates the temperature fluctuations in the building by creating a stable indoor temperature, which on it's turn leads to less pressure on the heating system.

When needed?

When looking at the monthly energy balance of the greenhouse, it shows that there is no heat demand in the months of June till September. However, the monthly balances are based on averages and it is not hard to imagine that the outside dry bulb temperature regularly drops below 15°C in all of these months. This expectation is proven when we look at a 24hr energy balance of a day in June and a day in September, §5.2.6. Both days show a significant energy surplus during noon but also a heating demand in the evening, night and early morning. It is this large solar energy peak (or cooling demand peak) that puts the daily mean energy balance in the positive numbers.

We can safely assume that this pattern of daily supply and demand is happening in most of the days in the period of June-September. The daily heat demand is higher in April, May & September compared to June,July & August and might sometimes be even completely absent. So, in contrary to what the monthly energy balance projects, there should always be a heat source available that can react quick to the heat demand.

This quick responding heat source will be a water storage tank, charged by the thermal energy of the sun.

See §7.4.2 for more information + calculations about this thermal buffer.

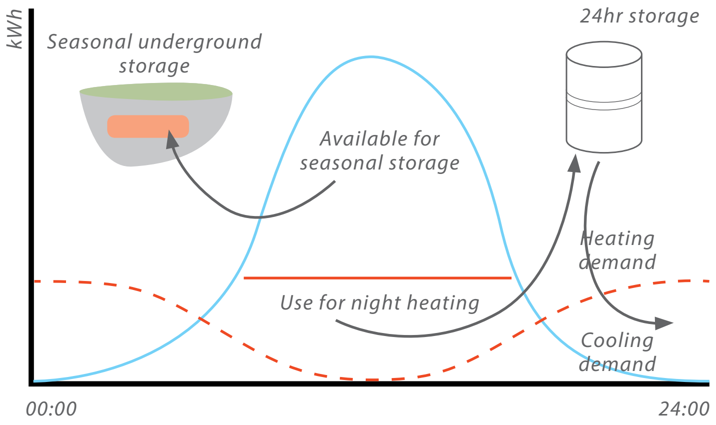


Figure 7.4: 24hr and seasonal thermal energy storage.

Seasonal energy storage - principle

Before abandoning fossil based heating installations, an alternative free or natural heat source should be found for the neighbourhood. These large scale heat sources are usually not present in the Netherlands. Thermal sources might be out of reach, like city heating grids based on industrial waste heat or the sources are not easily accessible, like geothermal heating. If thermal heat sources are not present, one could opt for creating a new thermal heat source: underground heat storage.

During the summer, excess thermal energy is stored in the earth so it can be retrieved again during the cold winter months. In this energy system, the greenhouses act as large solar collectors. Cold water is pumped through the floor of the greenhouse, where thermal energy is transferred from the floor to the water, thus cooling the greenhouse. This heated up water later exchanges its thermal energy with the underground storage.

Attachment IV shows a section of the map of Amsterdam (South-West area). The underground open-source energy storage potentials are drawn in this map. By coincedence, it shows that the Helmersbuurt area shows a relative high potential for the storage of thermal energy: 750-840 MJ/m^2.

Seasonal energy storage

Thermal energy storage in the earth: in Dutch called Warmte Koude Opslag (WKO) and in English Aquifer Thermal Energy Storage (ATES).

Underground thermal energy storage makes use of the high specific heat capacity of the aquifers and the small thermal conductivity of the earth, in other words: the earth can efficiently be used as a well insulated energy storage. (Edelenbosch & Wensum, 2009).

2 types:

- Closed source system: In this system, an energy carrying medium is passed though an heat exchanger, where thermal energy is passed from the medium to the ground to be stored for later use. Suitable for small residential projects.
- Open source system: the heat source and the cold source are separated from each other (doublet system) and the system literally transports the heat carrying medium (ground water) between the two sources. This type of storage is suitable for larger projects because of the higher energy demands, higher investment costs and complicated permission procedures. During the summer months, when the demand for cooling is high, cold ground water is pumped up to directly cool the buildings. Heat is exchanged and the water temperature rises in. The warmed up water is pumped back into earth and into a heat source. During winter, the system is turned around and the warm water is used to heat up the buildings. The heat is recovered by a heat exchanger and upgraded with a heat pump to reach the required heating temperature. The cooled down water regenerates the cold source.

Types

There are 3 different types of open source ATES systems (Drijver, 2014):

- HTS - High temperature storage: > 60°C - ~90°C
- MTS - Medium temperature storage: 30°C-60°C
- LTS - Low temperature storage: <30°C

High temperate energy storage system find their use in large scale storage from industry, waste incineration or power plants and is usually applied in combination with a city heating grid. An important advantage of HTS is the possibility to leave out a heat pump when retrieving the heat. This significantly increases the efficiency of the system.

MTS storage is a technique that aims at the middle-high temperature range. Low grade thermal waste on a middle-high temperature, like the waste heat from greenhouses, cooling machine or solar collectors is temporary stored in the water-carrying layers of the earth. This heat is later used by the producer and not shared with the city or other users. MTS is suitable for small scale (urban) projects that require low temperature heat but cannot generate this heat by them self.

LTS finds it's application in small scale projects that store temperatures not reaching above 30°C. This technology is very common in the Netherlands, as energy storage until 25°C does not require additional research and special permissions.

Energy storage should not be mixed up with geothermal heat extraction. This technique relies on the planet's core heat on a depth of several kilometres and is not applicable for small scale projects.

Temperatures

On which temperatures are LTS systems operating? To start: most important rule in ATES systems is to design a energy loop that is in balance (Drijver 2014). Generally speaking, the cold found in the earth has more value then the heat. In practise this typically leads to more heat infiltration in summer then cold is extracted during winter. If this surplus of heat is not retrieved, the temperature of the groundwater gradually rises over the years and cooling becomes less and less efficient. Not retrieving stored heat is an undesirable and unsustainable heat dump. An unbalanced ATES system exploits the sustainable cold source and makes the energy storage inefficient for future use.

In practise, the temperature of the water that charges the cold source has a minimum temperature of 6°C and the water that charges has a maximum temperature (by law) of 25°C. This return water mixes up with the ground water. This rises the average temperature in the cold source above 6°C and lowers the temperature in the heat source below 25°C. When designing an energy system, a cold source temperature of 8-10°C and a heat source temperature of 16-18°C can be apprehended (Edelenbosch & Wensum, 2009).

Summary:
LTS system (open source) is best applicable for the medium scale energy system in this research. The infiltrated heat and extracted cold should be in balance. The infiltration temperature should not exceed 25°C (maximum by law). For energetic calculations the following design temperatures are to be used: cold source: 8°C & heat source: 18°C.

7.2.4 | NFT & Tomato production

concept elaboration

Nutrient solution

Hydroponic farming bases itself on growing crops without the use of soil. Primarily, hydroponic production avoids the any possible of soil contaminations with soil-borne diseases. Secondly allows Nutrient Film Technology (NFT), a specific form of hydroponic farming, for outstanding control of the plants nutrition and water feed. The water flow can be narrowly controlled to remain in the optimal range and the nutrition composition of the water is constantly monitored. Important values like pH, oxygen and salt level can be adjusted to remain at the best level for maximum tomato yield. Literature survey has pointed out that plant growth can be stimulated if the root-zone temperature is kept on a specific temperature, for tomato production this would be 25°C.

In NFT, the warmed up nutrient solution is pumped towards the higher end of the production gutters, which should be placed under a 2.5% inclination. Gravity will force the solution to seep through the root system of the tomatoes. At the other side the solution is collected and drained back towards the nutrient tank. In this tank the nutriment is monitored and adjusted.

Since the plants use part of the water for evaporation, less water will return to the tank then the system pumped in before. This difference should of course be equalized, either simply by adding tap water or by pumping the retrieved water from the air dryer in the nutrient tank. In the last case, a circular system would be established.

System design

To determine the maximum capacity of the nutrient solution tank, one should consider a situation in which both greenhouses are housing fully grown tomato plants. It is advised to calculate 2 litres for large plants like fully grown tomatoes[1]. Going for a smaller nutrition tank is possible and might be cheaper at first, but also destabilises the irrigation+nutrition system and increases the risk of losing the whole production in case of an error or incident.

Capacity of Nutrition tank
Greenhouse A:
3402plants x 2L = 6800L
Greenhouse B:
3204 plants x 2L = 6400L
Greenhouse A+B
= 13.200L

A flow rate of 2 L^{-1}/minute[1] per gutter should be apprehended. This means the total flow will become:

Greenhouse A:
126 gutters x 2 L/minute x 60 = 15.120 L/hr
n_{TANK} = 2.5
Greenhouse B:
178 gutters x 2 L/minute x 60 = 21.360 L/hr.
n_{TANK} = 3.3

The temperature of the nutrient solution should be set on 25°C (§5.2.2).

The drawings on the right page represent greenhouse A (North Greenhouse).

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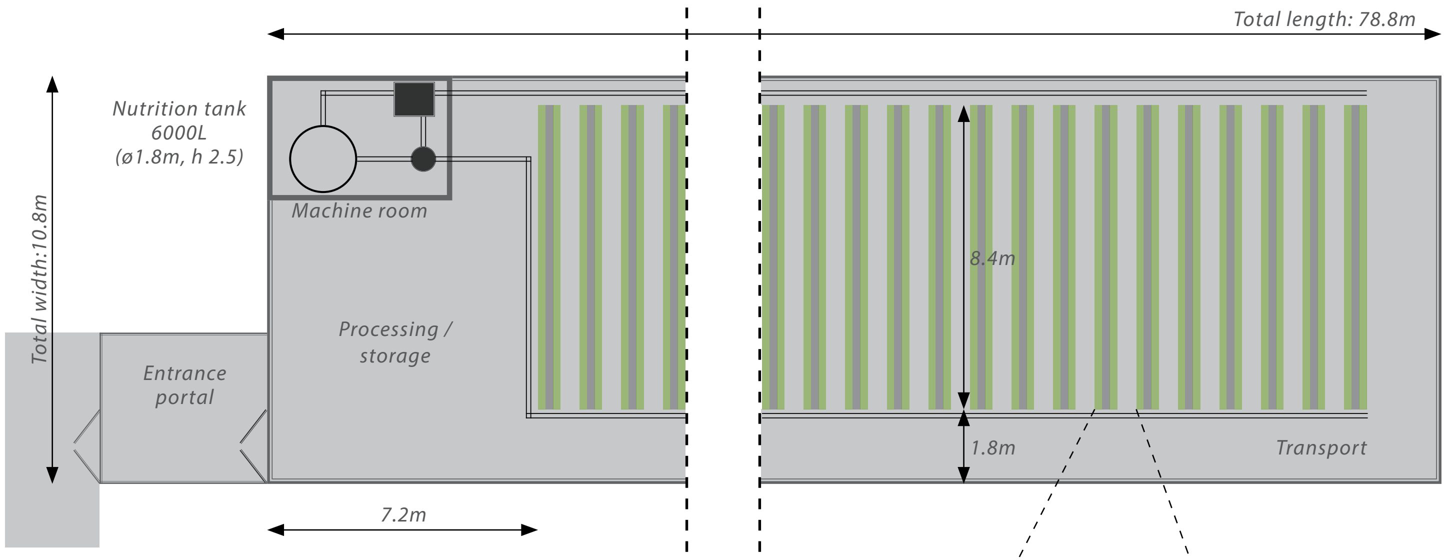
1) https://www.hydroponics.com.au/what-are-the-fundamentals-of-setting-up-an-nft-system/



Max. number of plants in Greenhouse

Greenhouse A
gross floor area =*10.8x78.8m;*
production floor area =*8.4x69.8m.*

Number of production tables (width = 1.1m):
69.8 / 1.1 = 63 tables
63 x 2 = 126 gutters
Plants per gutter:
(8.4m / 0.3m) - 1 = 27 plants
Total number of plants:
27plants x 126gutters = 3402 tomato plants

Greenhouse B - 8x107m
gross floor area =*8.0x107m;*
production floor area =*5.6x98m.*

There is space for 89 tables and 178 gutters with 18 plants. This makes 3204 tomato plants.

Total number of tomato plants = **6606**

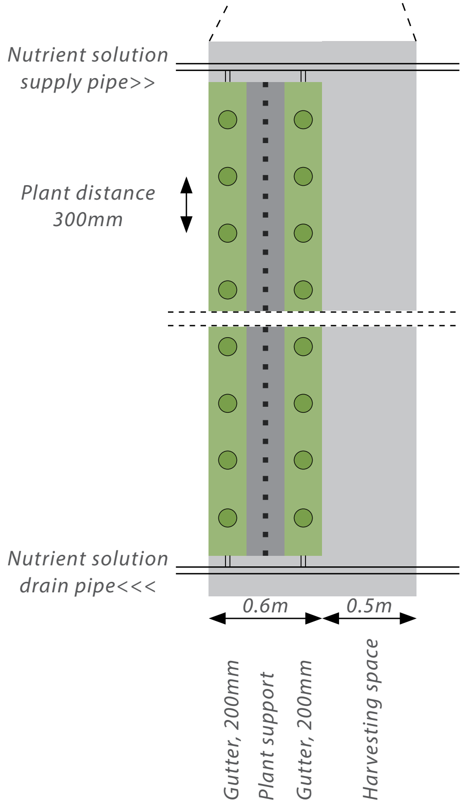


Figure 7.5: Plant production in the greenhouse (greenhouse A drawn).

7.3 | Heat & Cold demand - Summary

At maximum system capacity

This paragraph shows the heating and cooling of the system if all the earlier identified potential components (§7.2.1) are included, while being on their maximum possible sizes.

In this overview, inter-component energetic connections have not yet been established.

In the following paragraphs (§7.4.1 to §7.4.6), several inter-component connections and other elements of the new energy model are described and explained. In §7.5, the new system heating and cooling demand is shown.

Main parameters

greenhouse

- T_{IN} min 15°C;
- T_{IN} max 30°C;
- g-value glass 0.6;
- U-value glass 2.7;

Lidl

- Mean Indoor T 21°C.

Included components

- Greenhouse A | 10.8m x 78.8m (gfa 851m²);
- Greenhouse B | 8.0m x 107m (gfa 856 m²);
- Lidl Supermarket (sales floor area= 15.4x46);
- Apartment building A | 44 households (max.);
- Apartment building B | 77 households (max.).

Greenhouse production

food production
(pfa = production floor area)
Greenhouse A: pfa = 8.4 x 69.8 (586.3m²)
Tomato plants: 3402

Greenhouse B: pfa = 5.6 x 98 (548.8m²)
Tomato plants: 3204

Energy (figure 7.6)

greenhouse

- Annual heating demand: 372MWh
- Annual cooling demand: 1214MWh

supermarket & dwelling

- Lidl cooling demand: 136MWh
- Dwelling heating demand: 1007MWh

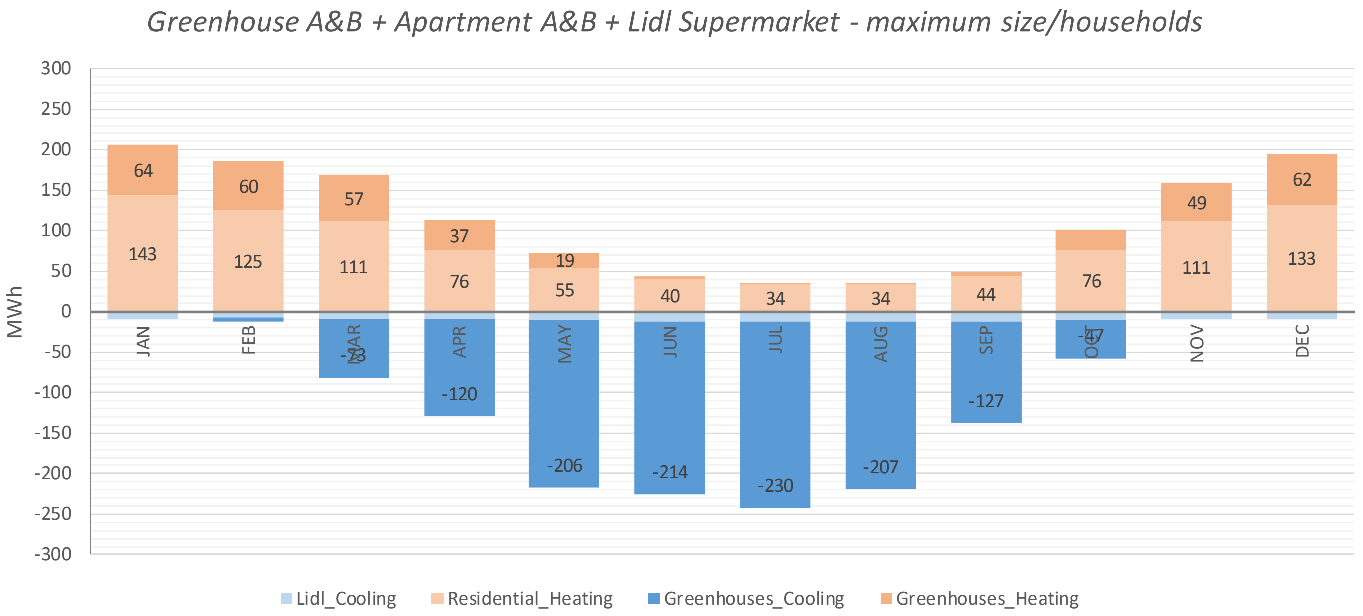


Figure 7.6: Energy demand of the system at maximum capacity (Greenhouse A+B on maximum size, Apartment A+B & Lidl Supermarket).

7.4.1| Lidl cooling 1: Greenhouse <> Lidl energy exchange

system elements & connections

Lidl <>Greenhouse energy exchange

The energy system connects three buildings with completely different functions with each other. A synergy between the components is achieved if energy can flow between supply and demand, if necessary with an energy storage station in the middle.

One potential energy exchange line is between the Lidl supermarket and the greenhouse, figure 7.9.

The indoor temperature of the Lidl is kept on 21°C, which means throughout the year there is a stable cooling demand. In the greenhouse, the heating system is activated when the indoor temperature is approaching the 15°C minimal set point temperature. This is where a window for heat exchange opens up: the supermarket has a constant heat surplus and every time the indoor temperature in the greenhouse gets below 21°C, it theoretically can use the rejected energy from the supermarket for heating purposes. The other way around will the supermarket be cooled with the low temperature air from the greenhouse.

The greenhouse is a semi-closed type. This means only as a last resort method, natural ventilation is used to bring down the indoor temperature of the greenhouse. Only if the designed cooling system can no longer cope with the peak solar loads, or if the cooling system starts consuming to much energy and becomes inefficient, the greenhouse shall open up its windows to allow the heat to escape. Since goes at the cost of the precious CO_2 concentration, this is a last resort option. Energy exchange between the greenhouse and the supermarket therefore requires a heat exchanger an can not be done directly.

The calculations are made from the perspective of the supermarket. The indicative calculation below is shown to point out the potential of the energy exchange.

We use the 24hr energy profiles to estimate how many hours the indoor temperature of the greenhouse is below the indoor temperature of the Lidl ($T_{GH} < T_{LIDL=21°C}$), see figure 7.7. Percentages are as follows: winter =100%, spring =66%, summer =30% & Autumn =50%. These percentages are reduction factors and are applied to calculate the monthly cooling capacity.

- Assume the efficiency of the heat exchanger: 75%;
- Ventilation exchange rate of the supermarket: n=3;
- T_{IN} Lidl = 19°C, T_{IN} GH = 15°C, r = 1.21kg/m³, c=1005J. kg.K, V_{LIDL} = 2053m³.

(1) Determine the air return temperature in the Lidl:

$T_{AIR} = T_{IN} - (\Delta T)*75\%$, $T_{AIR} = 19 - ((19-15)*75\%) = 16°C$

(2) Apply equation [7.1]:

$$Q_{VENT} = r * c * (n * (1/3600) * V) * (T_{IN}[K] - T_{AIR}[K]) \quad [7.1]$$
$$= 1.21 * 1005 * (3 * (1/3600) * 2050) * (292 - 289)$$
$$= 2077\ \text{Watt} = 2.1\text{kWh}$$

(3) Calculate monthly cooling capacity

$$Q_{COOL\_V} = Q_{VENT} * 24 * \#days * n \quad [7.2]$$

Example: January = 2.1kWh*(24h*31d) *100% = 4.8MWh

The annual effect of GH<>Lidl energy exchange is projected in figure 7.8.

In appendix II, more information about the calculations and parameters is given.

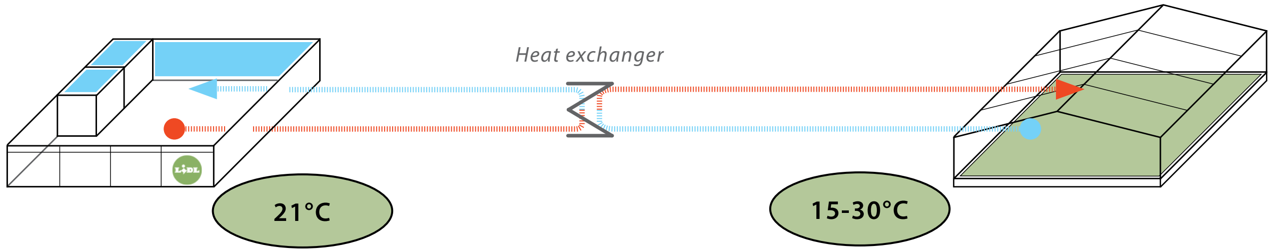
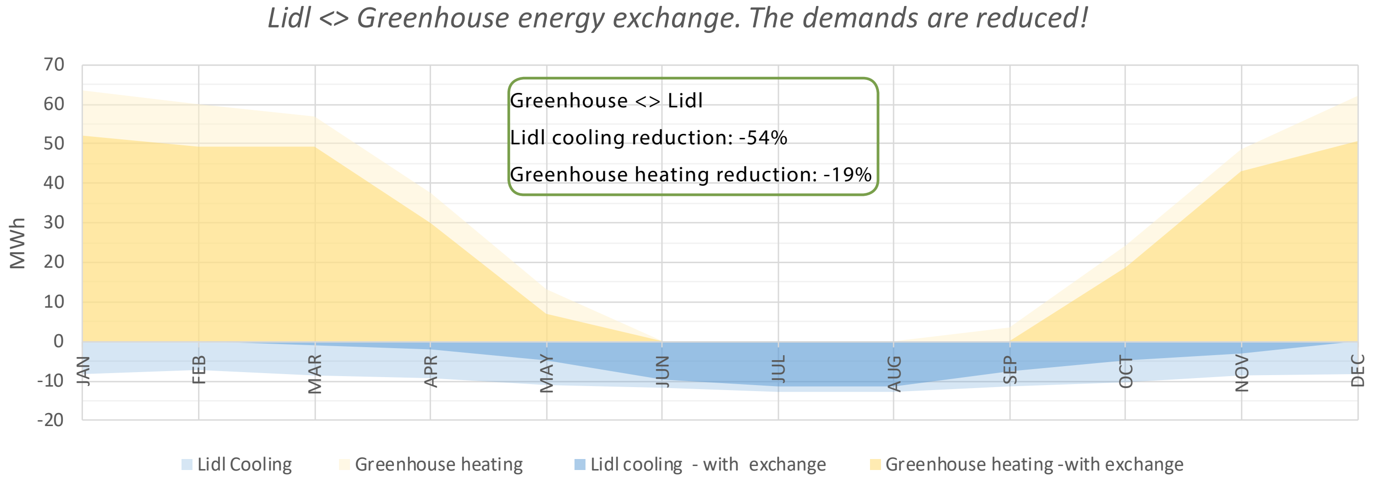
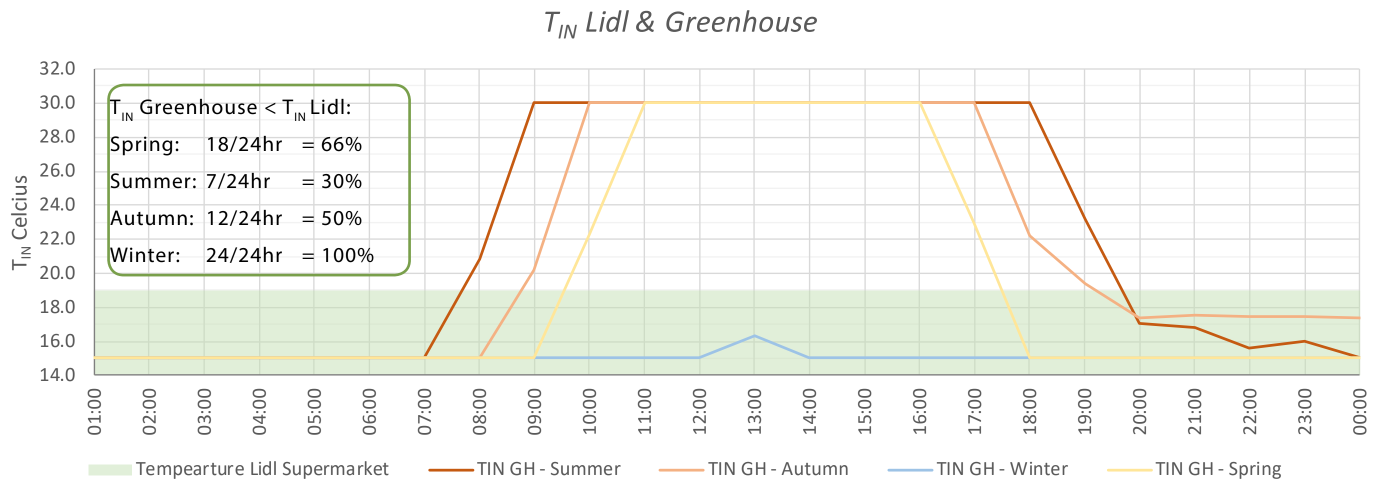


Figure 7.9: The principle



Greenhouse <> Lidl
Lidl cooling reduction: -54%
Greenhouse heating reduction: -19%

Figure 7.8: The heating demand of the greenhouse and the cooling demand of the Lidl are reduced by energy exchange.



T_{IN} Greenhouse < T_{IN} Lidl:
Spring: 18/24hr = 66%
Summer: 7/24hr = 30%
Autumn: 12/24hr = 50%
Winter: 24/24hr = 100%

Figure 7.7: Indoor temperature of the greenhouse and the Lidl supermarket. Figure points out when heat exchange is possible.

7.4.2| Greenhouse: Short-term thermal energy buffer

system elements & connections

In §7.2.3, the necessity of a thermal buffer during the warmer spring, summer and autumn months is pointed out. In short: the monthly energy balance depicts no cooling demand in the months June till August. The daily energy (§5.2.6) balances indicate the opposite and show a heating demand in the late evening, night and morning. A thermal buffer could overcome those temporary periods of heat demand.

In general, the heat demand for this greenhouse system is covered by:

- Floor heating during the winter months, while the winter system is active (see §7.9.3);
- Thermal buffer to overcome colder periods during the warmer months;
- Heat exchange with the supermarket (§7.4.1);
- Solar heat gain (passive heating).

Thermal buffer

§7.2.3 describes the necessity of a thermal energy buffer, even during summer. Figure 7.11 shows the heating demand of the two greenhouses when the minimum indoor temperature is kept on 15°C.

April shows a heating demand of 38MWh, this can be calculated back to a heating demand of 1212kWh/day. Since we know April is the coldest month of the summer season with an average outside dry bulb temperature of 8.4°C and average low temperature of 5.0°C, we can assume April to be the determining month to base the capacity of the thermal buffer on.

A thermal storage tank , filled with $37.000L^{-1}$ water (ø2.8mx6m) is added to the energy system. During the course of the day, the medium in the tank is charged by a heat pump. This heat pump upgrades the warm water coming from the greenhouse, where is was warmed up by the heat of the sun and the indoor greenhouse temperature during the day.

Buffer capacity - April

The peak monthly cooling demand is 38 MWh (1225 kWh/day).

First we should subtract the thermal energy that is added to the greenhouse by heat exchange with the supermarket. For the month April this is 8MWh. This leaves:

38MWh - 8MWh = 30MWh, or 1000kWh/day

We included a safety factor of 1.25:

1000kWh x 1.25 = 1250kWh

This equals

4500e6 Joule / day.

A storage tank of 37.000L is included in the system. The dimensions of the tank would be: ø2.8x6m, a convenient size as it is about 1 floor high when placed horizontal.

2) Maximum stored thermal energy is calculated with the equation:

$$Q_{STORED} = c * m * (T_{WATER} - T_{IN}) \qquad [7.03]$$

where

Q	Thermal energy stored in buffer (Joule)
c	Specific heat capacity, water = 4185 J.kg.K
m	mass of the water, 37.000kg
T_{Water}	Maximum water temperature = 35°C
T_{IN}	Indoor greenhouse temperature = 15°C

This makes:

$$Q_{STORED} = 4185 * 37000 * 20 \qquad [7.04]$$

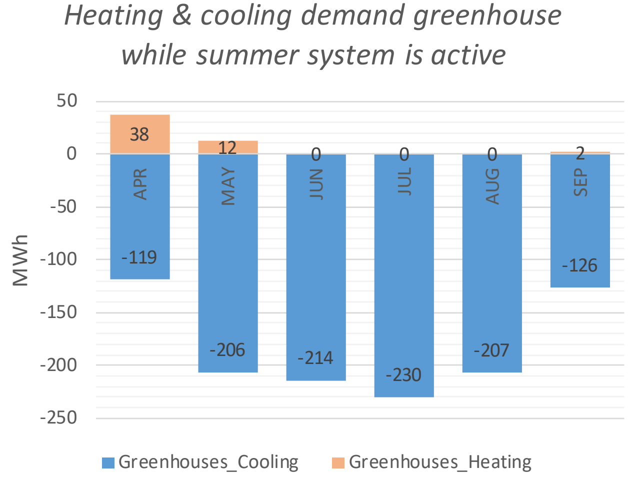
$$Q_{STORED} = 3100e6 \text{ Joule}$$

We now calculate:

$$Q_{HEATING} - Q_{STORED}$$

4500MJ - 3100MJ = 1400MJ, this is insufficient,

In theory it is easy to overcome this difference by either increasing the size of the tank or by increasing the temperature in the tank. (to 44°C). Both options are not a solution. The tank is already on the large size and a temperature increase would also mean an increase by investment energy from the heat pump. From a sustainable point of view it would make more sense to just allow for temporary temperature drops in the greenhouse. In general, this would not have a lasting negative effect on the plants, as long as the temperature does not remain low for to long and does not drop below 10°C (for tomatoes). There is also still the warm nutrient solution in the root zone of the plants, that remains on around 25°C.



Heating & cooling demand greenhouse while summer system is active

Figure 7.11: On first look, no heating demand in Jun-Sep

Buffer capacity - Other months

We know now that the maximum capacity of the storage tank is 3100MJ / day, or 861kWh and this energy content is insufficient to meet the heating demand for one day in April.

To determine the minimum capacity of the buffer in the other months (May-August), we hold on to degree days (dgd) (Dutch: graaddagen). On the website of Mindergas[1] an online degree days calculator can be found. The degree days this online tool calculates are derived from data from the Dutch Meteorological Institute (KNMI). The lower temperature set-point can manually be entered, in this case 15°C, and the number of degree days per month are quickly retrieved. For the calculations in this chapter, the monthly degree days of the past 5 years are averaged.

The following degree days are retrieved: April = 106, may = 53, June = 8, July = 1, August =5 and September = 16. We know April is the coldest month and therefore determines the maximum capacity. The standard capacity of the other months is based on the following calculation (September as example):

$$Q_{STORED\_SEP} = (\text{dgd Sep} / \text{dgd Apr}) * Q_{COOL\_APR} \qquad [x.x]$$

This makes:

$$Q_{STORED\_SEP} = (16 / 106) * 38\text{MWh} = 5.7\text{MWh}$$

Figure 7.12 shows the buffer capacity of the other months when the summer system is active. The heating demand of May and September actually rises.

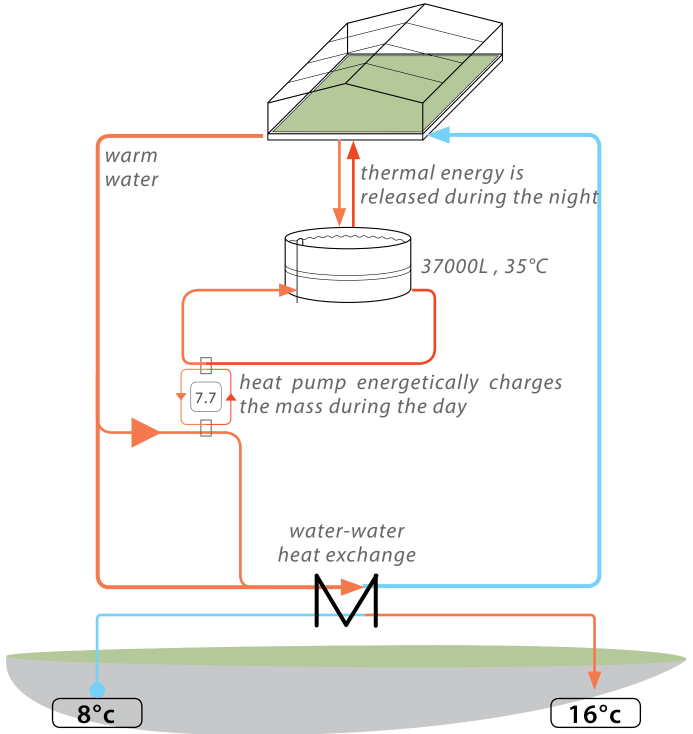


Figure 7.13: The place of the thermal buffer in the summer system

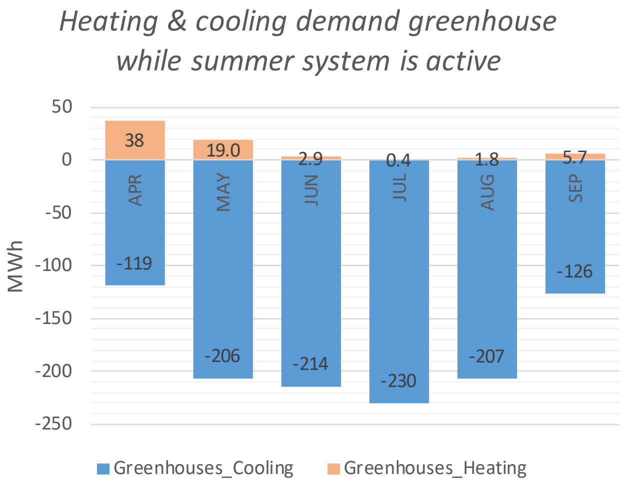


Figure 7.12: Monthly energy stored in the buffer

[1] *https://www.mindergas.nl/degree_days_calculation/new*

7.4.3 | Heat pumps

system elements & connections

Working

A heat pump is a sustainable alternative for the traditional boiler or cooler. If applied under the right conditions, with the availability of a 'free' heat source and with small temperature jumps, a heat pump uses considerably less primary energy.

A heat pump extracts thermal heat from the source side, upgrades this, and releases this on the receiver side. This is made possible by circulating a refrigerant fluid with a low boiling point through a compressor (1), a condenser (2), an expansion valve (3), an evaporator (4) and back to the compressor (1). These are the four main components of a heat pump.

Heat pumps can be applied between different energy carrying mediums, for example: water-water, outside air-water, ventilation exhaust air-water, brine-water and air-air.

Working principle:

1. In the compressor, the refrigerant is compressed in order to increase the pressure and by that the temperature;
2. The pressurized and heated gas is pumped through the condenser, where heat exchange takes place with the medium from the receiver side. This can for example be water for floor heating. The refrigerant and the energy carrying medium are of course always separated from each other when heat is exchanged;
3. Due to the drop in temperature, the gas changes phase to liquid form while the pressure remains high. Only after being pumped through the expansion valve, after which the diameter of the pipes increases, the fluid has the space to expand and the temperature drops;
4. In the evaporator element, 'free' heat from the heat source is exchanged with the cooled down liquid refrigerant by means of evaporation. In this element the fluid is turned into a gas again;
5. The cycle restarts at point 1.

The pressure increase of the refrigerant and the internal refrigerant temperature in the compressor and in the evaporator mainly depend on two factors. First, there is the demanded temperature increase between the source side and the receiver side of the system. Secondly it is the type of refrigerant that determines the internal pressures and temperatures. Each refrigerant type has its own saturated steam table. With this table, the cooling cycle can be projected on a h-log P diagram and the pressure and temperature changes can be determined. The temperature in the compressor and evaporator are used to calculate the efficiency of the heat pump. Exact definition of these internal temperatures by combining the data from the saturated steam table and the h-log P diagram goes beyond the scope of this research. Therefore an approximation is used, see *Efficiency of the heat pump* on the next page.

There is not a prevailing optimum solution for a heat pump type. Every project requires a new judgement based on geographical location, direct context, availability and typology of the heat source or heat demand. One rule that is always applicable when designing a heat pump system: a narrow temperature increase benefits the efficiency of the heat pump.

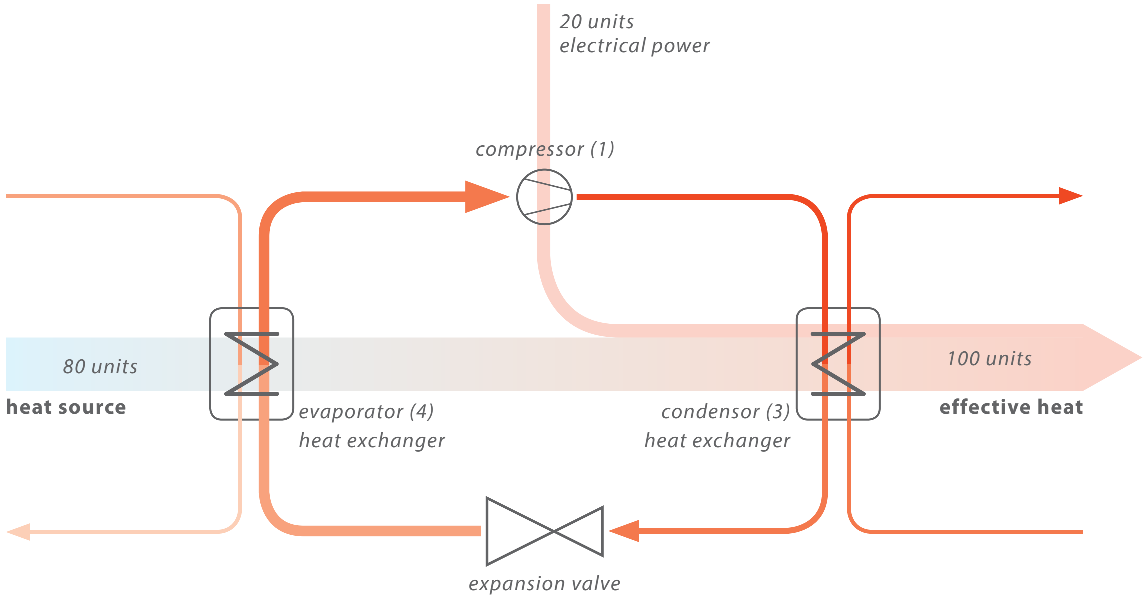


Figure 7.14: Principle functioning of a heat pump with a COP=5.

Efficiency of the heat pump: COP

The thermo-dynamical performance of a heat pump is expressed in COP. If a HP has a COP of 4, this means that for every kWh of invested electrical energy, 4 kWh of thermal energy is received (=400% efficiency). The COP can be calculated according to formula's that are based on the first law of thermodynamics:

$$Q_{EFF}= Q_{IN} + W \qquad [7.05]$$

&

$$COP = Q_{EFF} / W \qquad [7.06]$$

where

Q_{EFF}	*Effective energy [Watt]*
Q_{IN}	*Incoming energy [Watt]*
W	*Electrical investment energy [Watt]*
COP	*Coefficient Of Performance [-]*

If it is known what the required temperature of the outgoing medium must be and what the temperature of the incoming medium is, the theoretical maximum efficiency (i.q. the Carnot efficiency) of a heat pump can be calculated:

$$COP_{MAX} = 0.5 * T_{HIGH}.K / (T_{HIGH} - T_{LOW}) \qquad [7.07]$$

where

0.5	Efficiency of the heat pump machine, 50%
$T_{HIGH}.K$	Lowest temperature of the evaporator
T_{LOW}	Highest temperature of the compressor

If the heat pump upgrades the source temperature from, for example, -10°C to +35°C, then the evaporator temperature should be below the -10°C and the compressor temperature above 35°C. You always need a temperature difference to facilitate heat transfer.

For determining T_{HIGH} and T_{LOW} , you could expand the temperature jump of the heat pump by 5°C in both directions, so the jump in this example would become -15°>+40°C.

$$T_{HIGH}.K = T_{MEDIUM\_OUT}.K + 5° \qquad [7.08]$$

&

$$T_{LOW}.K = T_{MEDIUM\_IN}.K - 5°C \qquad [7.09]$$

where

T_{MEDIUM_OUT}	Temperature incoming medium, [K]
T_{MEDIUM_IN}	Temperature outgoing medium, [K]

Formula 6.3 shows that the COP will rise if the temperature jump gets smaller.

COP to SCOP/SPF
The COP is the theoretical maximum efficiency of the heat pump and represents a performance that in practise is not very often achieved. A more realistic factor is the SCOP, or SPF (Seasonal COP / Seasonal Performance factor). Included in this factor are the auxiliary electricity for pumps + ventilator and the dynamic temperature of the incoming medium. Usually this source temperature is seasonal dependant and may in- or decrease, especially when the outside air forms the thermal source of the pump.

It varies per machine, situation and geographical location how to convert the COP to SCOP precisely. For general calculations, a reduction of 0.3 - 0.7 should give a rough estimation of the SCOP.

$$SCOP = COP - [0.3>x<0.7] \qquad [7.10]$$

Calculation of the SCOPs

There are 4 heat pumps (A, B1&2 & C) added to the local energy grid to keep the system running and in balance. The SCOP of the pumps is calculated by applying formula 7.05-7.10:

Heat pump A - Greenhouse Heat pump

Function: This pump upgrades the energy of the ground water that is stored in the aquifers. This heat pump is only activated during the winter months, when there is heating required in the greenhouse.

- Type: water-water;
- Months active: okt-mar;
- Temperature jump in practise: 26°C > 35°C;
- Temperature jump for calculation: 26°C>35°C;
- Source: Thermal energy stored in aquifer. Water is pre-heated by supermarket waste heat;
- SCOP reduction: 0.3, this heat pump is not affected by the season.

1. T_{HIGH} = 308 + 5 = 313K [7.08]
2. T_{LOW} = 299 -5 = 294K [7.09]
3. COP_{MAX} = 0.5* (313/ (313 - 294)) [7.07]
   COP_{MAX} = 7.9
4. SCOP = 6.6 - 0.3 = **7.9** [7.10]

Heat pump B1 & B2 - Dwelling heat pumps

Function: These heat pumps increase the temperature of the warm water that is extracted from the aquifer or from the greenhouse to 50°C (space heating system) or 65°C (domestic water).

- Type: water-water
- Months active: jan-dec
- Temperature jump in practise: ~25°C- 26°C > 65°C/ 50°C
- Temperature increase for calculation: 25°C>60°C/50°C in summer, 26°C>60°C/50°C in winter;
- Source: warm water flowing from the greenhouse & hot water stored in the aquifer.
- SCOP reduction: 0.3.

SCOPs heat pumps, overview:

- Domestic water - summer/winter= 3.5/3.5
- Space heating - summer/winter= 4.4/3.5

Example calculation: domestic water - summer
(Temperature jump = 25°C > 60°C)

1. T_{HIGH} = 333 + 5 = 338K [7.08]
2. T_{LOW} = 298 -5 = 293K [7.09]
3. COP_{MAX} = 0.5* (338/ (338- 293)) [7.07]
   COP_{MAX} = 3.8
4. SCOP = 3.8 - 0.3 = **3.5** [7.10]

Heat pumps in system

Heat pump C - Buffer heat pump

Function: This pump guarantees the water in the energy buffer remains on a temperature of 30°C

- Type: water-water;
- Months active: October - March
- Temperature jump in practise: 20°C-25°C > 30°C;
- Temperature jump for calculation: 20°C>30°C;
- Source: warm exit water that leaves heat pump B;
- SCOP reduction: 0.3.

1. $T_{HIGH} = 303 + 5 = 308K$ [7.08]
2. $T_{LOW} = 293 - 5 = 288K$ [7.09]
3. $COP_{MAX} = 0.5 * (308 / (308 - 288))$ [7.07]
   $COP_{MAX} = 7.7$
4. SCOP $= 7.7 - 0.3 = \mathbf{7.4}$ [7.10]

Figure 7.15: The effect of heat pumps.
In this graph it become quickly visible how much of the thermal energy demand of the greenhouse and the dwelling comes from the source and how much is actually invested electrical energy. This invested electrical energy is the difference between the light and the dark colours in the graph. The general rule is: the smaller the difference, the less invested electrical energy and the smaller the environmental impact of the system. This does of course also mean that more energy should be stored in the underground energy storage to still meet the demands.

Figure 7.16 shows all three heat pumps that are used in the new energy system. Note: the energetic values that are shown are based on the final design of the energy system (§7.9)

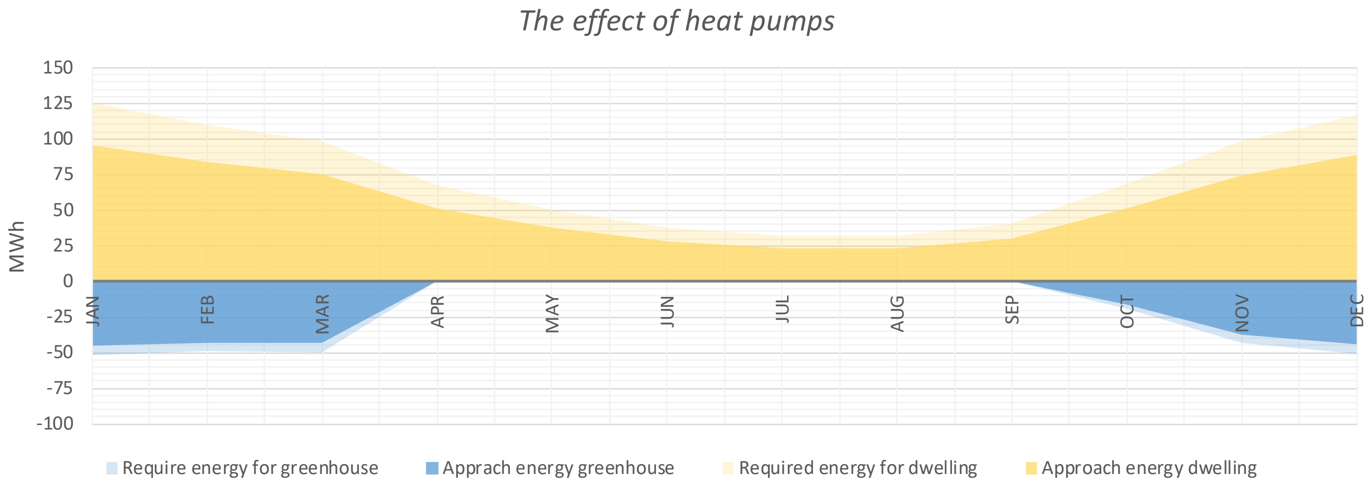


Figure 7.15: Heat pumps allow for less thermal energy storage in the system (at the cost of electrical energy).

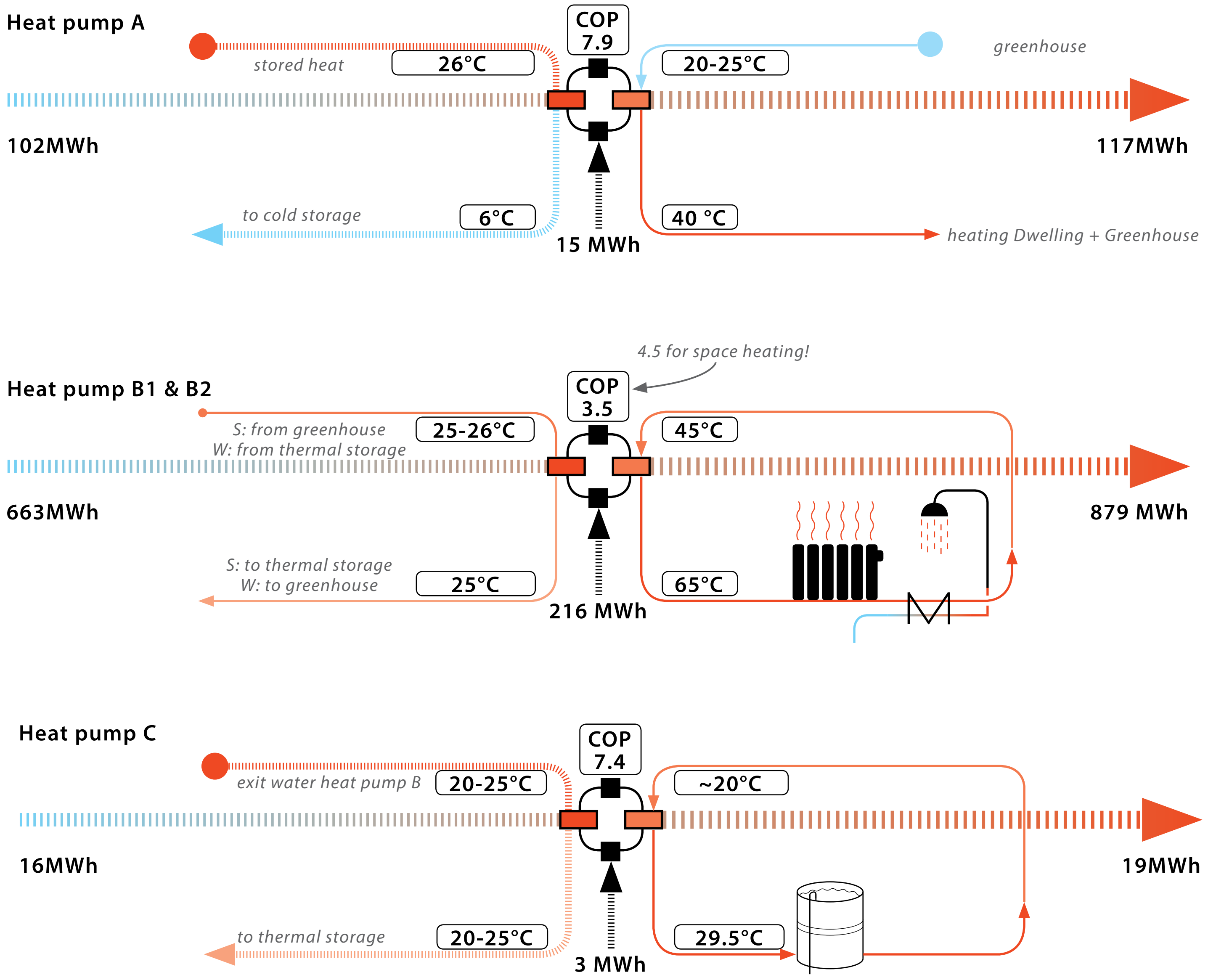


Figure 7.16: Visual representation off all the heat pump included in the energy model

7.4.4 | Lidl: heat recovery

system elements & connections

Current situation

Due to the high internal loads, the supermarket has a -seasonal affected- cooling demand throughout the full year, see figure 7.17. Peak cooling of around 450 kWh/day is found in July and August where February shows only 265kWh. If we look at the daily energy balance of the supermarket (§5.3.2), we find that there is an increased demand during opening hours and the customer occupation is clearly visible during peak hours.

At this point, supermarket HVAC systems cool the sales area to compensate for the heat that emitted by the product cooling units. This is a direct consequence of the recent year trend of placing glass doors in front of cooling displays. Before this intervention, the cold coming from the cooling machines compensated for the heat emitted by the compressor from the back of the refrigerator. Now that this cold is kept inside the machine, the HVAC system needs to work harder in order to control the supermarket temperature. It is very important that the indoor temperature remains below a certain set-point temperature to avoid condensation on the before mentioned glass doors. Currently, the most energy efficient solution is to only locally cool down the supermarket. In practise, this means a cold breeze is aimed at the refrigerator glass or all the cooling units are clustered in a separate low-temperature section in the supermarket.

During an interview with the Lidl it became clear the cooling furniture, so called plug&go machines, extract their cold from the same condenser roof unit as the HVAC. This is acknowledged by the research of Arias (2005,p.105). Heat from the compressor however, is exhausted directly into the supermarket area, explaining the high internal heat gain.

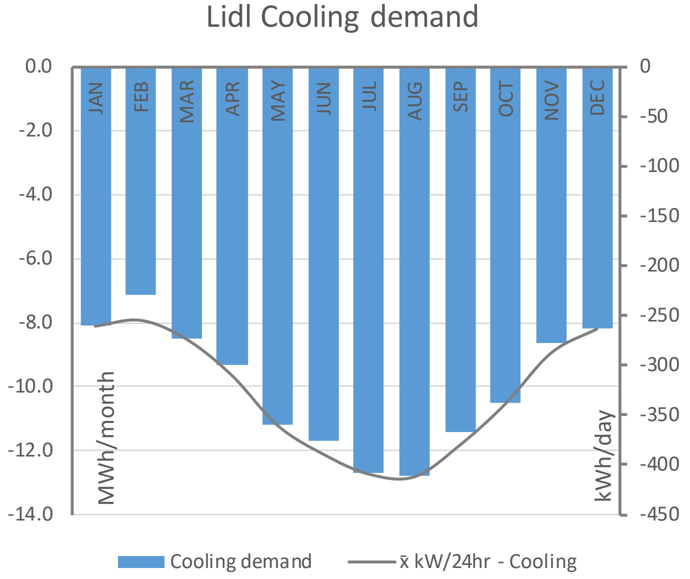


Figure 7.17

Heat recovery

There is already a small number if projects (e.g. Lidl Huizen and Coop (Jans, 2015)) where rejected heat from the cooling units is used. Methods of heat recovery can vary according to the heat demand, system design and project. One method is drawn in figure 7.18 (adapted from Arias, 2005). A bypass is added between the chiller and the dry cooler. The energy carrying medium in the bypass has a temperature of around 36°C (varies per system), but always much higher then the temperature of the water pumped up from the aquifer (16°C). Through an heat exchanger (n=50%), the temperature of the approach water is pre-heated before it enters the heat pump. This raises the SCOP of this heat pump by 0.6, subsequently making the whole system consume much less electrical energy. See the calculations.

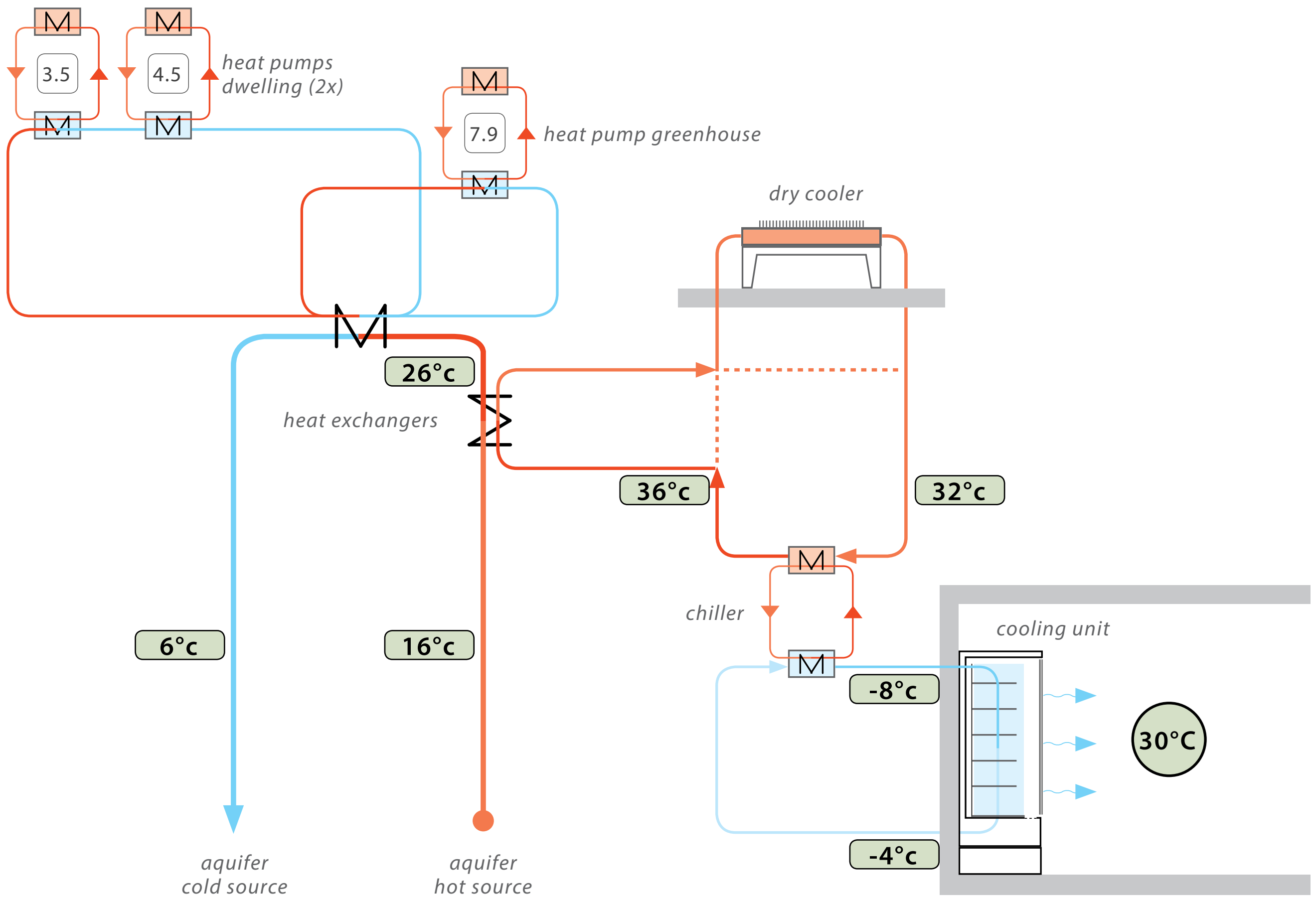


Figure 7.18: Supermarket waste heat pre-heats the approach water of the main heat pump = COP increase (adapted & altered from Arias, 2005)

COP dwelling heat pump: without pre-heating of the approach water by supermarket rejected heat;

T_{EXIT} = 65°C (338K), T_{APPR} = 16°C (289K)

$T_{HIGH}.K$ = 338°K + 5°K = 343K [7.08]
$T_{LOW}.K$ = 289°K - 5°K = 284K [7.09]
COP_{MAX} = 0.5* 318/ (318- 284) = 2.9 [7.07]
SCOP = 2.9 - 0.3 = 2.6 [7.10]

COP main heat pump: with pre-heating of the approach water.

T_{EXIT} = 65°c (313K), T_{APPR} = 26°C (299K), eff. heat exchanger = 50%

T_{APPR} = (16°C + 36°C) * 50% = 26°C

$T_{HIGH}.K$ = 338°K + 5°K = 343K [7.08]
$T_{LOW}.K$ = 299°K - 5°K = 294K [7.09]
COP_{MAX} =0.5* 343/ (343- 294) = 3.5 [7.07]
SCOP = 3.5 -0.3 = **3.2** [7.10]

<u>Delta SCOP = 3.2 - 2.6 = 0.6</u>

7.4.5 | Cooling of the greenhouse

system elements & connections

Greenhouse cooling - overview

In summer, cooling of the semi-closed greenhouse is realized by the following measures:

- *Floor cooling:* The leading method of controlling the indoor temperature is by means of floor cooling. Cold water, retrieved from the cold water storage in the underground aquifers is pumped through the floor, where it absorbs the surplus thermal energy, subsequently cooling down the space.
- *HVAC - Latent cooling (adiabatic / evaporative cooling)*: Air treatment: greenhouse air is circulated pass a (de)humidification unit. Depending on the current relative humidity in the greenhouse, the ventilation air will be pre-humidified to allow to adiabatic cooling. Done properly, this form of cooling has much more effect compared to merely sensible cooling. Due to the evaporative rate of the crops and the varying indoor greenhouse temperature, the humidification process is very complicated and dynamic process and calculating/ simulating it goes beyond the scope of this research. More in §7.4.7.
- *Window shades and screens:* This blocks out the sun and stops the solar load from heating the room. However, it also means that daylight is blocked out, which is essential for the metabolic activities for the plant.
- *Natural ventilation*: The is the last resort method to control the indoor temperature. Only if the designed cooling system can no longer cope with the peak solar loads, the greenhouse shall open up to allow for the heat to escape. Since this goes at the cost of the precious CO_2 concentration, this is a last resort option.

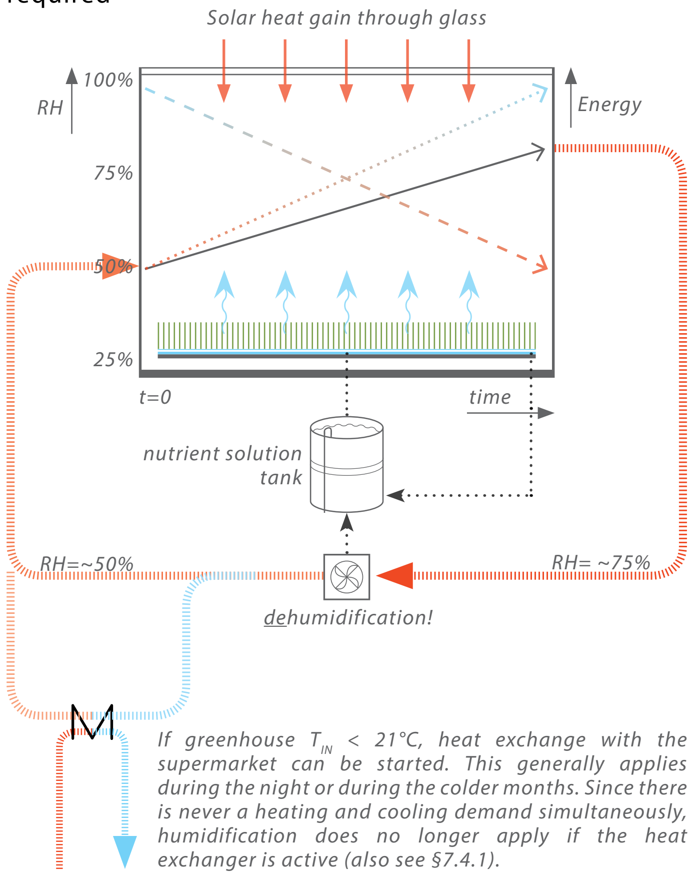
Adiabatic cooling

Adiabatic cooling by means of evaporative cooling is an efficient way to bring down the temperature in a closed greenhouse. The evaporation of water costs a lot of energy, which is extracted from the warm air. Water is added to the air in the form of fog, making it easy for it to evaporate. The relative humidity (RH) in the greenhouse will increase while the energy content remains equal. In other words, sensible energy is converted into latent energy, making water a powerful cooling medium. This cooling method is most effective in dry regions, when the RH difference is large and more energy can be extracted from the air.

Situation A, figure 7.19 - In a closed greenhouse, the RH can already be very high due to the natural evaporation of plants. This means there is barely any potential room available to increase the RH further by means of mechanical evaporation, as the saturation point will be reached rather quick. If this is the case, the air from the greenhouse should be mechanically dehumidified to make room for more natural evaporative cooling. Remember: since this is a closed greenhouse system, simply adding dry outside air is not an option! The moist retrieved from the air can be circulated back into the nutrition solution.

Situation B, figure 7.20 - If the plants show barely any natural evaporation, for example before germination or when the plants are still very small, mechanical evaporation can be activated to cool down the greenhouse air. Again: evaporative cooling in a closed space is only possible until the saturation point is reached.

Situation A:
Plant evaporation is <u>sufficient</u>: dehumidification is required



If greenhouse T_{IN} < 21°C, heat exchange with the supermarket can be started. This generally applies during the night or during the colder months. Since there is never a heating and cooling demand simultaneously, humidification does no longer apply if the heat exchanger is active (also see §7.4.1).

Figure 7.19

Situation B:
Plant evaporation is <u>insufficient</u>: humidification is required

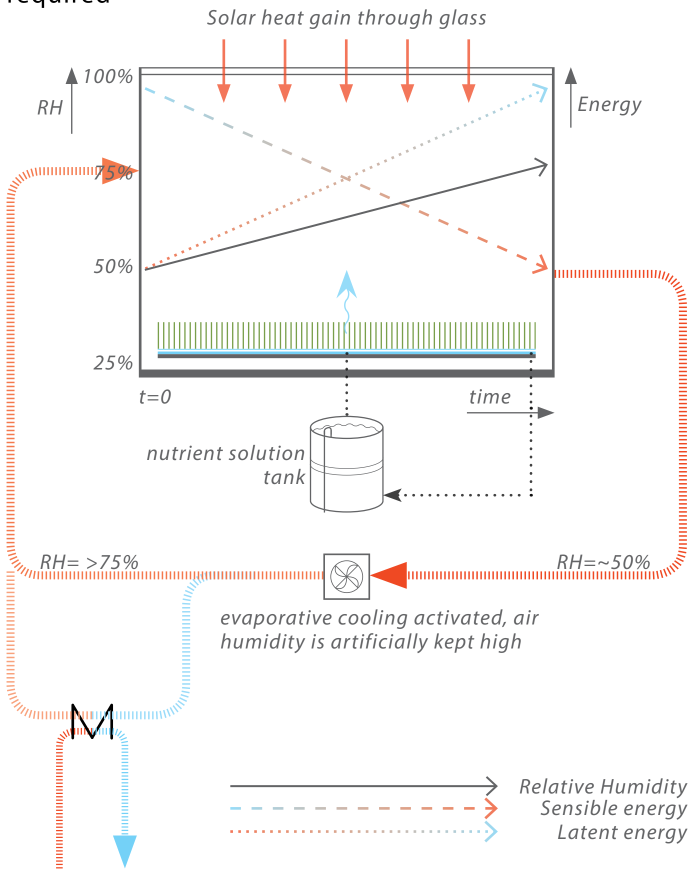


Figure 7.20

In practise, narrowly controlling the greenhouse RH is a complicated challenge as many internal and external factors influence the relative humidity. No further calculations on evaporative cooling are done in this research and the cooling method remains theoretical.

7.5 | Heating & cooling demand: new

all components on maximum capacity + inter-component energetic connections

New HC-demand curve

The following energetic measures have been integrated in the energy system to reduce the cumulative heating or the cooling demand:

- greenhouse operating as a solar collector;
- §7.4.1: supermarket <> greenhouse heat exchange;
- §7.4.5: reeuse of rejected heat supermarket;
- §7.4.3: Integration of heat pumps.

Figure 7.6 shows again the HC demand of the system at maximum component capacity. Figure 7.21 shows the new monthly HC demand, after establishing inter-component connections. Figure 7.22 illustrates how much thermal energy is stored and retrieved in/from the aquifer every month and shows the cumulative storage and consumption over the course of the year.

To much energy

On an annual basis, there is an energy surplus of 16 MWh (figure 7.22), this is including a safety factor of 10% on top of the calculated heat monthly heat demand. In the final design for the energy system, this oversupply needs to be diminished all the way to zero. Only then a system balance is obtained.

An underground energy storage system that receives to much energy suffers from an increasing mean underground temperature throughout the years. This leads to an unbalanced aquifer and makes it from a certain moment unsuitable for cooling purposes.
In §7.7.1 & 7.7.2 the system is scaled & altered in such a way, that balance is obtained.

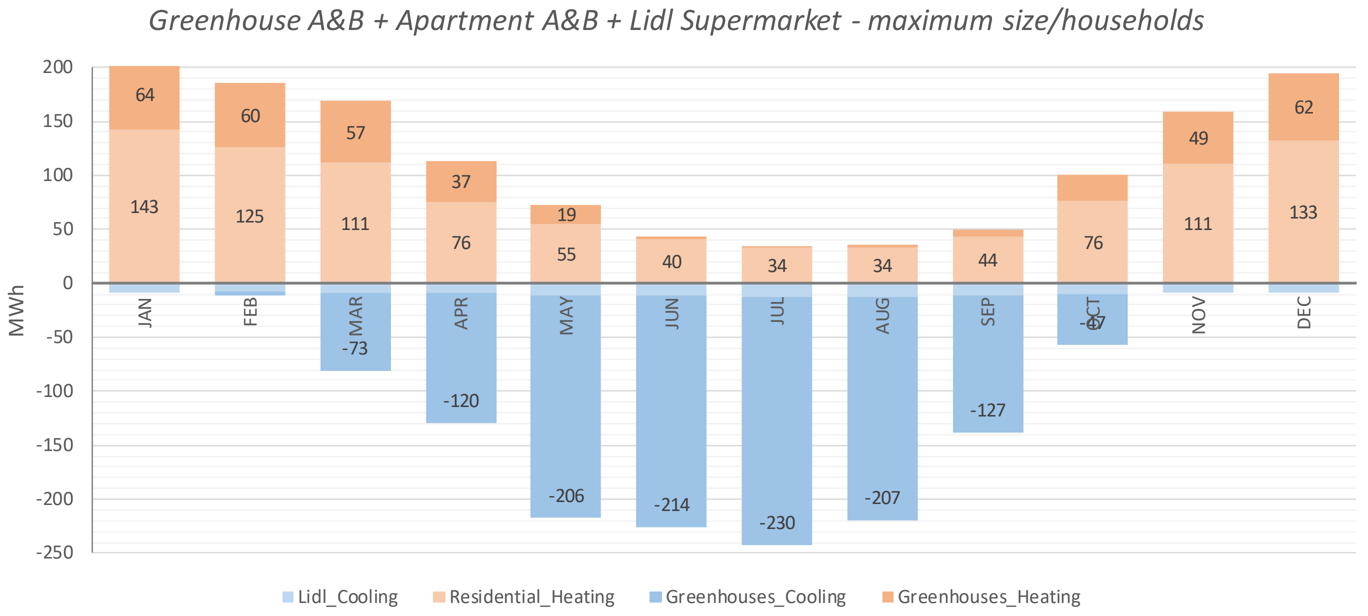


Figure 7.6: Heating & Cooling demand energy system at maximum component capacity

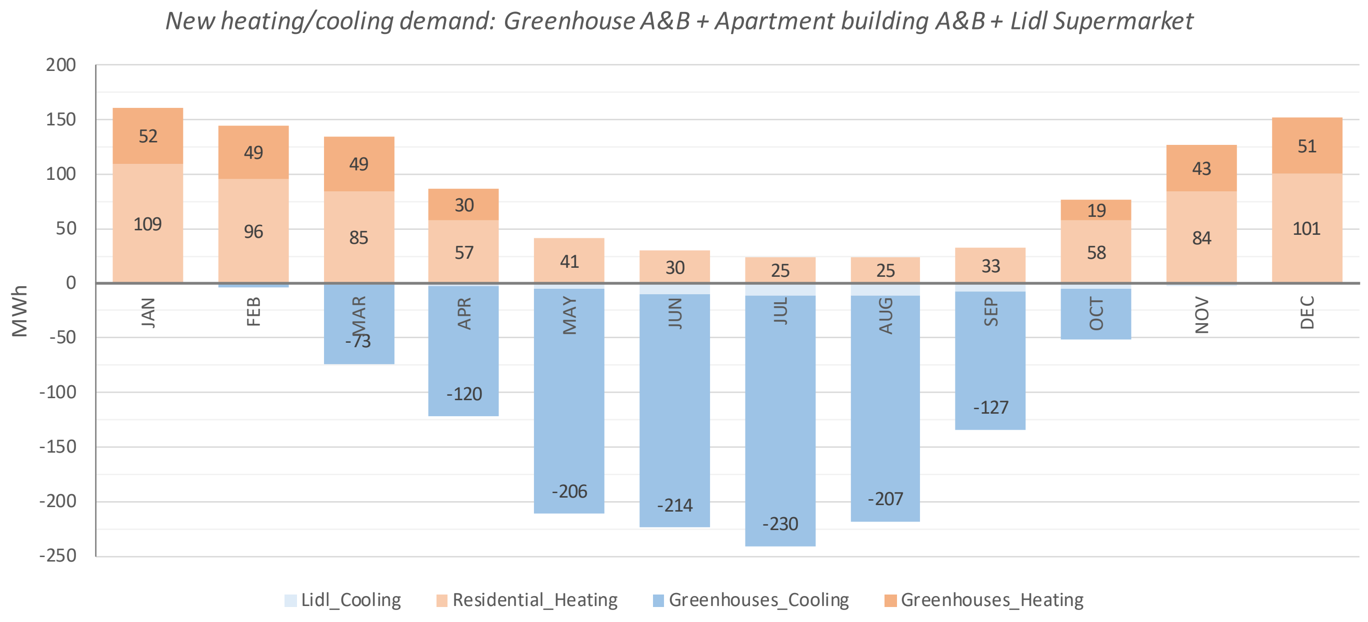


Figure 7.21: Monthly thermal energy stored/retrieved in/from underground aquifer + yearly cumulative storage/use

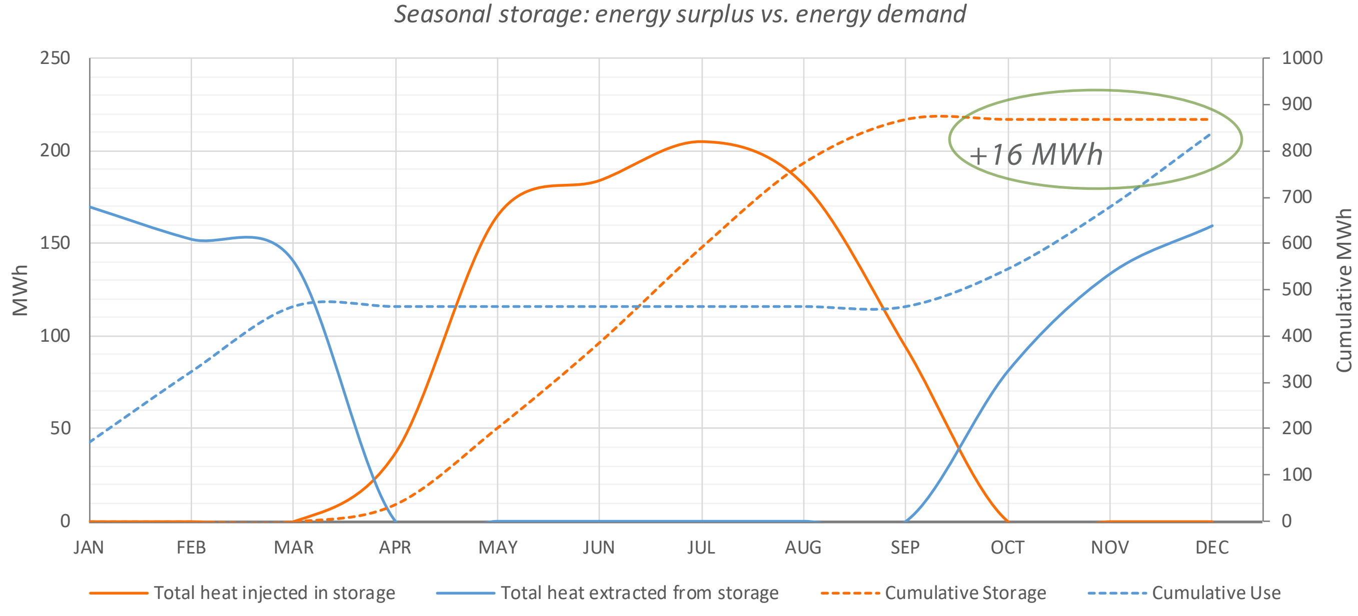


Figure 7.22: Monthly thermal energy stored/retrieved in/from underground aquifer + yearly cumulative storage/use

7.6 | Heating & cooling demand: Balance

all components on maximum capacity + energetic connections

Conclusion

Required annual heat storage *= 762 MWh*
+Safety factor, 1.1 *= 838 MWh*
Current available energy *= 855 MWh*
Current oversupply
855 MWh - 838 MWh *= +16 MWh!*

The graphs, the overview and the calculations point out that on an annual basis, there is a thermal energy oversupply of 16 MWh (including safety factor of 10%). All this extra thermal energy also puts more demand on the greenhouse cooling system, thus increasing the electrical energy consumption. An oversupply of this magnitude unbalances the ground temperature in the aquifers, leading to increasing temperatures and making cold storage in the earth at some point impossible.

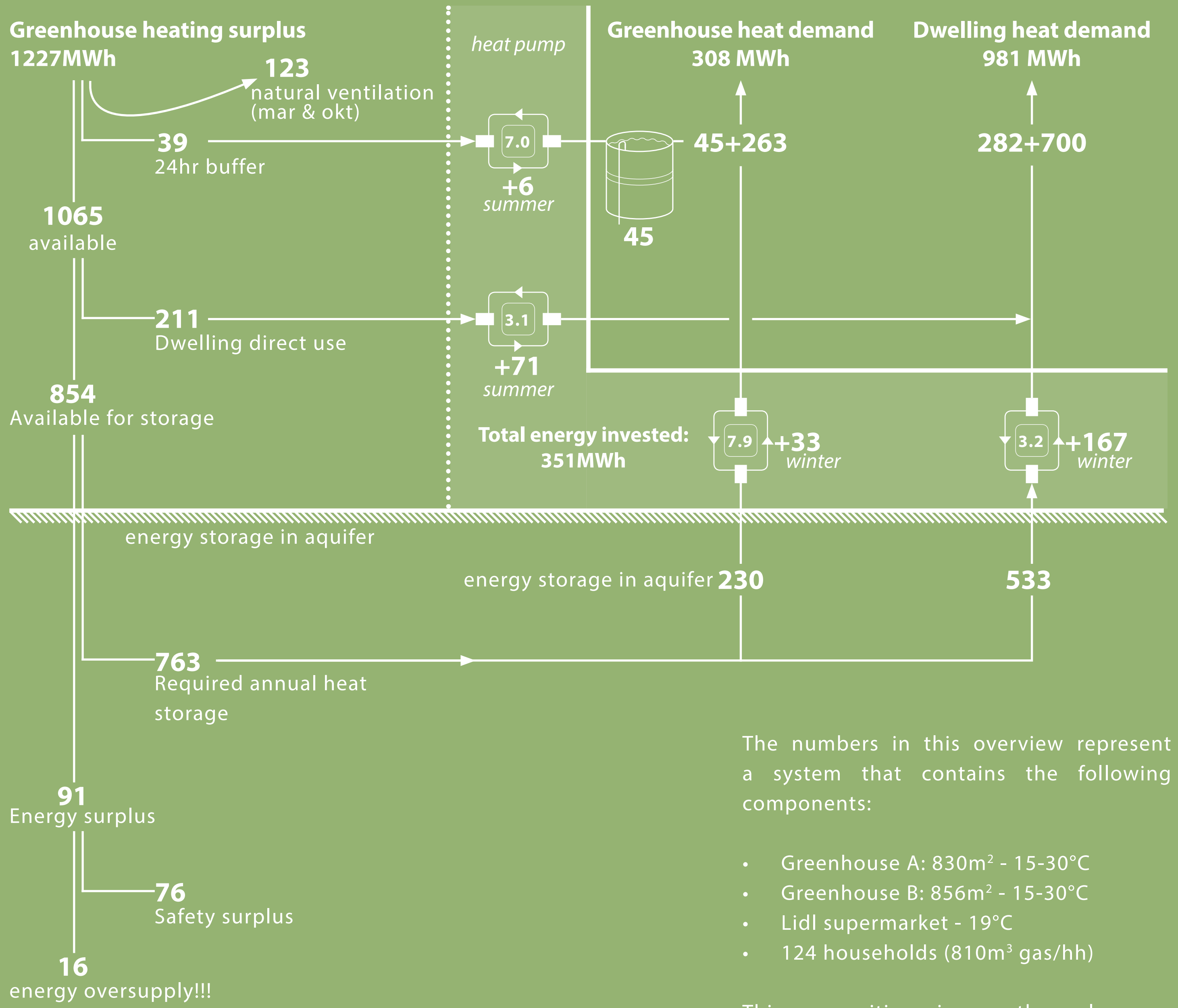
There are five profound alterations that can be made to the system to reduce this oversupply:

1. Change the parameters. Raise the maximum or/and minimum indoor temperature of the greenhouse to lower the cooling load and by that the energy oversupply. Quick calculations point out that if the indoor temperature range shifts from 15-30°C to 15-34°C, the desired energy surplus is reached. However, this stretches the acceptable maximum indoor temperature for tomato production to its limits and narrows down any safety margins. In addition to this, the temperature of the working environment of the greenhouse caretakers becomes at issue.
2. Change the facade properties. Lowering the g-value would mitigate the solar heat gain, this would however reduce the metabolic rate of the crops.
3. Rely more on natural ventilation and reduce the pressure on the HVAC system. The switch to opening up windows can be made earlier on the day. This is already a last choice cooling method because the greenhouse is a semi-open type. It would not be the right solution to mitigate the oversupply of energy at the cost of valuable CO_2 concentration.
4. Increase the heat demand of the total system and bringing it back into a balance. Could theoretically be done by adding a component with an annual heat demand of 16 MWh and no cooling demand, like another residential building. This solution would be most in line with the overall concept of this research: reducing the cumulative energetic footprint of the building block by having different functions work together. Adding an extra component to the local grid that relies on the oversupply of thermal energy would greatly benefit the efficiency of the concept. However, quick analysis of the city block does not reveal any convincing residential building besides the two that are already in the system. Without further and more accurate case research, this option is cannot be applied.
5. Reduce the size of one of the greenhouses. Greenhouse HC-demand relate to each other in a ratio of approx. 1:3 (annually). Making one of the greenhouses smaller would reduce the cooling demand much more then the heating demand, thus bringing the system in balance.

Option 1 and 5 are researched by calculations in the next paragraph.

New energy system - annual numbers

values are in MWh - small round-off errors can occur - heat is stored from apr-sep (summer system)



The numbers in this overview represent a system that contains the following components:

- Greenhouse A: 830m² - 15-30°C
- Greenhouse B: 856m² - 15-30°C
- Lidl supermarket - 19°C
- 124 households (810m³ gas/hh)

This composition gives an thermal energy oversupply of 15 MWh

7.7.1 | Alternative system composition: Option 1

Balancing the system

Parameters

red: changes relative to starting system

greenhouse

T_{IN} min	was 15°C, remains 15°C;
T_{IN} max	was 30°C, remains 30°C;
g-value glass	was 0.6, remains 0.6;
U-value glass	was 2.7, remains 2.7.

Lidl

Mean Indoor T	was 19°C, remains 19°C

Components

- Greenhouse A | 10.8m x 78.8m (gfa 851m²);
- Greenhouse B | 8m x 102m (gfa 816m²);
- Lidl Supermarket;
- Apartment building A | 44 households;
- Apartment building B | 77 households.

Production

food production:

Greenhouse A:	Remains 3402 plants
Greenhouse B:	
gfa = 8x100	= 640m²
pfa = 5.6x91m	= 510m²
83 tables, 130 gutters	= ~2988 plants (-7%)
Total number of plants	= ~5706 (-3%)

energy

- Gross roof area available for PV-system: 958m²
- This equals 115 MWh/y

Energy

greenhouse

Annual heating demand:	301 MWh
Annual cooling demand:	1199 MWh
Lidl cooling demand:	56 MWh
Dwelling heating demand:	981 MWh

energy storage

Annual thermal energy stored:	831 MWh;
Annual thermal energy extracted:	833 MWh;
Annual safety surplus (10%)	76 MWh;
Under-/over supply energy:	-2 MWh. (excellent)

heat pumps

Electricity demand heat pump A:	33 MWh;
Electricity demand heat pump B1:	159 MWh;
Electricity demand heat pump B2:	80 MWh
Electricity demand heat pump C:	6 MWh;
Total:	278 MWH.

Figure 7.23 displays how this energetic composition is in a balance.

A priori
The primary goal is to extract enough heat from the greenhouse in summer (the collector), to provide for the two apartment buildings and the greenhouse in winter. While doing this, the underground energy storage should remain in balance:

heat infiltrated summer + cold extracted summer
=
heat extracted winter + cold infiltrated winter

If all the components are combined on their maximum size while the parameters remain unchanged, there is an energy oversupply of 16 MWh (heat). The target is to nullify this oversupply with adjustments to the system.

It does not require radical interventions to nullify an oversupply of just 15 MWh. Small alterations to the system/parameters make it possible to achieve this balance. In this option, greenhouse B is made 5 meters shorter to reduce the heat gain.

In option 1, all the parameters remain the same but the size of greenhouse B is reduced. We know that the HC demand ratio of a greenhouse with T_{IN}= 15-30 is roughly 1:3 (annually). Scaling down the length of the greenhouse leads to a decrease of cooling demand 3 times faster then the heat demand decreases. If the size of Greenhouse B is reduced to 8 x 102meters, the overall energy system is brought into a balance.

down sides

- This option goes at the cost of a small number of tomato plants (~-3%).
- Option B still requires two greenhouses with relative strict indoor climates. This doubles the investment and maintenance costs. It would be more attractive from an economical, structural and organizational perspective if the energy grid could be balanced out with just one greenhouse. This possibility is researched in option 2!

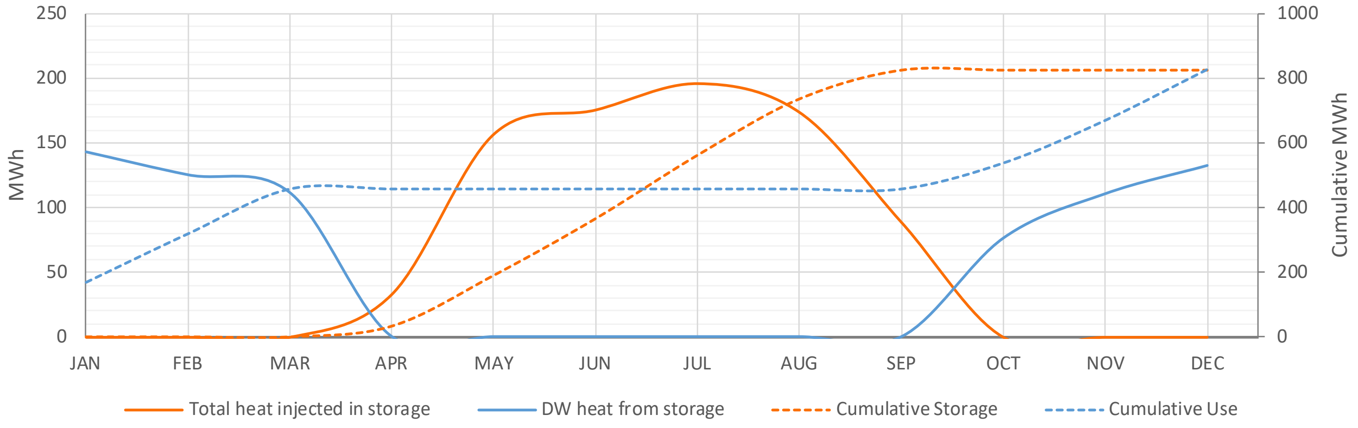


Figure 7.23: Energy storage option 1- Infiltrated heat and extracted heat, monthly amounts and the yearly cumulative demand.

7.7.2 | Alternative system composition: Option 2

Balancing the system

Parameters

grey/green: changes relative to option 1
red: changes relative to starting point

greenhouse

- T_{IN} min was 15°C, becomes 11°C;
- T_{IN} max was 30°C, becomes 27°C;
- g-value glass was 0.6, remains 0.6;
- U-value glass was 2.7, remains 2.7.

Lidl

- Mean Indoor T was 19°C, remains 19°C

Components

- ~~Greenhouse A | 10.8m x 78.8m (gfa 851m²);~~
- Greenhouse B | 8m x 107m (gfa 856 m²);
- Lidl Supermarket;
- Apartment building A | 44 households;
- Apartment building B | 49 households

Total: 93 households

Production

food production:

- Greenhouse A: Becomes 0
- Greenhouse B: Remains 3402

Total number of plants = 3402 (-49%)

energy

- Gross roof area available for PV-system: 1649m²
- This equals 195 MWh/y (+59%)

Energy

greenhouse

- Annual heating demand: 43 MWh (-85%)
- Annual cooling demand: 745 MWh (-38%)
- Lidl cooling demand: 56 MWh
- Dwelling heating demand: 563 MWh (-43%)

energy storage

- Annual thermal energy stored: 488 MWh; (-42%)
- Annual thermal energy extracted: 486 MWh; (-42%)
- Annual safety surplus (+10%) 44 MWh;
- Under-/over supply energy: + 2 MWh. (excellent)

heat pumps

- Electricity demand heat pump A: 5 MWh; (-82%)
- Electricity demand heat pump B1: 120 MWh; (-25%)
- Electricity demand heat pump B2: 60 MWh (-25%)
- Electricity demand heat pump C: 0 MWh; (-100%)
- Total: 185 MWH. (-34%)

Figure 7.24 displays how this energetic composition is in balance.

In this option, greenhouse A is completely abandoned from the energy system. This means there is less thermal energy collected in summer for the heating of rest of the system during winter. In other words: without a second greenhouse, there is to much total heating demand by the dwelling and greenhouse B left. To compensate for this, the indoor climate of greenhouse B becomes more intense: indoor temperature range shifts from 15°C-30°C to 11°C-27°C. Lowering the minimum temperature, lowers the heat request from the greenhouse during winter. Lowering the maximum temperature results in an increased cooling demand, which subsequently means more thermal energy storage.
Calculations point out that shifting down the temperature domain is still not sufficient to achieve a balance and the heat demand should be reduced even further. This is why 31 apartments of apartment building B are left out of the system. Now the system is in balance. Finally: lowering the minimal T_{IN} to 9°C also means that the 24hr thermal buffer for the months April-September becomes in theory obsolete. In practise, a thermal buffer will always be included as a safety backup.

pro's

- Leaving out greenhouse A opens up space to expand the PV-system. So both the energy demand decreases and the energy generation increases!
- One instead of two separate greenhouses requires much lest investment costs and is cheaper to operate and maintain.
- The logistics (pipes, channels, walkways, other installations) becomes less complicated and there is less interference with the existing adjacent structures.
- Water consumption reduces;

con's

- The total number of plants drastically reduces with ~50%, subsequently lowering the annual production yield and making the greenhouse less profitable. The payback time of the investment now gets twice as long;
- The capacity of the system reduces. If meteorologists predict the coming winter to be very long/cold, it becomes harder to anticipate and prepare the energy system by storing extra energy.

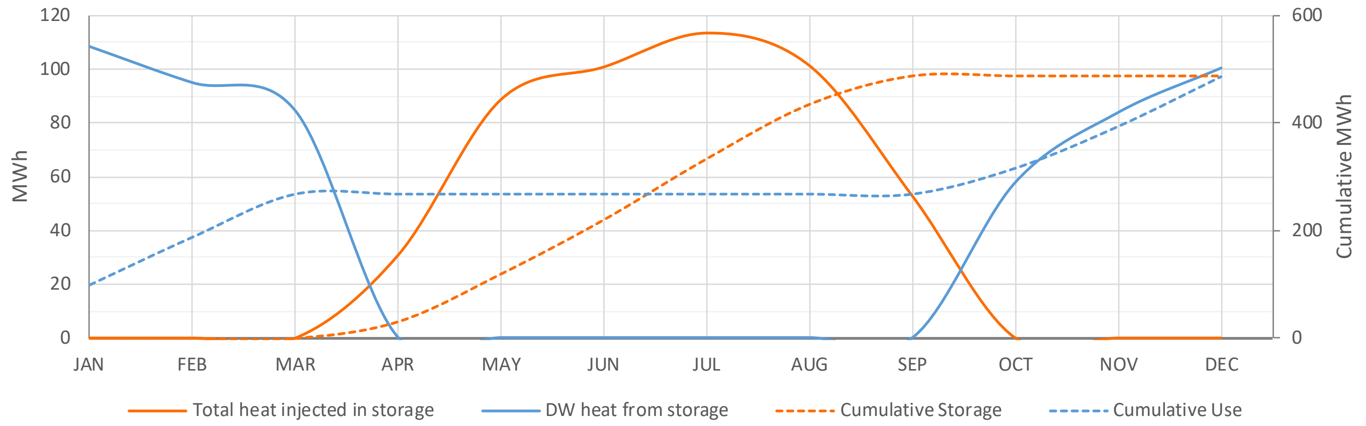


Figure 7.24: Energy storage option 2 - Infiltrated heat and extracted heat, monthly amounts and the yearly cumulative demand.

7.7.3 | Renovation & Improvements

93 households > 124 Households

In order to achieve a balanced underground energy storage whilst using just one rooftop greenhouse, the total number of included households is reduced to 109. This is an undesired decision and does not fit the research mentality nor does it make any sense to just include only a part of a building to the energy system. Concessions that somehow compromise the energy balance cannot be done and using only one rooftop greenhouse has the preference. The only alternative that remains, to get back to 124 households, would be to decrease the heat demand per household. Thermal energy saving interventions should be installed to mitigate the heating demand per apartment to such an extend, that 124 instead of 109 households can be connected the system. The system is in balance when:

- 93 households are included with a heat demand of 7900 kWh/year. This equals 810 m^3 gas/hh.
- 124 households are included with a heat demand of 6077 kWh/year. This equals 730 m^3 gas /hh (figure 7.26B)

This is a heat demand reduction of 33%/hh and can in theory be achieved with simple and relatively cheap energy saving interventions within the apartments. The right column mentions seven of these interventions. All interventions are easy to execute and do not require any radical changes to the structure of the building.

Figure 7.25 shows the plan of the standard apartment that can be found in apartment building B. The impact of the interventions is not calculated nor simulated. However, a reduction of minimal 33% is not unrealisticly high and it is safe to assume that this can be achieved with the mentioned upgrades.

Interventions

Building energy, see figure 7.25:

1. Install smart thermostats / boilers. Prevent over/under heating of the apartments due mistaken use or ignorance by the inhabitant(s).
2. Install smart / CO_2 controlled ventilation systems. Mitigate the heat loss due to over-ventilation;
3. After insulation at the inner surface of the exterior walls by means of a retention wall. According to Milieucentraal[1] , a retention wall can save of up to 9.5m^3 gas/m^2 outer wall per year. This would roughly be 76m^3 gas per year for this apartment (approximately 8m^2 of retention wall per apartment);
4. Add coating to the existing glazing. Adding a coating to an existing window is a relative easy and cheap intervention and can theoretically decrease the U-value from 2.8W/m^2.K to a value between 1.6 and 2.0 W/m^2.K. Additional study of the detailing might point that a completely new window + framework is much more effective and cost viable;

User related energy

5. Install a water conserving shower head. This is a very cheap and easy to install feature with a lot of energy saving potential;

Other

6. Installing a thermal buffer on the balcony in the shape of a private glazed space. From here, free heat can be retrieved for space heating in winter. The glass structure can be opened up in summer. This is a radical and costly intervention and the effect on this small scale is questionable. The intervention would however architecturally fit the overall city block upgrade with the rooftop greenhouse.
7. The rooftop greenhouse warms up the roof structure of the top floor apartments. So no more energy loss.

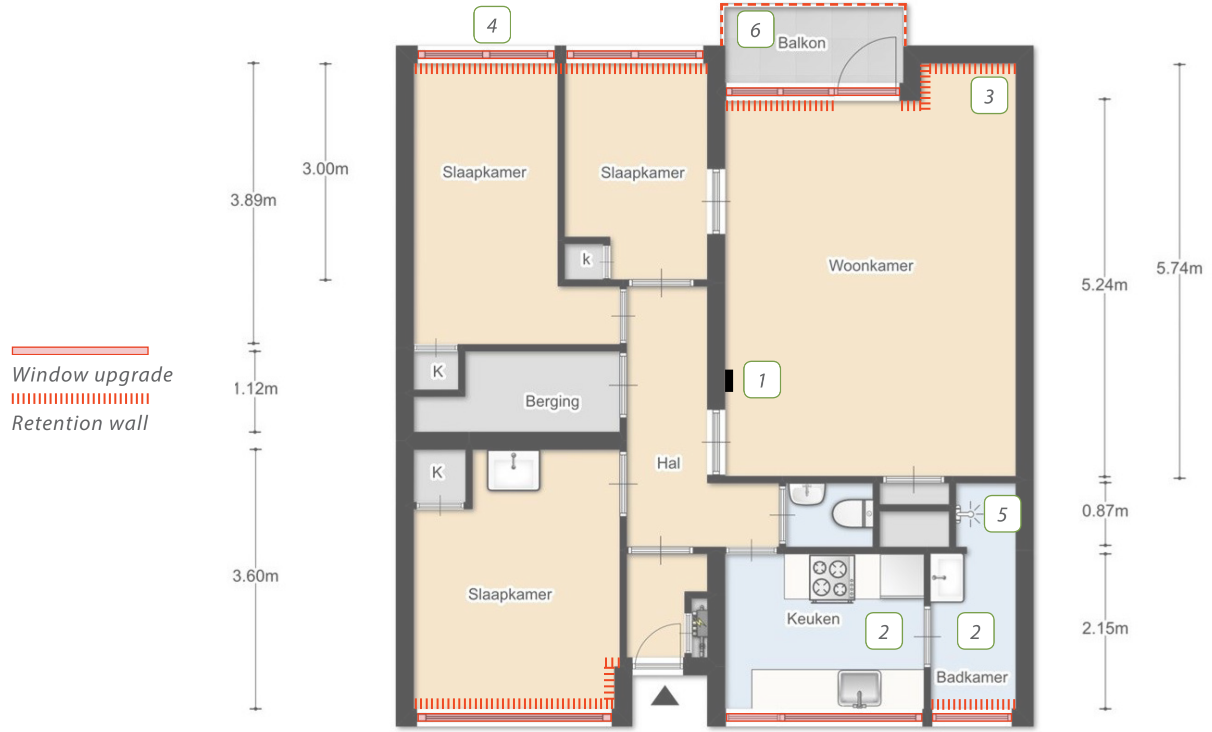


Figure 7.25: Plan of the Eerste Helmerstraat 18a (3rd floor). It is safe to assume this floor plan is repeated throughout the rest of the building, with exception of the ground and first floor. The illustration is retrieved from Funda.nl and made by droomhuis360.nl

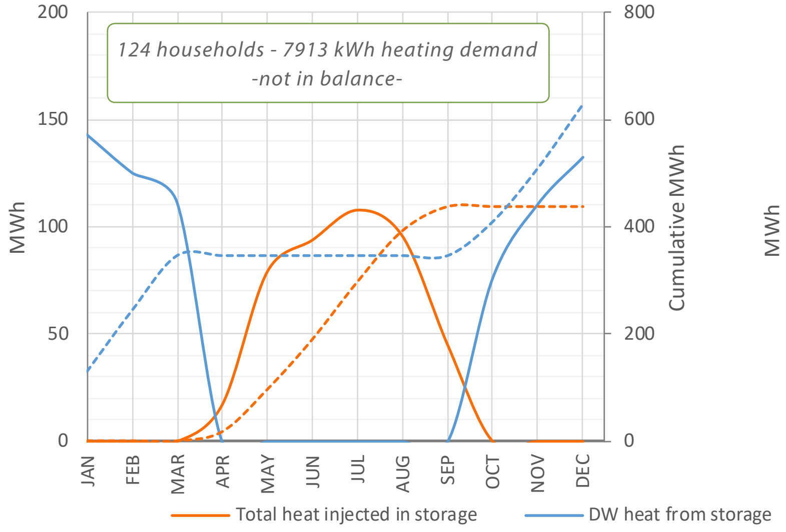


Figure 7.26A: No energy saving interventions applied.

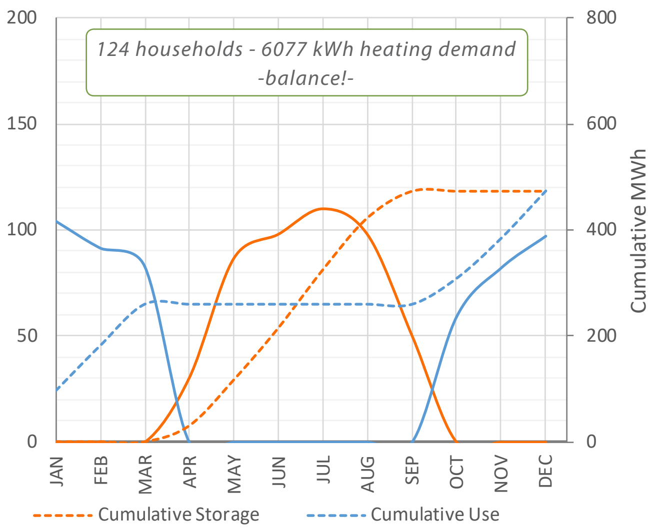


Figure 7.26B: Energy saving interventions installed.

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[1] https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/gevelisolatie-binnenkant/

7.8 | Heating & cooling demand: final

Conclusion: Option B

Required annual heat storage	*= 430 MWh*
+Safety factor, 1.1	*= 473 MWh*
Available energy	*= 472MWh*
Current oversupply/under-supply	
472 MWh - 473 MWh	*= -1 MWh*

The decision for option B comes forth out of the design though of this research:

Dwelling heat demand and supermarket heat surplus

=

Capacity of the system and determines the greenhouse indoor climate and size

Conclusion:

The energy design can be brought in balance with either two or one greenhouse(s). In this research, the system with one greenhouse is chosen. From an economic perspective, the major advantage of one greenhouse is half the investment and maintenance costs. From an energetic perspective the major advantage is the doubled available roof surface for the PV system. The disadvantages are: half the production capacity and a more intense greenhouse climate.

The scheme on the right page numerically visualises the energy system. It proves that the system is in an energy balance. Figure 7.28 shows the monthly energy that is stored in and retrieved from the energy storage plus the cumulative heat storage + heat extraction.

In the following paragraphs, the annual energy scheme and the summer- and winter system are presented.

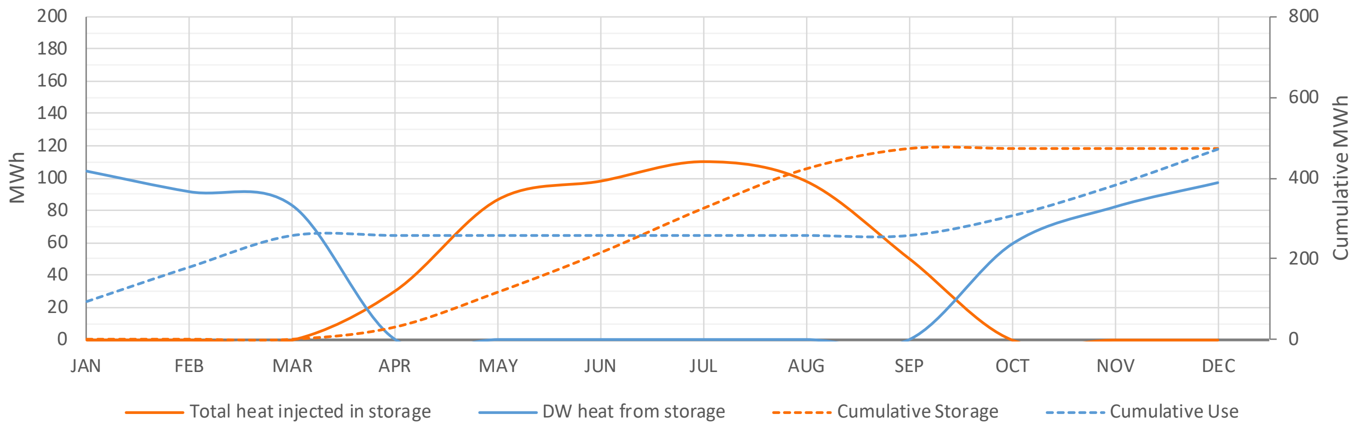
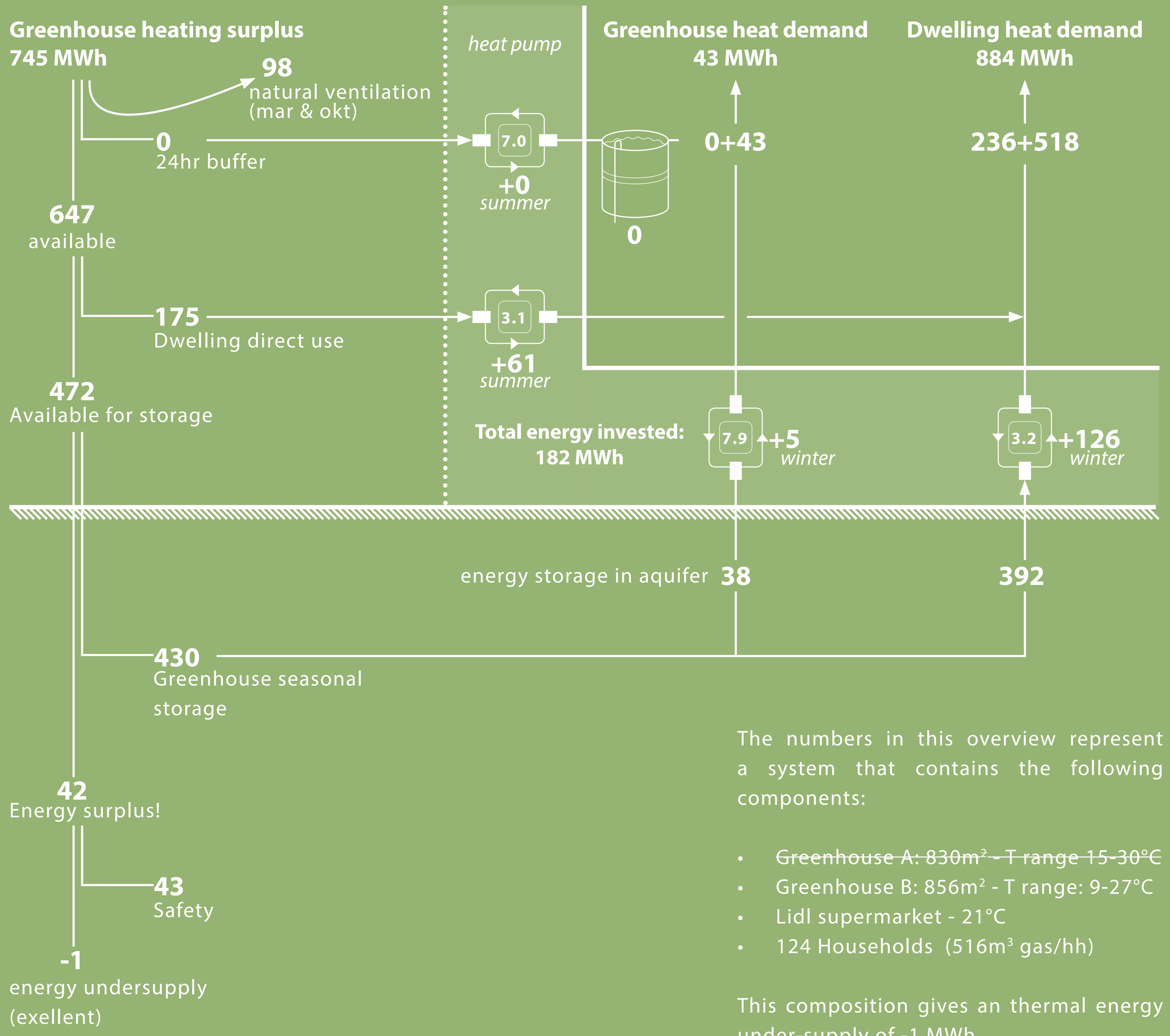


Figure 7.28: Monthly thermal energy stored/retrieved in/from underground aquifer + yearly cumulative storage/use > final energy system!

Final energy system - annual numbers

values are in MWh- small round-off errors can occur - heat is stored from apr-sep (summer system)



The numbers in this overview represent a system that contains the following components:

- ~~Greenhouse A: 830m² - T range 15-30°C~~
- Greenhouse B: 856m² - T range: 9-27°C
- Lidl supermarket - 21°C
- 124 Households (516m³ gas/hh)

This composition gives an thermal energy under-supply of -1 MWh

7.9.1| Final design energy model

Energy scheme - annual energy circulation

An energy balance

On an annual basis, the infiltrated heat+cold and the extracted heat+cold should be in balance. This keeps the ground temperature in the aquifer on it's initial level (~10-12°C) and keeps the storage suitable for future cooling purposes.

The heating demand of the two apartment buildings and the heating demand of the greenhouse during the winter months, determine the amount of energy that is extracted from the greenhouse. In other words, the heating demand determined the amount of active 'cooling' in the greenhouse. §7.7.2 & §7.8 shows that if the indoor temperature of the greenhouse is kept between 11°C and 27°C, the system is in balance.

At <11°C, floor heating will be activated. At >27°C, floor cooling will be activated and heat will be extracted from the greenhouse space to be stored underground.

The scheme on the right page shows how the energy 'circulates' between seasons and how the system relies on underground energy storage. The Lidl supermarket plays an supportive but very important role. Here, the energy retrieved from the greenhouse will be upgraded to a higher temperature before being stored underground. This upgrade is done by using the rejected heat from the cooling system of the supermarket (see §7.4.4). The cooling demand of the system is covered by the cold water of the Amsterdam canals (§7.9.2).

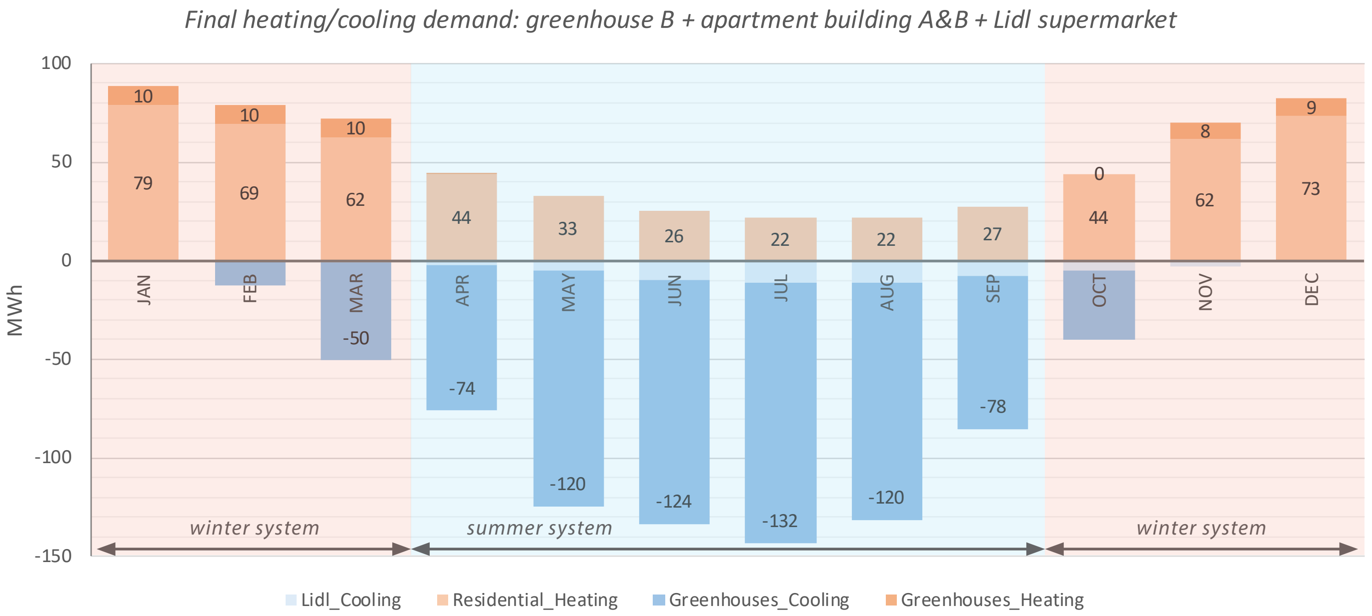
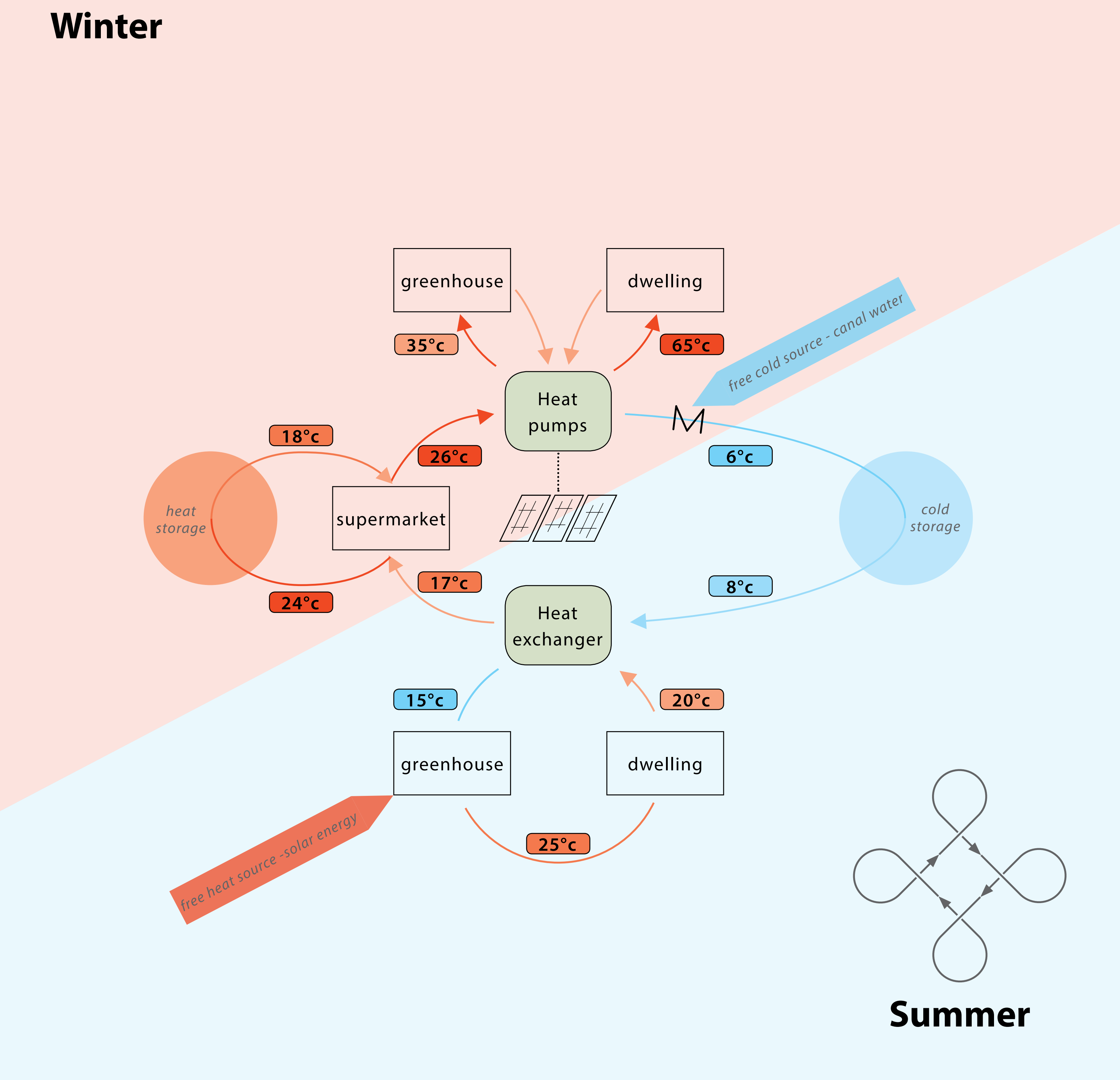


Figure 7.29: Final heating/cooling demand of all included components in the final system.



7.9.2 | Final design energy model

Energy scheme - summer system

Direction of the main system: cooling

During the summer months, the energy loop's main purpose is greenhouse cooling and dwelling heating.

Short term heating buffer

Sometimes during spring & summer, the outside temperature will drop below 11°C and heating is required in the greenhouse. Since it is not possible to reverse the whole energy system, the heating demand is then covered by a smaller thermal heat source: the short term thermal energy buffer. This buffer is charged during the day by the heat surplus of the greenhouse. A heat pump makes sure the temperature in this buffer remains around ~30°C.

Greenhouse<>Lidl energy exchange

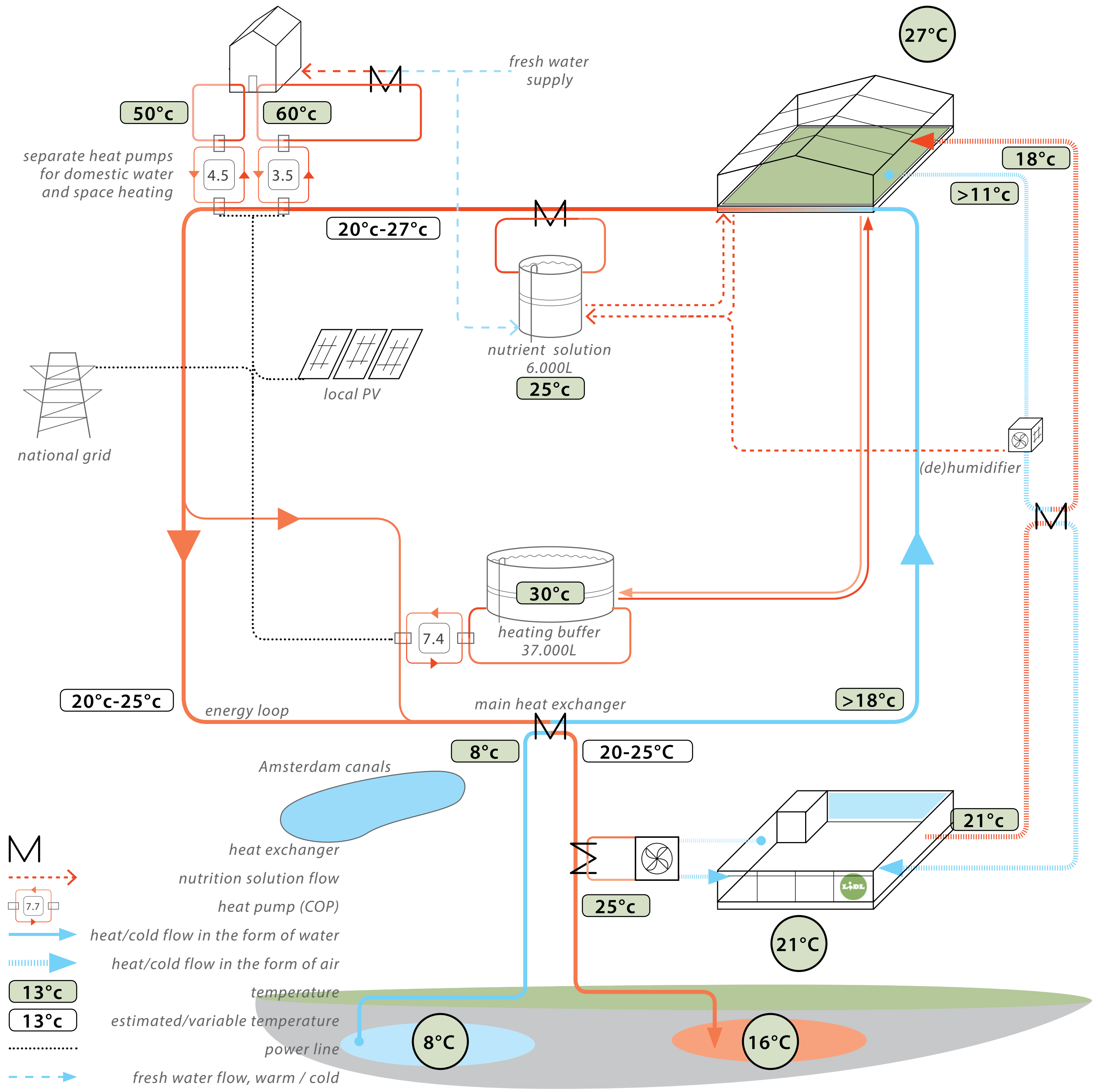
Now that the minimum temperature of the greenhouse is lowered from 15°C to 11°C, heat exchange with the Lidl is also becomes much more effective. The delta T increases from 3°C to 7.5° (exchanger n=75%), this leads to so much cooling power that during the cold months, cooling of the Lidl building is no longer required and the heating demand of the greenhouse is greatly reduced (§7.4.1).

The energy extracted to heat up the nutrient solution is neglectable in the bigger picture of the energy system.

The PV-system that is installed on the adjacent rooftops shall cover a large part of the heat pump electricity demand.

Charging the underground heat source

During the summer months, the greenhouse functions as the solar collector of the energy system. Cold water (§7.9.3), is pumped from the cold source where it will cool down the energy loop by means of an heat exchanger. The cold water in the loop cools down the greenhouse by extracting the heat from the concrete floor. Next, the warmed up water flows through the heat pump of the dwelling and then back to the central heat exchanger, where the solar heat is again exchanged with the source water. Before the warm water is pumped back into the heat source of the underground storage it will be preheated by the excess energy from the supermarket's product cooling system. The water is pumped back into the earth on a temperature of roughly ~24°C. Over the course of the following months, the temperature of the warm water storage will drop back to roughly ~16°C.



7.9.3 | Final design energy model

Energy scheme - winter system

Direction of the main system: heating

During winter months, the energy loop's main purpose is dwelling heating and greenhouse heating.

Warm storage water from the aquifer is pre-heated by the supermarket so it will approach the heat pump on a temperature of 26°C, this pre-heating increases the SCOP by 0.6 (§7.4.6). After the thermal energy is extracted, cold water is pumped back into the aquifer to charge the cold source.

Short term heating buffer
The thermal buffer is not in use when the winter system is active because the energy loop is already put in heating mode.

Greenhouse<>Lidl energy exchange
During the winter months, the effect of the energy exchange with the Lidl supermarket is even stronger due to the larger temperature difference.

Dwelling: two heat pump
Since there are two different temperature jumps (domestic hot water and space heating) , two individual heat pumps are connected to the energy loop. In practise, these two temperature rises will be covered by the same heat pump installation.

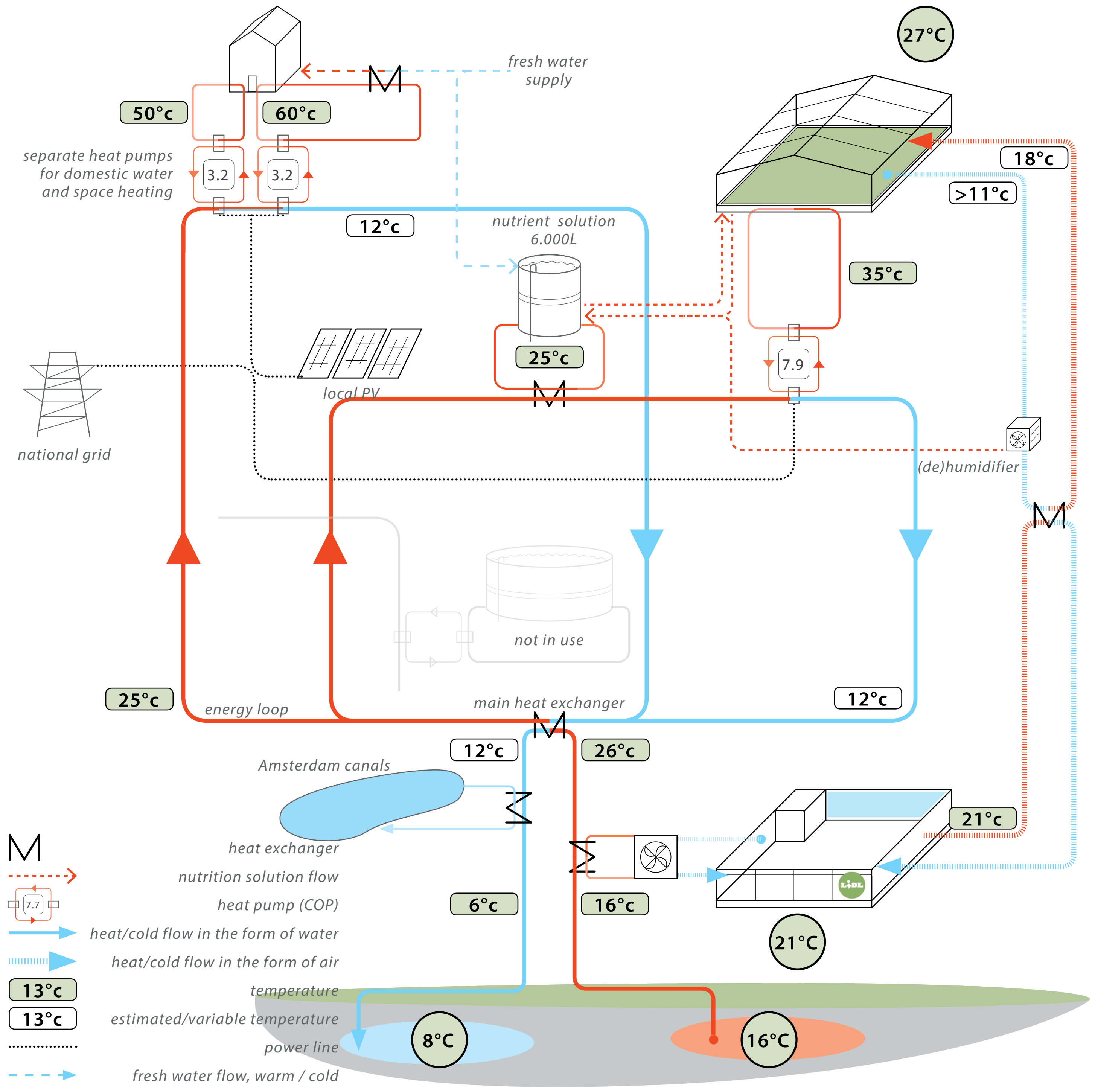
Greenhouse heat pump
The pre-heated water from the underground storage exchanges its thermal energy with the energy loop. Before being used to warm up the greenhouse floor, the energy is upgraded in a heat pump to a temperature of 35°C.

Charging the underground cold source

In the previous paragraphs, it has been made sure that the underground heating storage is in balance. Now it is time to take the cold source into consideration.

To make sure enough cooling energy is stored in the aquifer each winter to meet the cooling demand of the greenhouse each summer (745 MWh, §7.8), the underground cold source is connected to Amsterdam's largest free could source: the city canals. This body of water is practically and endless source of cooling power that often reaches temperatures below 6°C in winter. The nearest large canal is roughly only 100m away. Through the intervention of the underground storage, the free cold can be used to cool the greenhouses.

The warm water from the heat source gets first pumped through the main heat exchanger, where a large part of the thermal energy is exchanged with the cold water from the energy loop. After passing this station, the storage water is passed through a second heat exchanger, where the water is further cooled down to ~6°C.



7.10 | Local electricity generation

Available space

The drawing on the right page shows the North side of the city block. The rooftops on this side are -after a global observation- not suitable to have a greenhouse placed on top. The rooftops shapes are either to irregular for convenient and standard greenhouses or there are to many obstacles on the roofs (not drawn in the illustration).

Nevertheless, the roofs show potential to have a PV panels installed. Roughly 268 m² + 530 m² of rooftop space could be used for installing PV-panels, see the right page (figure 7.33).

In §7.8 it was concluded that only one greenhouse is sufficient to sustain the energy system. This means that 851m² of potential rooftop space, initially reserved for the second greenhouse, becomes available for holding another PV field, doubling the total space from 798m² to 1649m².

Figure 7.32 shows the monthly generated electricity. On a yearly basis, the PV-field could provide 198MWh.

How the total amount of generated electricity is calculated and by which system, is explained in §8.4.1

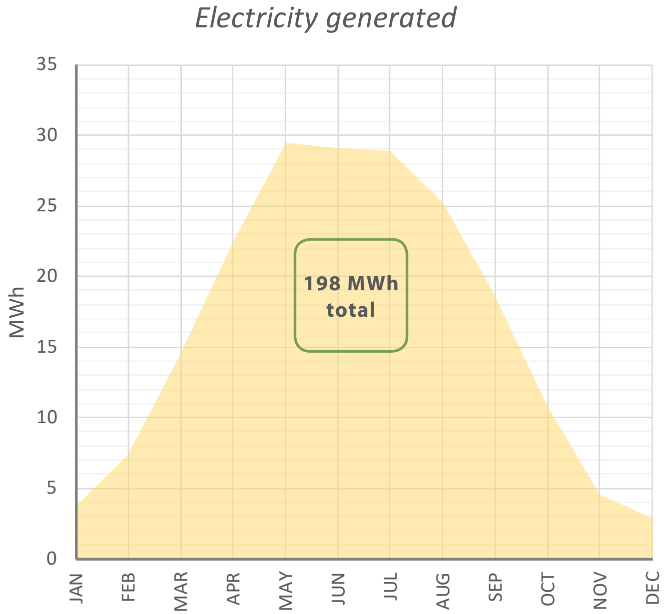


Figure 7.32: Monthly solar energy yield

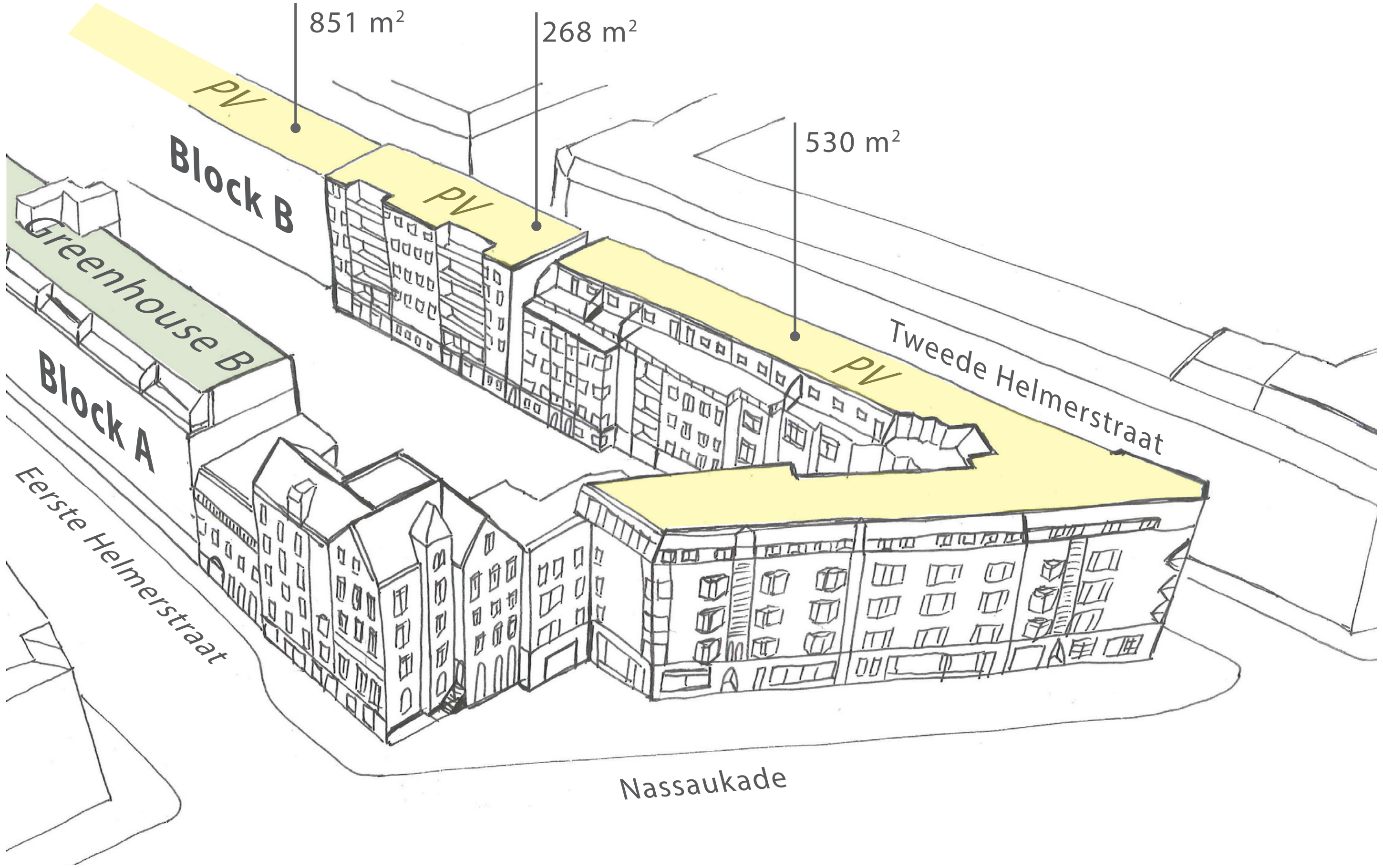


Figure 7.33: Potential rooftops at the north side of the city block.

Emission cutbacks

Chapter VIII

8.1 | Intro & Index

In this chapter we look at the effect of introducing a local energy system to the city block. This is done by comparing the CO_2 emission in the new energy model with the emission of the present situation in which no alterations are made. Final energy consumption [kWhf] is translated into primary energy demand [kWhp] and CO_2 emission [ton]. By expressing the environmental impact in CO_2 emission, we can compare the gas-based system with the new all-electric system.

The first part of the chapter deals with the carbon dioxide discharge of the apartment buildings, greenhouse and supermarket as if they were climatised by traditional methods. This model is also referred to as the *current situation*. Greenhouse cooling is in the current situation accomplished by using standard AC systems. Greenhouse heating is done by a cogeneration installation. The present Lidl Supermarket in the Helmersbuurt is considered to be the traditional one. However, since this Lidl is already disconnected from the gas network, CO_2 emissions are calculated based on the final electricity consumption of this supermarket. In both the new as the current energy system, the supermarket is does not require any heating and the apartments are not cooled in summer.

The second part of this chapter deals with the CO_2 emission of the new energy model. Gas has been designed out of the system. The primary energy demand now comes mainly from the electrical investment of the heat pumps. To determine the monthly energy demand of the refurbished supermarket, the electricity demand per square meter of the Lidl in Stein is projected on the supermarket building of the refurbished Lidl in Amsterdam (explained in chapter IV). Finally, an additional post for greenhouse user- & operational related electricity consumption and a post for miscellaneous are added.

In the final concluding part, the different CO_2 posts are added up and the two energy models are compared with each other. The difference in CO_2 emission forms the conclusion of this research.

Index

current situation

new energy model

Calculating the CO_2 emission cutback

Step 1 | Determine energy demand current situation > convert to primary CO_2 emission

Dwelling
space heating & domestic water

data from literature survey, applied to exiting apartment buildings

Greenhouse
space heating & cooling

conventional heating & cooling methods, T_{IN} = 11°C-27°C

Supermarket
electricity consumption

data analysis current & model Lidl

Step 2 | Determine electricity demand in new system > convert to primary CO_2 emission

Dwelling
electricity demand heat pump

heat pump demand according to the designed local energy grid

Greenhouse
electricity demand heat pumps

heat pump demand according to the designed local energy grid, T_{IN} = 11°C-27°C

Supermarket
electricity consumption

electricity use from Lidl Stein, applied to modernised Lidl supermarket

Final step | Compare the results

total electricity demand = *local energy production* + *national grid*

Σ energy demand current situation >>> primary energy >>> CO_2 emission
Σ electricty demand from national grid >>> primary electricity >>> CO_2 emission *subtract*

Research conclusion

8.2 | CO_2 Emission

final energy > primary energy > CO_2 emission

The generation of electricity based on natural gas, coals of oil (fossil energy) takes place in a power-plant with a relative low efficiency. During the transport of the electricity to the final user, the total efficiency decreases even further. In the end, transforming fossil fuel to the grey electricity coming from the wall socket, happens under an efficiency of 39%-42% (lower- and upper value (NEN 7120). For the calculations in the research we hold on to an efficiency of 40% , figure 8.1.

To make gas (m^3) and electricity (kWhf) consumption comparable with each other, energy uses are first converted to primary energy uses. Primary energy units - joules- represent the energy content of the different energy carriers. Final gas use is the same as primary gas demand and can directly be expressed in MJ. Final electricity (kWhf) is converted to kWhp or MJp by including the transportation losses and power plant efficiency. Now, final gas use and final energy consumption are one-on-one comparable.

Conversion table - overview

The list below gives an overview of the conversion factors and values that are used in the rest of this chapter:

gas

- Caloric upper limit: (=energy content)
  1Nm^3 gas = 35.17 MJ
- Caloric lower limit:
  1Nm^3 gas = 31.65 MJ
  (=*without retrieving condensation heat= 3.52 MJ)*

- CO_2 emission factor: = 56.6 kg/GJ
- CO_2 emission 1 m^3 gas = 1.788 kg
  (*Check: 56.6 / 1.788 = 31.65 MJ)*

electricity

- Efficiency power plant, including transportation losses = 40%
- CO_2 emission factor = 0.526 kg/kWhp
- 1 kWhf = 9.0 MJp

Sources are mentioned in the paragraphs.

Figure 8.2 compares the efficiency of an cogeneration installation with a traditional installation. This figure is used in §8.3.3.

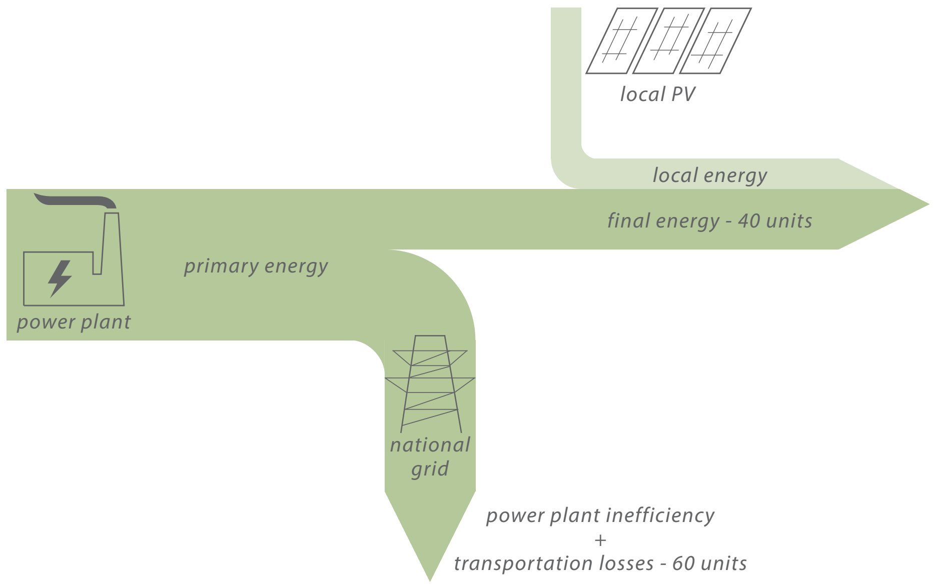


Figure 8.1: From primary electricity to final electricity.

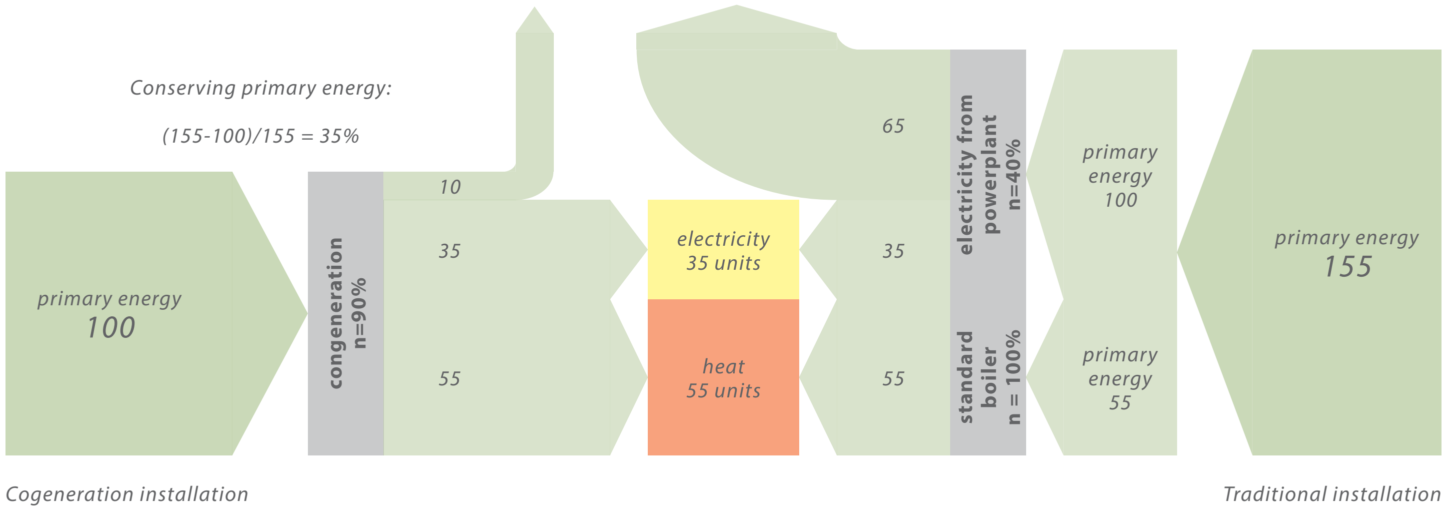


Figure 8.2: See §8.3.3: Efficiency of a cogeneration installation compared to conventional installations (start reading from the left).

8.3.1| CO_2 emission, present system

Dwelling

Fossil based High temperature heating.

The two residential components, one 77 household gallery flat and one 44 household staircase entrance building, both depend on high temperature heating. For calculation purposes, the gas demand for domestic hot water and the demand for space heating are combined.

The gas demand for one household is 813 m^3/yr, this results in a total demand of 100.812 m^3 (124 households).

Calculation

Conversion values
According to the RVO, 1 m^3 (normal cubic at 271.15K & 101.324kPa) of gas contains 31.65MJp energy (=0.03165 GJp) (Zijlema, 2016B; Geelen et al, 2016; SenterNovem, 2007). This is the lower caloric value of gas, where condensation heat from the boiler is not reused. The CO_2 emission coefficient of 2017 is 56.6kg/GJ (Zijlema, P.J., 2016A&B).

The CO_2 emission in kg (or ton) can be calculated with the following formula:

$$CO_{2\_em} = (V_{GAS} * GJp * CO_2\,ec)/1000 \qquad [8.01]$$

where
CO_{2_em} Total CO_2 emission [ton];
V_{GAS} Total volume gas used [Nm^3];
GJp Contained energy: 0.03165 [GJp];
CO_2 ec CO_2 emission conversion factor:56.6 [kg/GJ].

This gives:

100.812 * 0,03165 * 56.6 = 180.593 kg
= 181 ton.

Figure 8.3 shows the monthly CO_2 emission of the two apartment buildings plus the CO_2 emission caused by the supermarket electricity demand.

8.3.2 | CO_2 emission, present system

Supermarket

Electricity use

The electricity consumption of the present Lidl supermarket is calculated from the energy data (2016) provided by Lidl. This supermarket is already disconnected from the gas network.

Conversion values
For general calculations, a conversion factor of 0.4 can be applied to calculated the required primary electricity demand (Schepers & De buck, 2009). This number is based on the efficiency of Dutch power plant: 40%. So basically, 1 kWhp = 2.5 kWhf.

Generating 1kWhp of electrical energy emits 0.526 kg of CO_2 (Bunt-Esveld, 2014). This is the conversion factor for grey electricity.

Calculation

The CO_2 emission in kg (or ton) can be calculated according to the following formula:

$$CO_{2\_em} = kWh_p * CO_2\,ec \qquad [8.02]$$
&
$$kWh_p = kWh_F * (1/0.4) \qquad [8.03]$$

where
CO_{2_em} Total CO_2 emission [ton]
kWh_p Primary energy demand [kWh]
kWh_F Final energy demand [kWh]
CO_2 ec emission conversion factor: 0.526 [kg/kWhp]

This gives:
(1) kWhp = 258.314 * (1/0.4) = 645.785
(2) CO_{2_em} = 645.785 * 0.526 = 339.683 kg/yr
= 340 ton/yr

See figure 8.3 below.

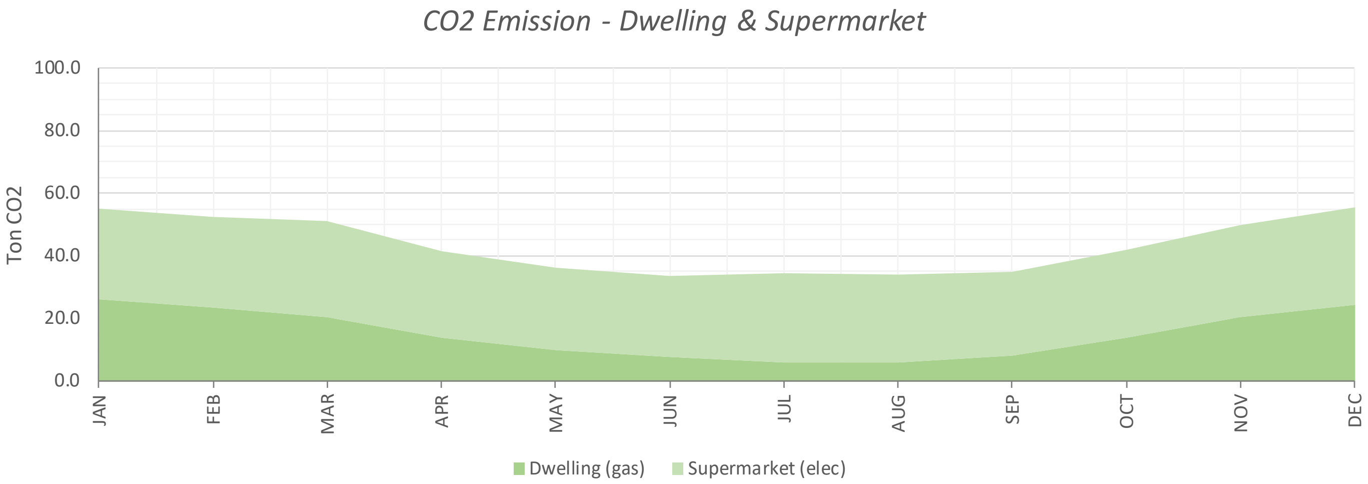


Figure 8.3: Monthly CO2 emission of conventional heating installations in dwelling and the present Lidl supermarket.

8.3.3| CO_2 emission, present system

Greenhouse

Heating

In traditional greenhouse agriculture, heating is generally achieved by the following means (Jansen, Bootsveld, Knoll & De Zwart, 2006):

- Boiler installations (fossil fuel);
- Cogeneration (fossil fuel);
- Biomass as fuel in heating installations;
- Geothermal heat;
- Heat pumps (upcoming);
- Waste heat of third parties.

Co-generation machines have the advantage to both generate heat as well as electricity, for own use of to sell back to the network. The CO_2 that is emitted due to the burning of the fossil fuel can be pumped into the greenhouse. This has a positive effect on the growth of plants, especially in a semi-closed system. Let's assume that the traditional greenhouse from this research would be heated by a co-generation installation.

The efficiency of a co-generation installation varies per manufacturer and depends on the scale of the project. For general energetic calculations, it can be be assumed that for every 100 units of primary energy invested, 10 units are lost, 35 units are converted to electrical energy and 55 units are converted to thermal energy (Smit & Van der Velder, 2008). Even though the thermal efficiency of a co-generation machine (~90%) is lower compared to a standard boiler installation (~100%), the co-generation machine consumes roughly 35% less primary energy due to the generation of electricity.

Figure 8.2 on page 193 gives a visual representation of the efficiency of the co-generator. These values form the base of the CO_2 calculation.

Cooling

If cooling combined with a underground cold source is not applicable or possible, a standard cooling system has to be applied. For choosing an optimal cooling installation, the following guidelines apply (TNO & Deerns, 2007):

- The system efficiency ,COP_{COOL}, should be as high as possible;
- The Global Warming Potential (GWP) of the refrigerant should be as low as possible. In practise this means opting for a natural instead of synthetic refrigerant. E.g: CO_2 (natural) has a GWP of 1 where R410A (synthetic) has a GWP of 1890;
- Select a cooling system with a limited refrigerant amount in the system;
- Have a low leaking percentage guaranteed by the manufacturer.

In general, it is taken for fact that standard compressor cooling machines function with a COP of 4.0. However, practise has pointed out that annual average COP_{COOL} revolves more around 3.0 (TNO & Deerns, 2007)

According to the tables provided by TNO & Deerns (2007, table 2.2), a cooling machine with the specifications mentioned below has a COP_{COOL} of 3.5.

- No underground cold source available;
- Compression cooling machine (reversed heat pump);
- Water cooled condenser (instead of air cooled systems);
- Dry cooling tower (wet cooling towers exhaust the excess heat by open-evaporative cooling).

Calculations - Cooling

If the COP is known (or in this case picked), the electrical investment energy can be calculated with equation 8.04:

$$COP_{COOL} = Q_{COOL} / W \qquad [8.04]$$

where

COP_{COOL} Efficiency of the cooling unit [-]
Q_{COOL} Required cooling load [kWh]
W Invested electrical energy [kWh]

This gives:
$Q_{COOL\_>27^\circ C} = 724$ MWh & $COP_{COOL} = 3.5$, this gives:

$$W = 723616 / 3.5 = 207 \text{ MWh}_e / \text{yr}$$

The CO_2 emission in ton is calculated with equation 8.02 & 8.03. This results in an yearly CO_2 emission of 272 ton.

Calculations - Heating

We assume the cogeneration installation is gas-based.

Since the heating demand is known (55 units), we can subesequently determine the generated electricity (35 units) and the energy losses (10 units).

For calculation purposes, we assume that the generated electricity is directly used on by the greenhouse itself. This electricity is subtracted from the final electricity demand of the cooling system.

The CO_2 emission due to the gas consumption of the cogeneration installation is calculated with equation 8.01. The conserved CO_2 emission due to the generated electricity is already included in the graph below.

See Figure 8.4 below.

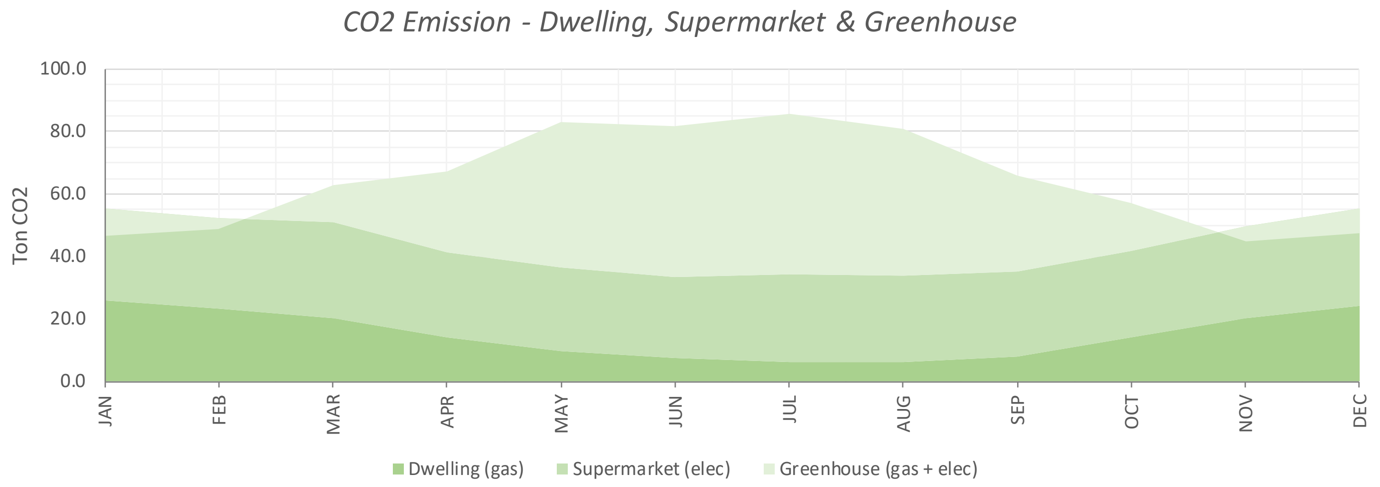


Figure 8.4: Monthly CO2 emission by the conventional heating/cooling installations in the greenhouse + dwelling and the present Lidl supermarket.

8.4.1| CO_2 emission, new energy model

Local energy production

Local electricity generation

For more information about the PV-system on the city block, see §7.10.

The local generated electricity is calculated according to the following parameters:

- Watt peak 1 panel = 350Wp, this is a high performance PV element (example: LG NEON R 350 Wp Black);
- Size panel (w*h) = 1.02x1.7m (standard size);
- Conversion efficiency = 90%;
- Assume: 1m² gross roof area = ~0.6 m² efficient area (35° panel inclination, n=0.60). This factor can be a higher if a lower angle is chosen;
- Full Sun Hours (FSH) according to KNMI data (Schiphol weather station, 2016 data);

Calculating the PV output

The daily, monthly and annual electricity yield is calculated with formula 8.05, 8.06 & 8.07 (also see figure 8.5):

$$W_{PV} = kWP_{M2} * n * A_{NET} * FSH \qquad [8.05]$$

with

$$kWP_{M2} = (WP_{PANEL} / (w*h))/1000 \qquad [8.06]$$

&

$$A_{NET} = A_{GROSS} * (1/1.5) \qquad [8.07]$$

where

W_{PV}	*Generated electricity [kWh];*
A_{GROSS}	*Total available rooftop surface [m²];*
WP_{PANEL}	*Watt Peak per panel;*
kWP_{M2}	*Watt Peak per square meter [m²];*
$w*h$	*Width x height 1 panel [m¹];*
n	*conversion factor, 0.9 [-];*
FSH	*Full Sun Hour [-]*
A_{GROSS}	*Total potential roof space [m²]*

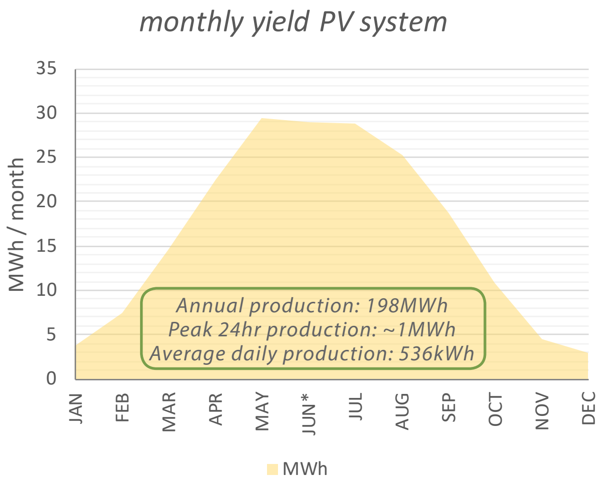


Figure 8.5: Monthly solar energy yield

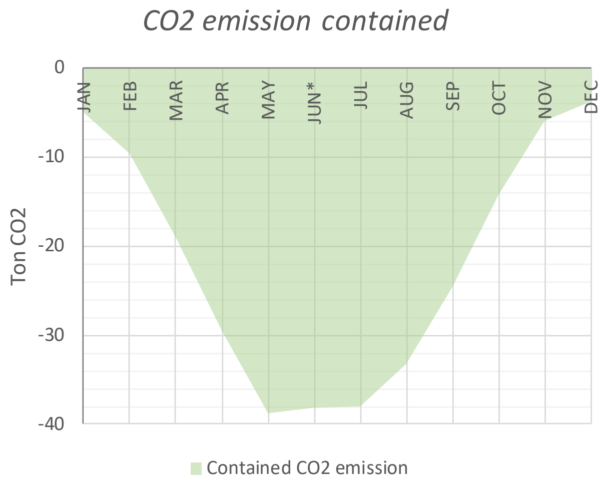


Figure 8.6: Monthly CO2 ' contained' by renewable production.

8.4.2| CO_2 emission, new energy model

Supermarket

Lidl Stein > Lidl Helmersbuurt

As is explained in chapter IV, the electricity demand of the refurbished Lidl is determined by taking the monthly electricity demand per m² of Lidl Stein and apply that to the supermarket in Amsterdam. The supermarket in Stein has set the energetic and sustainability standard for all future Lidl supermarkets and so it gives a good and reliable estimation of the future energy consumption of the supermarket in Amsterdam.

Calculation

The CO_2 emission in ton is calculated with equation 8.02 & 8.03:

(1) $kWhp = 214.446 * (1/0.4) = 536.115$

(2) $CO_{2_em} = 536.115 * 0.526 = 281.996$kg/yr

$= 282$ ton/yr

See figure 8.7 below. The expected CO_2 emission, final electricity demand of the present supermarket and the final electricity demand of the new supermarket are projected. The future supermarket emits 58 tonnes (17%) less CO_2 than the present supermarket.

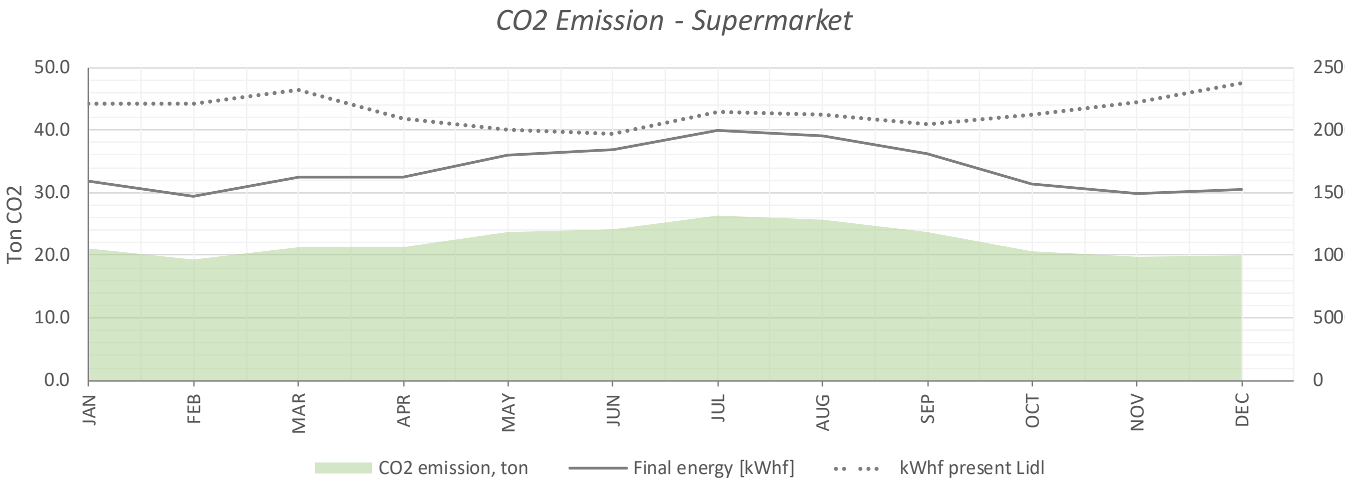


Figure 8.7: Monthly CO2 emission caused by the electricity demand of the new Lidl supermarket.

8.4.1| CO_2 emission, new energy model

Heat pumps

Intro

There are 3 heat pumps in the local energy grid:

- Heat pump A: The main pump. Upgrades the temperature of the water coming from the warm aquifer and heats the water in the energy loop;
- Heat pump B: Brings up the temperature of the domestic water and the water used for building heating to 65°C;
- Heat pump C: brings up and keeps the water in the 24hr thermal buffer on 30°C when the summer system is active.

The electrical investment and coherent CO_2 emission is calculated in this paragraph.

Equation 8.02 & 8.03 are applied.

Heat pump A: Underground storage

Application: Heat pump upgrades the thermal energy from the source before it is directed towards the greenhouse

Type: water-water
Months active: October - April
Temperature jump: 26°C > 40°C
SCOP: 6.3
Source: warm water from aquifer (16°C), pre-heated with the rejected heat from the supermarket (makes 26°C).

thermal energy upgraded:
Σ $kWh_{PRIMARY\_TH}$: 40 MWh

invested electrical energy
Σ MWh_{FINAL} : 6 MWh_F
Σ $MJ_{PRIMARY}$: 52255 MJ_P
Σ $MWh_{PRIMARY}$: 15 MWh_P

Σ CO_2 emission : 8 ton

Heat pump B1 & B2: Dwelling

Application: Heat pump brings up temperature for domestic water and high temperature heating.

Type: water-water
Months active: January-December
Temperature jump:
winter: 40°C > 65°C & summer: 24°C > 65°C
SCOP: winter: 4.6 & summer: 3.1.
Source(s): summer: warm water from GH B & winter: warm water from aquifer.

thermal energy upgraded:
Σ $kWh_{PRIMARY\_TH}$: 566 MWh
invested electrical energy
Σ MWh_{FINAL} : 187 MWh_F
Σ $MJ_{PRIMARY}$: 1683 MJ_P
Σ $MWh_{PRIMARY}$: 467 MWh_P

Σ CO_2 emission : 246 ton

Heat pump C: 24hr buffer

Application: Heat pump guarantees the temperature in the thermal buffer remains on 29.5°C.

Type: air-water
Months active : April-May
Temperature jump: 25°C > 29.5°C
Source: Greenhouse B

The lower temperature limit in the greenhouse has shifted from 15°C to 11°C to bring the energy system in balance. Greenhouse B barely requires a thermal buffer anymore during the warmer months now. The small heat demand that is still present, for example in the month April, results in a very low electrical investment relative to the other two heat pumps. In addition to this, the thermal energy exchange with supermarket already covers a large part of the heating demand. For this we leave this pump out of the CO_2 calculations.

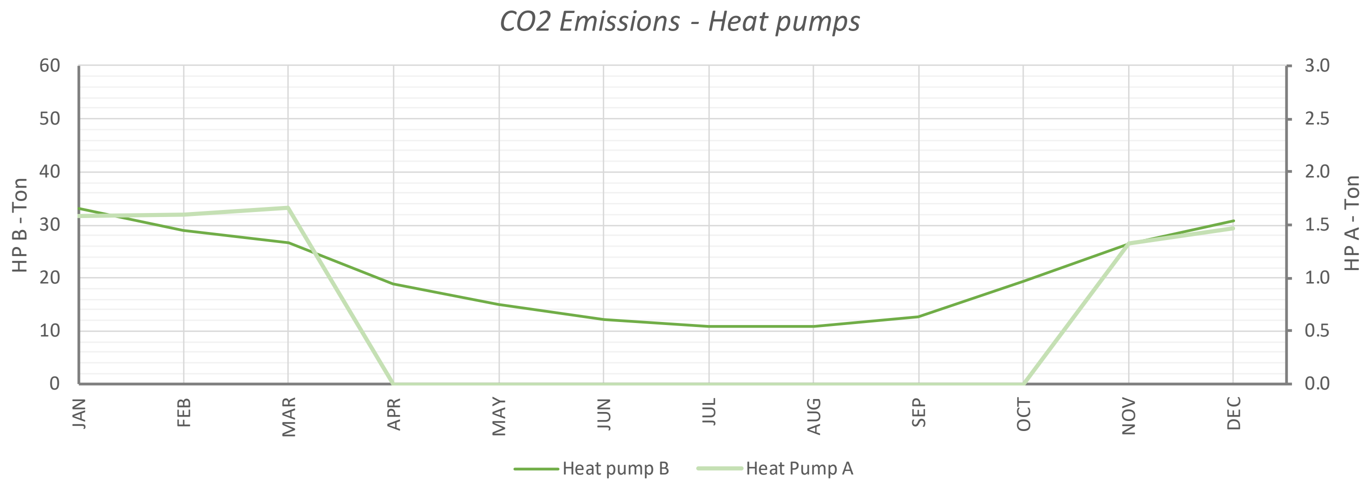


Figure 8.8: Monthly CO2 emission caused by the electricity demand of the heat pumps in the energy model.

8.4.4 | CO_2 emission, new energy model

Miscellaneous

Miscellaneous

Aside from the three heat pumps discussed in chapter 7.4.5, which are responsible for the major part of the electricity demand, there are support machines integrated in the system that drive the different circulations of water and air. All these machines, mostly pumps, are listed below:

- (de)humidifier;
- Auxiliary water pump thermal buffer. Pumps water from the storage tank through the floor heating system in the greenhouse. Active in summer;
- Nutrition solution circulation pump. Pumps around the irrigation water for the crops. Active throughout the year;
- Auxiliary water pump for energy storage. Pumps water from the heat source to the cold source and visa-versa;
- 2x air pump for heat exchanger. One at the side of the Lidl and one at the side of the greenhouse. Facilitates Lidl<>Greenhouse thermal heat exchange. System is mostly active during winter, when the $T_{IN\_GH} < T_{IN\_SUPERMARKET.}$ During summer, this energy exchange is activated only 30% of the time (at night).

The electricity demands for these supporting units are not specified per machine and neither is the coherent CO_2 emission due to this demand. Instead, another 1000kWh/month (800kWh in summer) is added on top of the total electricity demand to simulate the miscellaneous installations.

Greenhouse electricity

Lighting

For determining the electricity demand of the greenhouse -excluding the electricity required for the heat pump- we apply a DesignBuilder simulation. To distillate the electricity demand for the lighting system, all the other machines + activities have been checked of. Artificial lighting in this greenhouse is used to illuminate the space during working hours. This makes gardening/harvesting work possible when daylight is still insufficient in the early morning or late afternoon. Artificial lighting is NOT used in this greenhouse system to energize the plant's photosynthesis at night, even though this would increase the yield, especially during the winter months.

Parameters used DesignBuilder:
- Type: suspended armatures;
- Lighting schedules:
  Winter: 07:00-10:00 & 15:00-19:00 (all days)
  Summer: 07:00-10:00 & 17:00-1900 (all days)
- Lux: 500;
- Working plane height: 0.80m.

Under the above parameters, DesignBuilder simulations determine an electricity demand for the lighting of 11.700kWh/yr.

Rest.

To quantify the electric power demand for the rest of the operational activities in the greenhouse, the lighting demand is simply multiplied by a factor 1.5.

Total electricity demand:
11.700 x 1.5 = 17.250kWh/yr

8.4.5| CO_2 emission, new energy model

Overview

All CO_2 emissions combined

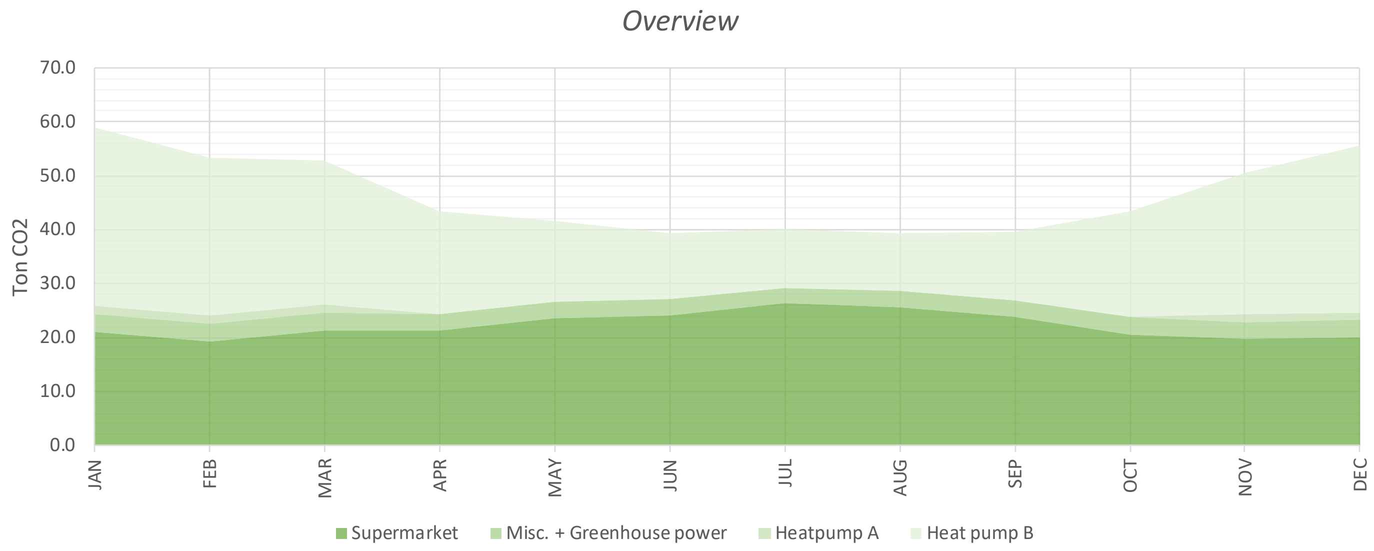


Figure 8.9: Monthly CO2 emission of the new energy system (only electrical energy used).

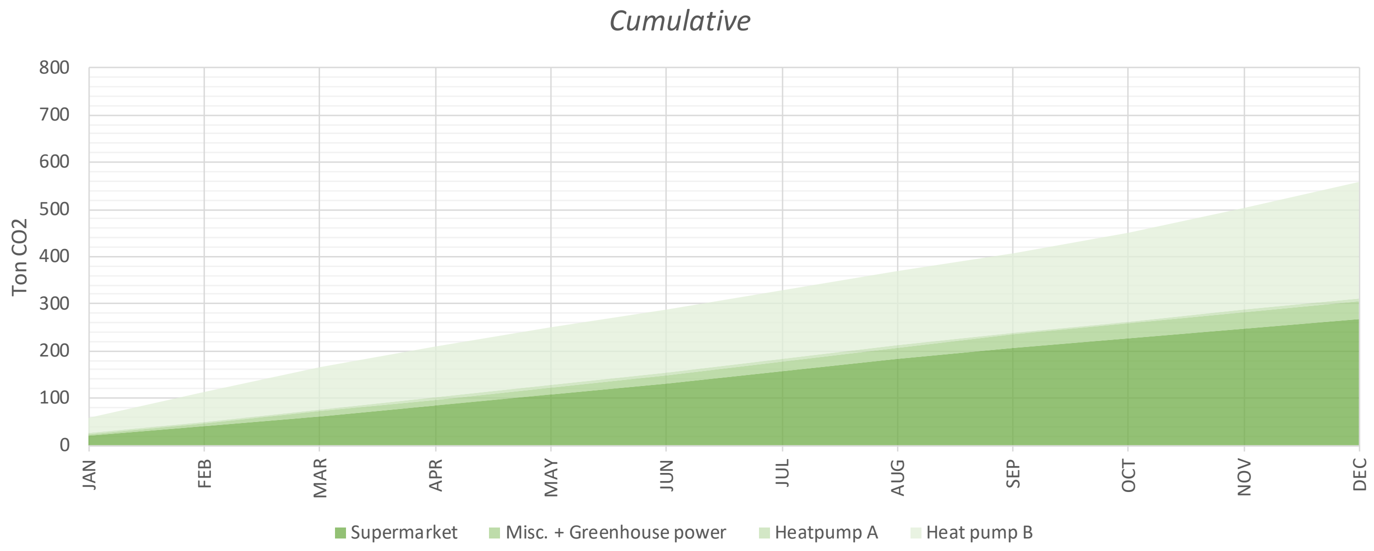


Figure 8.10: Proceeding of the cumulative CO2 emission caused by the new energy model.

8.6 | CO_2 cutbacks - Comparing the systems

CO_2 contained

Currently, the two apartment buildings, the supermarket and the (theoretical) greenhouse have an annual CO_2 emission of 749 ton. This value is based on conventional climate installations that run on natural gas or standard grey electricity.

If the new local energy grid is installed, the 2 apartment buildings, the supermarket and the greenhouse have an CO_2 emission of 558 ton. This value is based on a system that is completely disconnected from the gas network. This model contains 192 tons of CO_2 each year. This is an emission reduction of 26%.

Finally, all the roof space that is not used to construct a greenhouse on top, can be used to install PV-systems. Renewable electricity generated with this system can be considered as *conserved CO_2 emission* and is subtracted from the total CO_2 emission of the system.

The final energy model saves 452 ton of CO_2 each year. This is an emission reduction of 60%.

See figure 8.11 and 8.12. In appendix V, an overview of all the used parameters and settings to achieve this CO_2 reduction can be found.

Biological countermeasures: trees

It is always interesting to compare CO_2 emission of a building, city or system with the natural ability of CO_2 uptake by trees.

We assume the CO_2 uptake for a standard forest to be 180.000 kg/CO_2/acre in 45 year, which equals 4.000 kg in 1 year. Of course this 4000 kg is only applicable with a full-grown, well maintained forest and if this forest has the ability to grow for a full 45 years. During the first years of a young forest, the uptake is much less.

- CO_2 emission present: 749 ton/yr
  This equals 749.000 kg / 4.000 kg = 187 acres
- CO_2 emission local energy grid: 298 ton/yr
  This equals 298.000 kg / 4.000 kg = 75 acres.

To compensate for the remaining emission of the new energy system, 75 acres of new forest should be planted. Or in other words, due to this local energy grid, 112 acres of forests do not have to be planted anymore. This is provided that no additional energetic refurbishments will happen in the future that decrease the environmental impact even further.

For imaging:

- 183 acres = 260 soccer fields (7000 m²). This roughly equals the complete surface of Rotterdam-The Hague Airport.
- 75 acres = 107 soccer fields This roughly equals 75% of the old city centre of Delft or about 14 Lidl Waddinxveen Distribution Centres (52.000 m²).

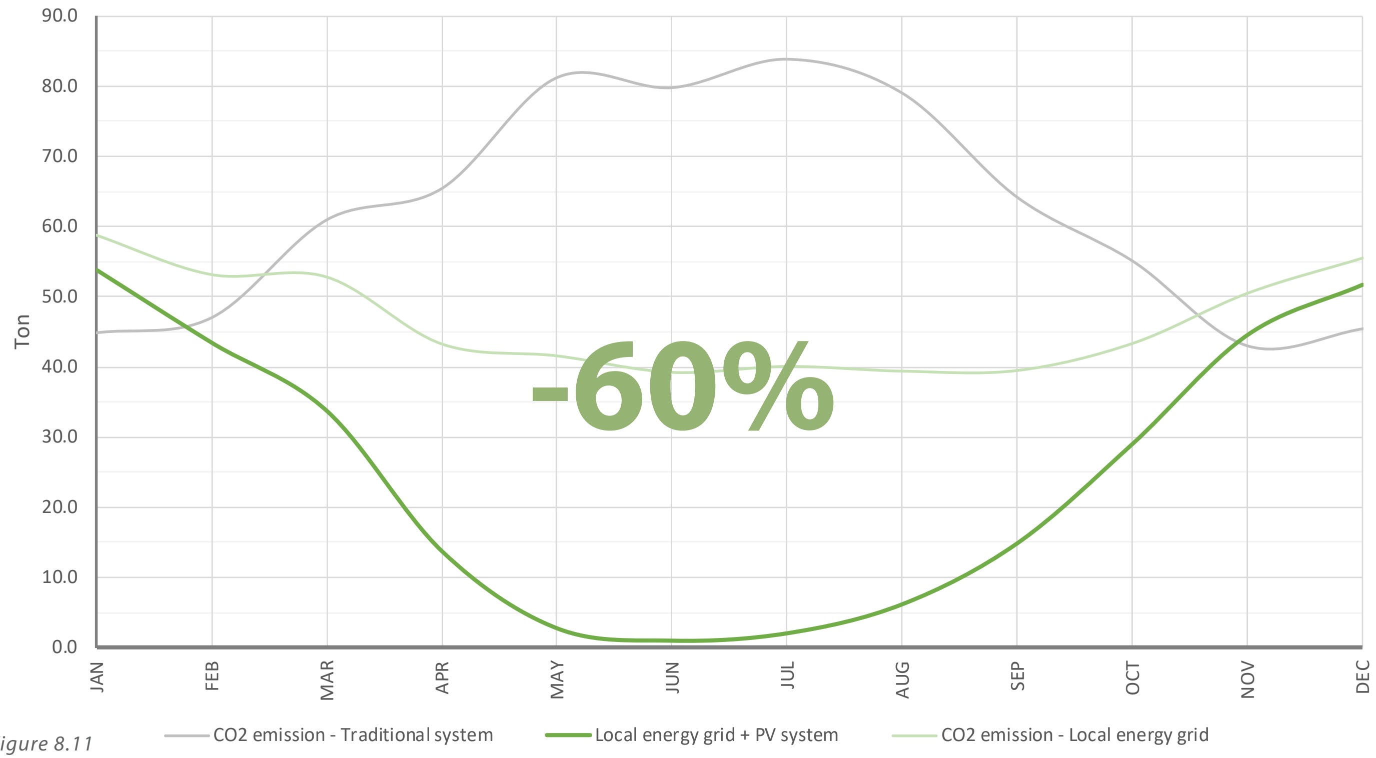
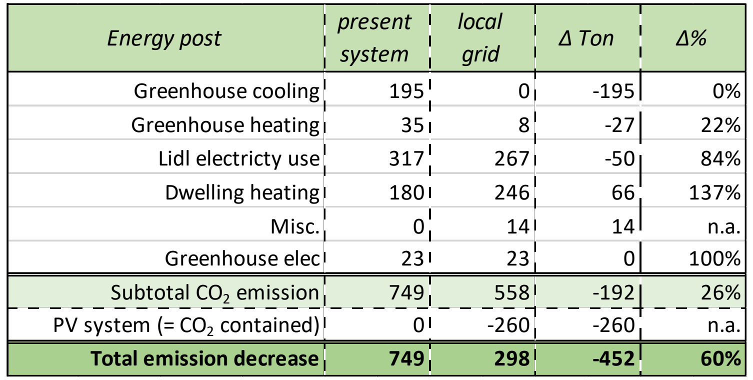


Figure 8.11



Energy post	present system	local grid	Δ Ton	Δ%
Greenhouse cooling	195	0	-195	0%
Greenhouse heating	35	8	-27	22%
Lidl electricty use	317	267	-50	84%
Dwelling heating	180	246	66	137%
Misc.	0	14	14	n.a.
Greenhouse elec	23	23	0	100%
Subtotal CO_2 emission	749	558	-192	26%
PV system (= CO_2 contained)	0	-260	-260	n.a.
Total emission decrease	**749**	**298**	**-452**	**60%**

Figure 8.12

8.7.1 | The Lidl in the new system

Building cooling & greenhouse heating

Cooling demand reduction

Within the domains of this study is only looked at the *building related energy* demand. Building related energy uses about 10% of the total electricity demand in a supermarket (§4.4.2 & §4.5). For calculation purposes we assume that this full 10% is utilised by the spacial cooling system of the supermarket. This means that the maximum room for improvement would in theory be 21.400kWh, 10% of 214MWh.

The cooling demand of the Lidl supermarket in the new energy model is covered by means of:

1. Heat exchange with the greenhouse;
2. Standard cooling installation for the remaining cooling demand

Floor cooling by the fresh water supply is not taken into account in any energy calculations.

According to the energy balance defined in § 5.3.3, the yearly cooling demand of this Lidl would be 120 MWh a year.

Cooling by cold exchange with the greenhouse
The indoor temperature in the Lidl is kept on 21°C or lower. The indoor temperature in the greenhouse is maintained between 11°C and 27°C. If the indoor temperature of the greenhouse drops below 21°C, which happens almost daily (see figure 8.13), heat exchange with the supermarket could be started to warm up the greenhouse with excess heat. At the same time this exchange cools down the supermarket.

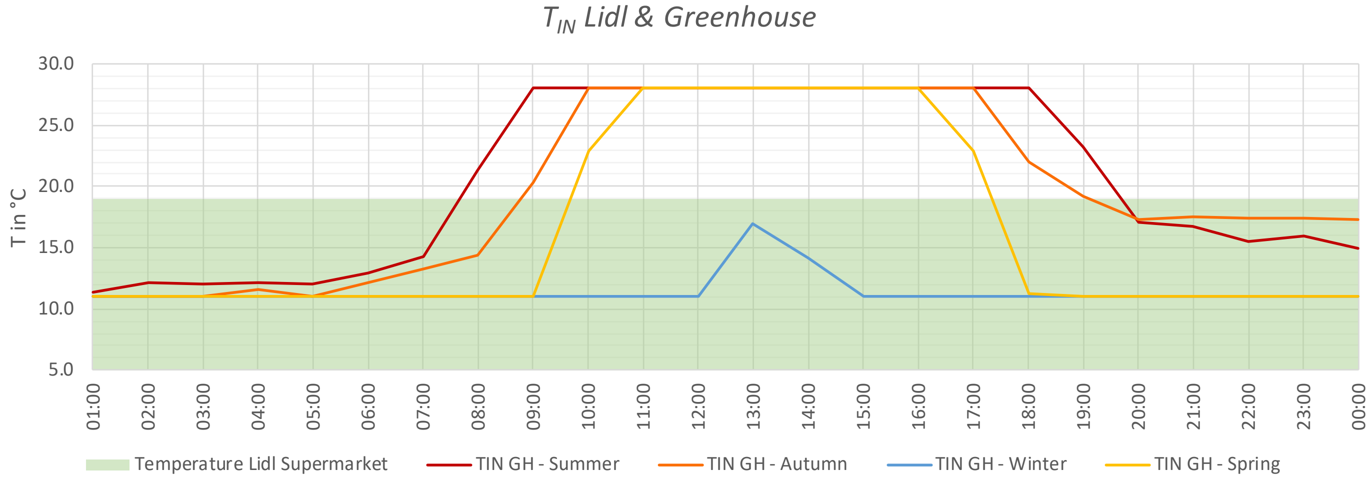


Figure 8.13: Indoor temperature of the greenhouse and the supermarket for one day of each season (estimation).

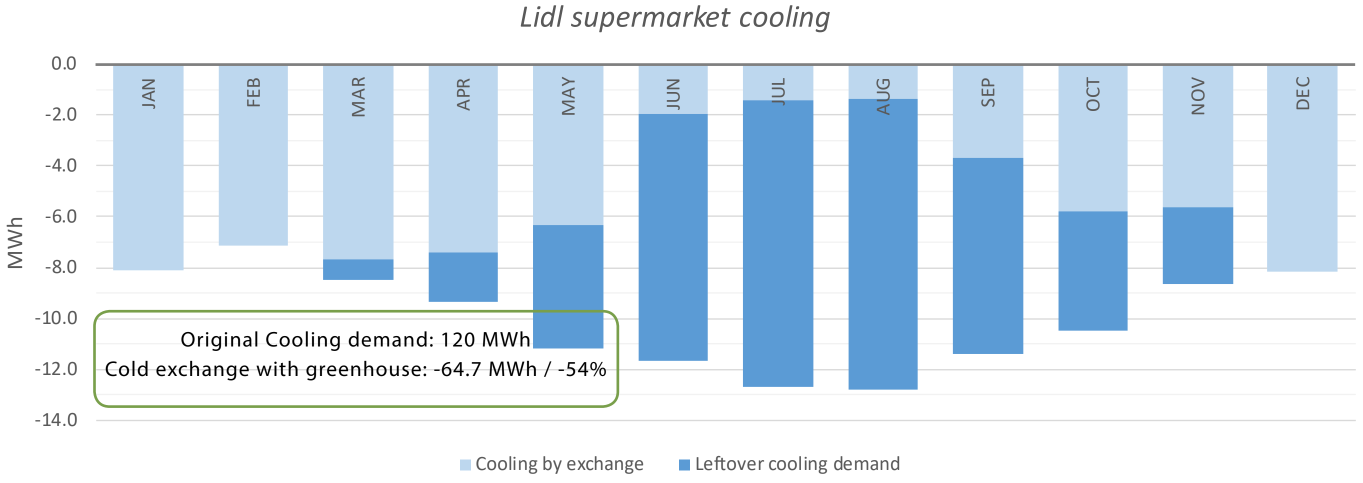
The effect of this cooling method varies per month: the effect of greenhouse heating and supermarket cooling is larger during the winter months. For each month, the Lidl's cooling capacity and the greenhouse heating capacity is calculated. The following parameters are used:

- exchange rate supermarket = 3 (5.13m^3/s);
- volume Lidl = 2053m^3;
- infiltration rate greenhouse = 5.13m^3/s;
- efficiency heat exchanger = 0.75;
- greenhouse indoor temperature = average monthly temperature with a minimum of 11.0°C. We can assume that the greenhouse takes over the ambient air temperature if the solar gain is zero;
- To include in the calculation when $T_{GH} < T_{LIDL}$, factors are applied. These factors are derived from figure 8.13.

For the complete calculations, see appendix II.

The remaining cooling demand is covered by a conventional cooling installations.

In the second part of this paragraph, the supermarket's contained CO_2 emission due to energy exchange with the greenhouse is determined.



Original Cooling demand: 120 MWh
Cold exchange with greenhouse: -64.7 MWh / -54%

Figure 8.14: The cooling demand of the Lidl supermarket is reduced by energy exchange with the greenhouse and floor cooling by the fresh water supply.

Reduced electricity demand for the cooling system

See figures 8.15 to 8.17.

Figure 8.15 shows the building related electricity demand according to the analysed electricity data in chapter IV [kWh]. Previous calculations pointed out that this post is 10% of the total electricity use, or 21.400kWh. Figure 8.15 is the same as figure 4.12 in §4.6.

Figure 8.16 shows the distribution of the building related electricity over the 12 months, but then according to the monthly cooling demand that was determined in §5.3.3. The sum of all months remains 21.400 kWh, but the division is changed according the Lidl energy balance. Both graphs roughly proceed on the same way through the year, but figure 8.16 shows more seasonal fluctuation. The calculation regarding CO_2 containment is based on the values in figure 8.16.

Figure 8.17 is based on figure 8.16, but now the influence of energy exchange with the greenhouse is included. The building related electricity demand of December till February is completely nullified and the demand of the remaining months is reduced. The grey line indicates the original situation.

Building related electricity demand:

- Before greenhouse cold exchange: 21.400 kWhf
- After greenhouse cold exchange: 9844 kWhf

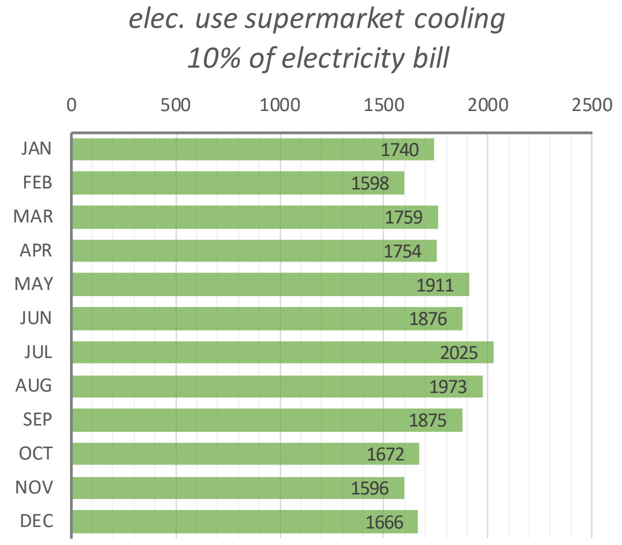


Figure 8.15

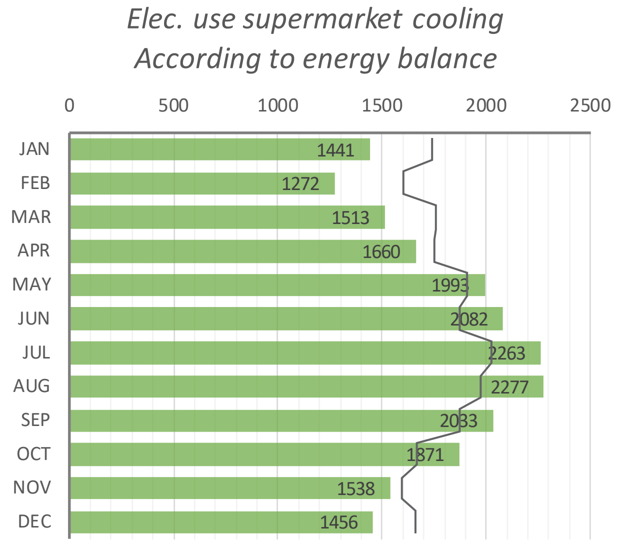


Figure 8.16

CO_2 emission cutbacks

Maximum possible CO_2 emission reduction:
Total electricity use: 214MWh
10% > 21400 kWh
21.400 kWhf = 53.500kWhp (x 2.5, n=40%)
53.500 kWhp = 28.141kg CO_2 (0.526kg/kWhp)

If the complete *building energy* is nullified, 28 tons of CO_2 emission is contained each year. However this is not the case:

By means of heat exchange with the greenhouse and floor cooling with the city block fresh water supply, the annual cooling demand of this Lidl can be decreased with 54%. So:

54% x 28.141kg = 15.196 kg CO_2 contained.

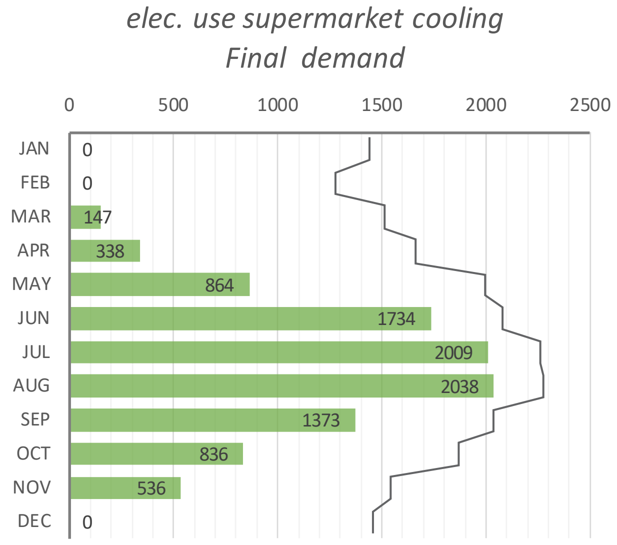


Figure 8.17

8.7.2 | The Lidl in the new system

Product cooling

From a conventional dry cooler to aquifer cooling

Conventional means of supermarket climatising and product cooling include dry coolers, recognisable from the condensers units usually found on the roofs of the supermarkets. This is where the cold is extracted from the outside air and transported to the supermarkets AC-system or product cooling/freezing displays.

In the condenser, the heat in the refrigeration fluid is exchanged with the cold from the outside air. Just like the heat pump, the efficiency of the unit will increase if the temperature jump is kept to a minimum. The average outside dry bulb temperature in the Netherlands generally varies between 4°C in winter and 18°C in summer. Direct consequence of this temperature fluctuation is a changing (S)COP of the cooling unit throughout the year.

The new local energy network already relies on an open source (doublet) underground thermal energy storage. The condenser of the supermarket cooling installation can also be connected to this central cold storage. This would result in a steady source of ~8°C cooling water and an increase of the efficiency of the cooling unit during the summer months. During the winter months, when the underground source is used for heating purposes, the supermarkets can still rely on the conventional dry cooler (T_{OUT} winter months = ~4°C to ~11°C).

This reconfiguration of the supermarkets cooling system would decrease the environmental impact of the total system beyond the current 55%. However, there is not enough data available (e.g. the cooling demand of the product cooling displays) to express this reduction in numbers and therefore remains theoretical.

8.8 | The influence of climate change

Climate predictions and climate goals (concise)

To design for the future, a general idea of the approaching climate changes is essential. The global climatological situation can be accurately predicted for the 21st century. According to the Intergovernmental Panel on Climate Change, the following global changes are expected:

- Temperature rise of 1.1-6.4°C;
- Precipitation will intensify;
- A water level rise of 18cm-59cm.

Regional predictions are more complicated to perform and rely more on speculations. The Dutch meteorological association (KNMI) presents the following expected climate changes (KNMI, 2015):

- On average, winters will be milder and summers will be hotter;
- Winter precipitation increases and extreme winter precipitation occurs more often. Extreme precipitation in summer also occurs more often;
- The oceans water level rises and the rate of this rise will increase over the years.

20-20-20 European Union climate goals
Between the 27 member states of the European union, the following concrete core objectives have been determined:

1. 20% less total energy use compared to 1990;
2. 20% less emission of CO2;
3. 20% of the total energy should come from renewable resources.

The 20-20-20 agreement is just one milestone in the global effort against climate change (more on page 35).

Progress: 20% less CO_2 emission
According to the 20-20-20 agreement, The Netherlands should decrease their CO_2 emission with 16% (the average of all EU member states is set on 20%, precise percentages vary per country). In 2012, this reduction was already 15.2% and it is expected this target will be achieved in 2020.

Progress: 20% of demand from renewable sources
In the year 2020, the Netherlands should run for 14% on renewable energy (relative to the 1990 situation. The EU average is set on 20%, precise percentages vary per country). A status check by the Dutch Central Office of Statistics (CBS) in 2014 revealed that only 5.5% of the total energy demand is covered by renewable energy[1]. If the target of 2020 is still to be reached, the share of renewable energy has to increase with 1.4% yearly, which is a lot. According to the Nationale Energieverkenning 2017 by ECN Beleidsstudies (Schoots, Hekkenberg & Hammingh, 2017, p.84), it is unlikely that the 14% minimum will be achieved.

Climate change

Components that are connected to the energy system find their heat demand covered by the rooftop greenhouse, that acts as a solar energy collector. This allows for a total disconnection of the national gas supply. Conventional gas-based heating systems are replaced with heat pumps. This increases the electricity demand of included components, which is then partly covered by the installed PV field. The rejected heat from Lidl supermarket is used to pre-heat the water before it is upgraded by the heat pump, thus increasing the COP and lowering the electrical investment. As the components in the system now rely more on renewable energy (thermal and electrical) the primary CO_2 emissions reduced by 414 tons per year.

The KNMI predicts a gradual rise in temperature over the years (1) and an increased frequency of short term periods with below average minimum temperatures (2) and above average maximum temperatures (3). Even periods of extreme temperatures become more frequent.

(1) A gradual rise of the outside temperature would lower the remaining environmental impact of this energy system even further. The heating demand of the dwelling and the greenhouse will go down, which subsequently leads to a decreased cooling demand of the greenhouse. This sounds counter-intuitive, but remember that cooling is primarily done to extract heat for underground seasonal storage.

(2) The greenhouse is however more vulnerable to long periods of (extreme) cold. The floor heating system is only effective (and efficient) until a certain temperature drop. If the outside temperature gets below this level, additional fossil fuelled heating system must be put into action in order not to lose the crops.

(3) Longer periods of above average outside temperatures would not have dramatic consequences to the greenhouse. It is not likely that the floor cooling system is able to maintain the maximum indoor temperature of 27°C. However, should the maximum possible cooling capacity be reached, the greenhouse can always just open the facade and let surplus heat escape. Longer periods of high temperatures does not necessarily damage or reduce the crop production, provided there is enough irrigation and evaporation water available of course.

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[1] https://www.cbs.nl/nl-nl/nieuws/2016/13/nederland-voorlaatste-op-ranglijst-eu-hernieuwbare-energie

The Design

Chapter IX

9.1 | Design

Design description

In this paragraph, the main design decision and features will be explained (see figure 9.1 & 9.3):

- The greenhouse is placed on the roof South residential building and measures 107x8 meter (856 m^2). The reason why the roof of this apartment building is opted above the roof of the North apartment building has to do with the energetic performance. Calculations point out that much more heat is collected through a full sized greenhouse B than a full sized greenhouse A. This has most likely to do with the length-width ratio of the two greenhouses: greenhouse B (107x8m) has a much larger South oriented facade than greenhouse A (78x10.8m).
- The roof of the North residential building is used to construct a PV-system which stretches over the full length of the city block. The PV installation also covers the roof surface of the buildings at the back of the city block (not illustrated). In total there is 1649 m^2 gross roof area available for PV-panels generating ~198 MWh of electricity a year.
- A smaller processing building is added on top of the school building. This space is used for supportive functions like food processing, quality control and packaging. The space can also be used for small public events. This glass structure in not included in the energetic calculations and does therefore not play a role in the energy system.
- The main greenhouse is accessible through the existing staircase + elevator that is currently used to enter the apartments. The processing house can be accessed through another existing staircase at the back of the school building.
- Greenhouse installations are located in and around the staircase tower, which can also be used for vertical air channels and other vertical lines of transport. The stockroom and installation room of the Lidl is located at the foot of the staircase tower.
- The roof of the Lidl supermarket is not suitable for any greenhouse farming purposes as it is located in the shadow of the adjacent dwelling practically every day of the year. This forces the greenhouse to the roof of this adjacent building. In line with the 'greening' of the city block, the roof of the Lidl is turned into a vegetated water retention roof (illustrated on the next page). This will enhance the aesthetic quality and attractiveness of the city blocks inner courtyard. In addition to this, a green roof will contribute to the mitigation of the urban heat island effect and it can hold on to rain water in dry periods. Since the vegetation roof is added on top of an existing roof, the thickness of the soil is thin and the vegetation type is limited to mosses and grasses and the roof is not accessible for leisure.
- The greenhouse and the energy system is designed in such a way, that any future Lidl expansions are not obstructed by the system. An expansion of the Lidl would benefit the energy system as more supermarket waste heat will be available to keep the greenhouse above 11°C and less heat will be demanded from the underground energy storage.

Architectural and aesthetic quality are of inferior importance in this energy dominated research.

9.2 | The position of the Lidl

Energy

In the new energy model, the Lidl supermarket is connected on two levels with the local network (figure 9.2):

1. Heat exchange with the greenhouse. Warm supermarket air (~21°C) is circulated through an exchanger, where heat is transferred with the colder air of the greenhouse (11°C-21°C). This energetic connection warms up the greenhouse and reduces the cooling load of the supermarket (see §7.4.1, 7.4.2, 7.9.2 & 8.7.1);
2. Use of supermarket rejected heat. Waste heat of the supermarkets cooling system is passed by the warm water that is pumped from the hot underground source. This pre-heats the water from 16°C to an estimated 26°C, thus narrowing the temperature jump for the heat pump and increasing the COP. (see §7.4.6 & 7.9.2).

Food production

In this concept and research, the greenhouse is operated under the flag of the Lidl and so, the urban greenhouse primarily produces vegetables for this specific Lidl. This brings the supermarket directly into the food network. By means of further research, analysis of customer consumption behaviour and consultancy of external parties, an operational plan should be set up on how the first Lidl Greenhouse can run optimally and how it can establish a competitive position in the food network.

The greenhouse is designed around the production of tomatoes and a total of 3200 plants can theoretically be grown at the same time (§7.2.4). The greenhouse and the Nutrient Film Technology can of course also be used to grow other crops, like different types of lettuces or paprika's.

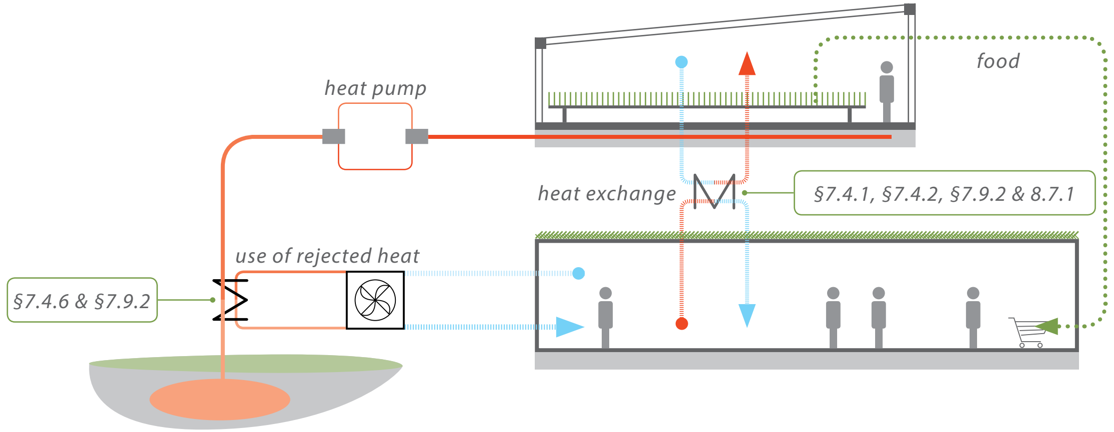


Figure 9.2: The Lidl in the energy network

9.3 | Social sustainability

This greenhouse-supermarket-dwelling energy grid is a rather radical intervention in an existing and densely populated urban environment. The public and municipality might expect (and deserve) more in return than only locally produced food and a reduced CO_2 emission.

As a place where many people are brought together, the Lidl supermarket could play a prominent role in local social cohesion. During this research the focus was aimed at environmental sustainability, but what about social sustainability? This paragraph is a quick brainstorm on the role of the future supermarket beyond food retail.

Social sustainability

Social sustainability is an undefined term and can be applied with varying meanings and in ranging contexts. Due to the absence of a concrete definition, it is also hard to measure or even impossible to tell if a neighbourhood or project is *socially sustainable*. Parties that are involved with the liveability of building projects and social environments come up with different perspectives and interpretations on social sustainability. At the same time these projects do show resemblances with each other and an idea on social sustainability can be formed.

One interpretation is that a social sustainable approach is a continuous process in which everybody can participate. The final goal is to strengthen the relationships between people: social cohesion. Social sustainability encompasses subjects like social equity, (cultural) diversity, accessibility, continuity and flexibility. Further elaboration on the definition of social sustainability goes beyond the scope of this research.

By definition and function, a supermarket centralises itself in the middle of society and is a place for functional gathering. Most people frequent the supermarket a few times a week or even on a daily basis. Because of this, a supermarket forms a potential context to include a social function. Even if the urge for socializing does not apply, there is always second motivation to visit the supermarket: simply doing the groceries.

Alternative solution

In the first design, the added rooftop greenhouse has three main purposes:

- *energy* - The glass greenhouse structure acts as a solar collector. The thermal energy that is extracted from the greenhouse is stored for winter heating;
- *food production* - In the final design, the greenhouse has space to grow approx. 3200 tomato plants;
- *marketing* - A greenhouse on top of a supermarket reflects a sustainable business attitude and shows climatological responsibility (towards the customer).

If the importance of social sustainability is raised above the importance of food production, the greenhouse building could be re-purposed. It remains important that the glass structure can act as a solar collector since the whole energy system revolves around this feature. Nevertheless, the primary function does not necessarily have to be an urban farm in order to meet this requisite.

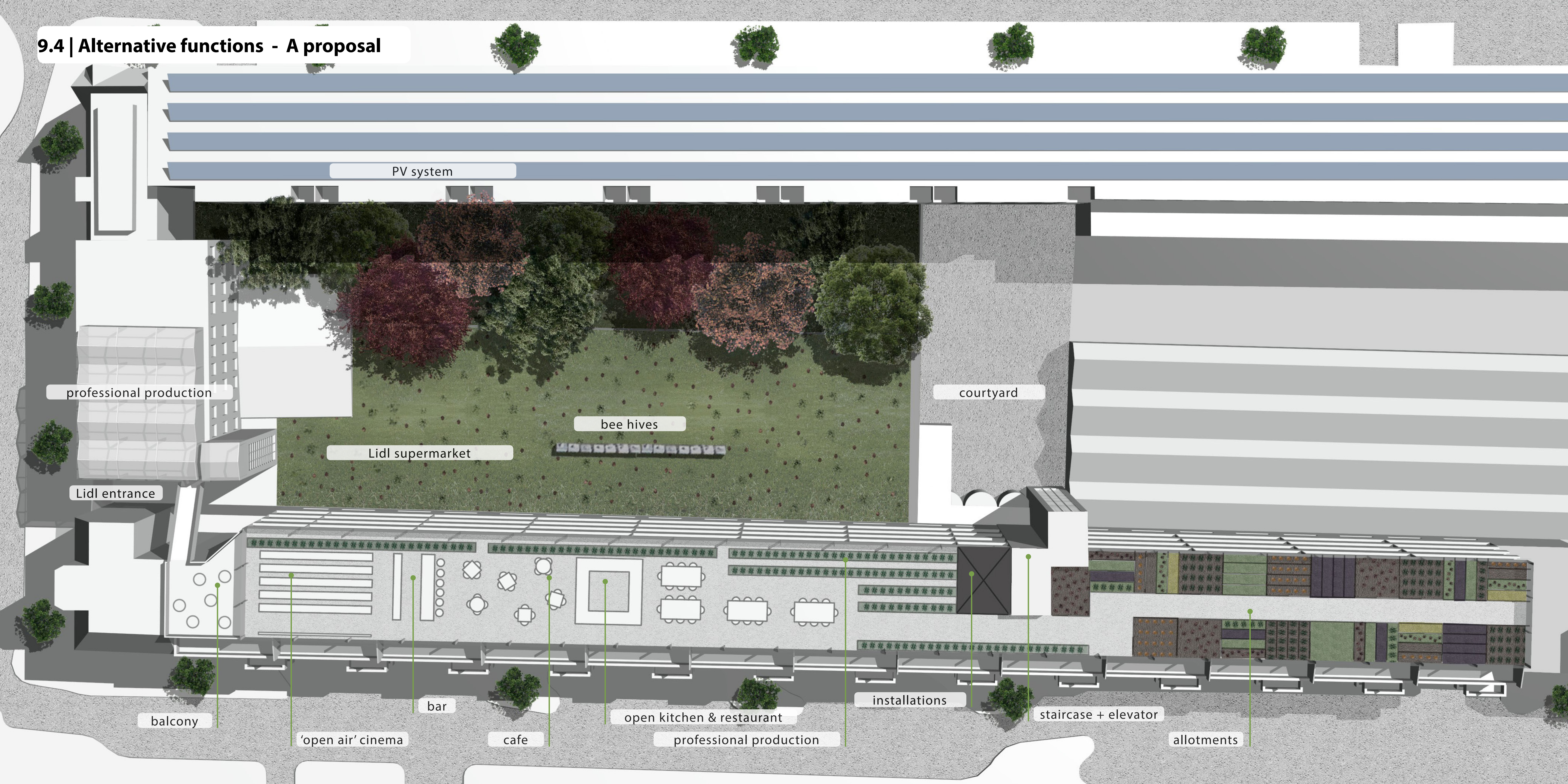
Finding the best solution/design for social sustainability in this specific context is a whole new study. Nonetheless, there is one aspect that is fundamental to the cause: physically bringing people together. Alternative functions than an urban farm have more potential to directly commit to the social cohesion. A second question that should be asked is: which function(s) could contribute to the overall attractiveness of the city block and neighbourhood?

A proposal in which not only the Lidl, but the whole neighbour profits from the urban upgrade would be preferable.

Some alternatives:

- Indoor allotments ('Volkstuintjes'). The warm indoor climate would allow locals to grow their own food throughout the full year.
- Catering function like a coffee corner or small restaurant. The served vegetables and herbs could be produced locally and the business could be organized by the Lidl itself;
- Rooftop playground. The greenhouse forms a safe, dry and enclosed public area that can be locked at night;
- Exhibition / sculpture garden for local (outdoor) art;
- Botanical garden / public park. Many botanical gardens have a greenhouse section on their grounds;
- 'Open air' cinema. A cinema with a view (common in Mediterranean countries). The enclosed and sheltered environment allows for a long movie season;
- Market space. During winter months, small neighbourhood markets and garage sales could be organized in this large space instead of going on a winter intermission;
- Public space. An open space that can (partly) be used for any residential initiatives and purposes they see fit;
- Urban camping. Cheap tourist accommodation on a central location like this could be very attractive in a tourist city like Amsterdam. This does however not directly give back to community.

9.4 | Alternative functions - A proposal



Conclusions & Discussion

Chapter X

10.1 | Research conclusion

How can we combine the energy flows of a supermarket and a greenhouse and connect them to the adjacent dwelling to reduce the cumulative environmental footprint of the three functions?

A CO_2 reduction of 60% can be achieved if the greenhouse and the supermarket form an energetic synergy, in which the greenhouse heating requirement is partly covered by the supermarket heating surplus. The greenhouse functions as the solar collector in the energy model. It generates sufficient thermal energy during summer on which the dwelling and greenhouse can rely during winter. This delayed energy sharing is only possible by means of open source underground energy storage. In the winter, the same storage system is used to accumulate cooling energy to meet the greenhouse's summer cooling demand. The Amsterdam canal system forms the cold source for the system. The Lidl supermarket is also connected to the underground storage system: in winter, the rejected heat from the product cooling installations is used to pre-heat the warm return water before it is pumped to the heat pumps. This increases the efficieny of these pumps. In summer, the rejected heat warms up the water before it is pumped into the earth, so that it maintains a steady temperature of 25°C.

The objective of this research is to lower the cumulative carbon footprint of a greenhouse, Lidl supermarket and adjacent dwelling by energetically connecting them with each other. A designated city block in Amsterdam forms the research case of this study.

Five potential components
One gallery flat with 77 households and one apartment building with 44 households in this city block that show the most potential have been identified. The greenhouse forms the a new element that is introduced to the urban environment. In theory, there is space for two separate greenhouses of 856m^2 and 851m^2 on the rooftops of the aforementioned residential buildings. The Lidl supermarket forms the fifth component.

Summer and Winter system
Two energy models have been designed: a summer and a winter model. The summer design revolves around the cooling of the greenhouse + heating of the dwelling and the charging of the underground thermal energy storage system. The winter model is reversed and revolves around the heating of the greenhouse + dwelling and the charging of the cold source.

1 Lidl supermarket
15 x 46m, T_{IN} = 21°C

\+

1 rooftop greenhouse
8 x 107m, T_{in} = 11-27°

\+

124 households
622m^3 gas / household

connected according to energy model

60% cumulative CO_2 reduction

or **452 ton** /year

Local grid - balancing the energy system
Calculations point out that one 8x107m rooftop greenhouse, that is kept on an indoor temperature of 11°C-27°C and that is integrated in the energy system according to the design in this study, can generate enough thermal energy during summer to sustain the 124 households. A condition is that the thermal energy demand of the included apartments is reduced by 33%.

Energy
The 124 households in the two apartment buildings have a combined heat demand of 753 MWh/yr. The greenhouse shows a heating demand of 107 MWh/yr and a cooling demand of 744 MWh/yr when the indoor temperature range is set on 11-27°C. Before integration in the new energy system, the Lidl supermarket has a cooling demand of 120 MWh a year when T_{IN} = 21°C. The Lidl has no heating demand. By making an energy connection between the Lidl supermarket and the greenhouse, the supermarket's cooling demand can be reduced to 56 MWh/yr (-54%) and the greenhouse's heating demand can be reduced to 46 MWh/yr (-57%).

CO_2 contained
The effect of the new energy system is expressed in primary energy CO_2 emissions [metric ton]. According to the calculations performed in this study, the present components have a cumulative CO_2 emission of 749 tonnes a year. If all the components are put into a local energy grid that is according to the design in this research, 298 tonnes CO_2 emission remains. This is a reduction of 60%.

10.2 | General discussion - conclusions

This research points out the confident effect of including a greenhouse in the built environment and implementing an energetic synergy between this greenhouse, adjacent dwelling and a mid-sized supermarket. Nevertheless, the final result of this study does not present the only solution and there is room for discussion.

Points of argument include (but not limited to):

1. The inefficiency of high temperature heating installations integrated in a low temperature energy system.
2. The incentive to opt for one highly cooled greenhouse instead of two greenhouses that are more tolerable on the maximum indoor temperature to balance out the energy system;
3. Lowering the dwelling heat demand by 33%?;
4. Taking a sustainable position as a building engineer instead of a profitable position as an economist.

(1) Low temperature energy grid

The words *local energy grid* have been used many times in this study. Within the domain of this research, it refers to an energy system that operates on a low temperature (~35°C) and does not have inter-district energy lines. The system would cover one building, a cluster of buildings or at maximum, a neighbourhood. Energy lines are kept short and preferably easy and cheap to install. As inter-district connections are excluded, no industrial high-caloric thermal energy sources are connected to the grid, hence the low temperature.

The study case in this research contains apartment buildings that are heated by conventional high temperature installations. Heat pumps are the most efficient if the temperature jumps are kept small. Partially for this reason, the technology is more common in recent city expansions or buildings that are heated by floor heating or CCA, preferably with the input from a 'free' heat source. The large temperature jump in this context (26°C to 50°C-65°C) drastically reduces the efficiency of heat pumps (COP=3.1). This makes this gas-free alternative not compatible with conventional methods if performance is expressed in primary CO_2 emission. For the heating of the apartments, calculations point out much lower CO_2 emissions in the present system than the updated system.

Point being: further research is needed on the integration of high temperature heating installations in low temperature energy grids. The preferable solution would be alterations on the component level, like switching from high temperature radiators to low temperature floor heating systems. This is however a radical and costly intervention that is not always suitable in old 20th century city blocks.

(2) One/two greenhouses

The new energy grid is connected to an underground energy storage. Regarding the temperature, this storage must to kept in balance on a yearly base (by law). If all the components are connected to the system on their maximum size: 124 households, 2 greenhouses (T_{IN} = 15°C-30°C) and one Lidl supermarket, the total energy system would not be in balance. To achieve a balance, two alternative options are thought up and evaluated:

1. ~1.5 greenhouse on 15°C-30°C & 124 apartments or;
2. 1 greenhouse on 11°C-27°C , 124 apartments.

The choice was made for the second option. Main motivation for this is the doubling of the available potential rooftop surface for expanding the PV-system if one greenhouse is abandoned. Gas is designed out of the new energy model and so the electrical energy demand increases due to the application of heat pumps. The conventional production of grey electricity emits a lot of CO_2 (0.526kg/kWhp), where the production of renewable energy is free of emission (excluding embodied energy). It benefits the cumulative CO_2 emission of the system when a large part of the electricity demand will be covered by energy generated on site.
On the other hand: the whole system now relies on one single greenhouse solar collector. This makes it harder to guarantee that at the end of the summer season, enough thermal energy is stored underground to sustain the system throughout the whole winter. What if a cold and mild summer is succeeded by a strong winter? Having two greenhouses would greatly reduce the risk of having insufficient energy stored. Other considerations against a single-greenhouse model also include: strict cooling set-points and 50% decrease in production capacity.

(3) Dwelling heat demand reduction

The greenhouse indoor climate has been set on 11-27°C, it is undesirable for crop production to shift this range any further down. So, in order to include all 124 households whilst still using only one greenhouse structure, the heat demand of the households should be brought down with 33%, from 810 m^3 to 619 m^3 gas per household. Preferably this should be achieved with the minor interventions that are mentioned in §7.7.3. Whether this reduction is achievable in practice should be further investigated. If this would not be manageable with the proposed interventions, the number of included apartments has to be lowered or more radical and costly energy saving methods should be applied.

(4) Profitability submissive to sustainability

This final design for the energy system comes forth from a sustainable point of view. Relative to the starting point at maximum system capacity, alterations to the system parameters are made in such a way that the system can sustain itself while using only one greenhouse. This decision comes at the cost of productivity on the one hand but also requires only half the investment/maintenance costs on the other hand.

If this research were to be developed from the perspective of economy and profitability, opting for a double greenhouse system would be a much more viable choice. The greenhouses would then require a strict and intense climate to optimise annual yield.

10.3 | General discussion - Limitations

The set-up and outline of this study have some weaknesses.

Greenhouse energy balance

This study requires expertise on greenhouse agriculture as well as building engineering and energetics. Fundamental information to acquire before designing an energy system is knowing when, where and how much energy is required or available. This is done by defining and calculating the energy balances of each included component. Defining an energy balance of the greenhouse relies on expertise that balances on the border of building engineering and the field of agriculture. In the basics, it is possible for a building engineer to calculate the in- and outgoing fluxes of a glass greenhouse construction as it shows many resemblances with standard atria. The moment plants are added to the greenhouse, expertise on plant responsive behaviour to indoor and outdoor climatological aspects is vital. The influence of plants on the indoor climate is in this research based on educated assumptions. This still adds a level of uncertainty to the energy balance of the greenhouse.

Rules and regulations

This study addressed just the energetic viability of connecting a greenhouse with a supermarket and apartment buildings. In actual urban design, the viability of local energy grids also has social, economical, technical and jurisdictional determinants. The last one will in practise be the most influential factor. In this sense, this research is mainly theoretical and a translation to reality would require many field studies, local political and residential support, management enthusiasm and permission/exemption processes. Nevertheless, there are precedents that indicate the (economical) success of these projects.

Transport losses and inefficiency greenhouse cooling

In the design of the new energy system, it is assumed that the total calculated greenhouse thermal energy surplus (read: cooling demand) is retrieved from the greenhouse space and stored underground for later use. This is done by means of floor cooling, where the cold water extracts the energy from the greenhouse floor. In practise, this maximum energy transfer efficiency between the greenhouse and the storage is most likely not achieved. Furthermore, more detailed calculations, have to point out the efficiency of this cooling/energy retrieving method in practise. Transport losses -even though the distance is very short- are also not taken into account. If these system+installation inefficiencies and losses add up, it might be concluded that again two instead of one greenhouse is required to keep the energy system in balance and to guarantee enough thermal energy storage during summer to sustain the system in winter. At least it is good to know that there is space for that in this context.

Transferability

Results from this study are not necessarily transferable. Each city block is unique and for that, each city block should to be reassessed to seek for potential energy combinations and synergies. Not all city blocks have large and convenient flat roofs to install greenhouses on. Not all city blocks contain a supermarket and neither is there always a large body nearby that can function as the cold source. Logically, local energy grids do not inevitably have to contain a supermarket or a greenhouse. This research has not been conducted to prove that a greenhouse-dwelling-supermarket energy triangle is the only solution for reducing the carbon footprint. This research points out that for a specific city block in Amsterdam, a supermarket, greenhouse and apartment buildings can work together to be disconnected from the gas network and bring down the cumulative CO_2 emission. In the end it is about looking for small scale energetic potentials in the existing built environment that can help bringing down the urban environmental footprint.

Calculations and energy tool

All the calculations concerning the energy balances, PV yield and CO_2 emissions have been performed in Microsoft Excel. At the end of the research the worksheets contained enormous amounts of numbers and graphs. Even though this research has been performed with great care, caution and accuracy, minor calculation or typing mistakes can not be ruled out. The excel tool and work sheets are available for further application in research and can be retrieved from the TU Delft repository.

Despite the concerns, this study may offer insight and inspiration in the potential and positive impact of local energy grids.

10.4 | Recommendations for future research

Bringing greenhouses to the urban environment has been done in several projects already. Adding small scale greenhouses to city blocks for energetic purposes is new. Realization of this type of local energy grids in the future requires additional research in the following domains:

Financial viability. Maintenance costs or the greenhouse business model have not played a decisive role in this research. Investment costs have in general been taken into consideration but these are not elaborated nor expressed in (estimated) amounts. In reality, the financial perspective would play a role in determining the minimum scale of the greenhouse. The economical viability requires concrete numbers before any (rooftop) greenhouse is constructed.

Crop variety. Efficiency in production increases if a greenhouse produces only one crop species. However, if the greenhouse is directly providing for one nearby supermarket, a variety of crops is desirable. Demand and supply need to be matched with each other in order to find the most effective crop composition.

Competitiveness with conventional food production.
The energetic and financial costs and benefits of local production need to be compared with traditional food import. How can local food production out-compete the current food production and distribution? In other words: how can this Lidl Greenhouse combination establish itself in the current food system?

CO_2 sources. Research on how the indoor CO_2 concentration of the greenhouse can be raised with the aid of the adjacent buildings is desired. What are the options of a *local CO_2 grid*? Would pumping the exhaust air of the adjacent dwelling perhaps benefit the plant growth and food production? Is the investment in infrastructure worth the gain from production increase?

Climate systems. Heat for the underground storage is extracted from the greenhouse by pumping cold water (>18°C) through the mass of the floor. The total thermal energy that is extracted from the greenhouse is assumed to be equal to the cooling demand of the greenhouse. Further research is required to see if this is actually the case. If not, a larger greenhouse might in reality be needed to meet the minimum energy storage required.

Existing urban context & new context
From the calculations in the research it can be concluded that the local energy grid would perform better (expressed in CO_2 emission) if all the components run on low temperature heating. Keeping the temperature jumps in the heat pumps as small as possible mitigates the electrical energy investments of the heat pumps, making them a much better alternative than gas-based installations. Nowadays, this is usually only the case in modern buildings and new neighbourhoods and not in old city centres. More research could be done on increasing low temperature energy to high temperature energy on a sustainable way, so that the greenhouse method in old inner cities becomes even more attractive. The best solution would be to find non-industrial functions, located in city centres with a high temperature waste heat.

Biomass as fuel.
Growing vegetables also produces inedible (dry) biomass as a waste product. The greenhouse from this research would produce an estimated 2400kg each year. (Graamans, 2015, table A2.2). Research on how this biomass can best serve as biofuel for the generation of heat and electricity is needed. Perhaps, a part of the dwelling's high temperature energy demand can be retrieved from a local biomass plant. This would contribute the overall CO_2 containment of this energy system.

10.5 | Lidl validation & TU Delft research

Lidl involvement/validation

Throughout the course of this research, close contact was maintained with Arnold Baas, manager Energy matters at Lidl Holland. During the final stage of the research, the Lidl was invited to the university for a progress report on the TU Delft research and this thesis. During this meeting, the research methodology, the energy system, the provisional conclusions and the first urban designs were presented and discussed. Partly based on the new insights and information gained during this meeting, the research was continued and the designs were further elaborated.

Before submitting the final version of this research, the thoughts of the Lidl on the concept, energy system & urban design were discussed. These are the first questions/uncertainties that emerged after the intermediate presentation:

- *Structure*: Construction strength and structure of the buildings supporting the greenhouses;
- *Organisation (1)*: Actual implementation of the plans in this research means collaboration with a lot of parties, mainly residents and municipality. The more people involved, the more opinions that need to be respected and administrative/bureaucratic related delays will sky rocket;
- *Organisation (2):* Also Baas acknowledges that highly intensive urban farming is not the best function for the glass structure. An in-between solution should be persuaded in which both the Lidl as well as the local residents have direct profit. How the Lidl is going to organise and exploit this function, is a agenda item for internal discussion.
- *Permits:* Baas is convinced that a forward-thinking city like Amsterdam is open towards progressive and unconventional urban interventions like the one elaborated in this research. However some concerns arise regarding city planning permissions, ownership rights, municipality regulations or housing corporations.

TU Delft research - Contacts & chronology

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Chronological outline of the research:
- February '17 - First contact with the Lidl;
- April '17 - Commencement of the research;
- May '17 - Introduction student & first pitch (Luuk);
- December '17 - Mid-term presentation Luuk & Nick + discussion;
- January '18 - submission TU Delft research + student research.

10.6 | Acknowledgements

One year ago, I would not consider doing a fully energy related graduation research. However, as this research proceeded it gradually converged into designing a small scale local energy system with the objective to maximise the CO_2 reduction. Now I can say that I absolutely do not regret this development. It was educational, to step out of the familiar world of detailing and facade design and gain all the new knowledge and perspectives on sustainability, energy, circularity and urban design.

It has taken the support, input and expertise of a variety of people to produce this specific work.

First of all I would like to thank Prof. dr. ir. Andy van den Dobbelsteen for his support and open-mindedness throughout the research. At the commencement of my research, he let me free in finding my own circularity related challenges and he actively involved me in his own Lidl research. This confidence is very much appreciated. In addition to this, I am still very thankful for giving me another abroad opportunity earlier in 2017.

I would like to thank dr. ir. Peter van den Engel for his *to the point* tutoring, in which his directness exactly reminded me where my level of knowledge was in regard of specific topics. I genuinely appreciate this form of guidance and it always motivated me to immediately dive deep into the literature again or to think twice about my design decisions.

Luuk Graamans took the role of third mentor upon him during my graduation research. I would like to express my appreciation to him for helping and taking the time for me during my research, in particular during the start-up phase. Luuk´s own vertical urban farming related graduation thesis formed a helpful guide to my own research.

In respect to gaining insight in all things energy related to the Lidl supermarket, I would like to say special thanks to Arnold Baas. As the representative for the Lidl, Arnold took the time for me as the external mentor and provided me with all the necessary data, knowledge, experience and a literal behind-the-scenes look at the Lidl. Arnold was easy to reach and his helpfulness and openness certainly contributed for this study to reach a level of accuracy that would otherwise not be possible. Along with this, I would like to thank the rest of the Lidl team, who initiated this TU Delft-Lidl collaboration in the first place.

Finally, I would like to express my gratitude to a special friend. Without her aid, expertise and time, my report would have been much less visual. I sincerely hope there are going to be many more of these collaborations in the future.

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Spread chapter III, page 52: *Accenture Consulting (date unknown). Coop_Italia_Marquee. Retrieved from https://www.accenture.com//www.accenture.com/t20170203T014539__w__/us-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Images/Local/us-en/9/Coop_Italia_Marquee.jpg*

Spread chapter IV, page 66: *ADAS U.K.. (2017, February 16). New categorisation of food scares will help develop strategies to prevent food chain being compromised [Photograph]. Retrieved January 4, 2018, from http://www.adas.uk/News/new-categorisation-of-food-scares-will-help-develop-strategies-to-prevent-food-chain-being-compromised*

Precedent study page 73: *Google Inc.. (2017, June). [Screen capture of Google streetview. Location: 188 Alberdingk Thijmstraat Amsterdam, Noord-Holland] [Photograph]. Retrieved October 12, 2017, from https://www.google.nl/maps/@52.3638224,4.8762816,3a,73.7y,29.41h,102.92t/data=!3m6!1e1!3m4!1slRTbAE9cPL4K6_QhF7EH5g!2e0!7i13312!8i6656*

Presendent study page 77: *Distrifood. (2014, September 29). [Discounter Lidl trekt de groene kaart] [Photograph]. Retrieved October 27, 2017, from http://www.distrifood.nl/formules/nieuws/2014/9/discounter-lidl-trekt-de-groene-kaart-10121943*

Spread chapter VI, page 120: *Eemsbode. (2017, April 12). Ook de Lidl verhuist naar de zuidzijde van de Willemstraat. [Photograph]. Retrieved October 31, 2017, from http://www.eemsbode.nl/nieuws/40628/woonservicezone-delfzijl-met-80-woningen-ah-en-lidl/*

Spread chapter VII, page 128: *Duurzaam Den Haag. (2016, April). Dakboerderij De Schilde op 20 mei open voor publiek [Photograph]. Retrieved January 4, 2018, from http://duurzaamdenhaag.nl/dit-zijn-we/blog/dakboerderij-de-schilde-20-mei-open-publiek*

Spread chapter VIII, page 180: *Lidl. (2017, May 19). 11 Reasons You're Going to Want to Shop at Lidl [Photograph]. Retrieved November 13, 2017, from https://www.popsugar.com/food/Reasons-Shop-Lidl-43551313*

Spread chapter IX, page 204: *Catering Meesters - Kookkunst op Locatie. (n.d.). Fresh.Revolution! [Photograph]. Retrieved January 5, 2018, from http://www.cateringmeesters.nl/urbanfarmers/*

Spread chapter X, page 214: *Eginoire, S. (2015, January 1). Wholesum Harvest employee Jesus Solis harvests ripe tomatoes off hanging vines; these tomatoes will get shipped across the country. [Photograph]. Retrieved January 4, 2018, from http://ediblebajaarizona.com/high-tech-organic-wholsum-harvest*

Spread appendices, page 234: *Gotham Greens. (2015, October 24). 3 friends built a greenhouse on a roof and got 625 tons of produce! [Photograph]. Retrieved January 4, 2018, from http://www.collective-evolution.com/2015/10/24/3-friends-built-a-greenhouse-on-a-roof-got-625-tons-of-produce/*

Appendices

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| APPENDIX I: Decomposing the electricity demand - §4.4.2

Intro

The electricity demand can be decomposed into the following posts:

- Product cooling;
- Lighting system;
- Product preparation / bake-off;
- Building climatising;
- Rest.

This chapter explains how these posts are determined / estimated for the Lidl supermarket in Stein. Once the distribution of Stein is known, the percentages can be projected on the Lidl in Amsterdam.

The percentages found for the Lidl in Stein are compared to values that can be retrieved from literature (table 10.4).

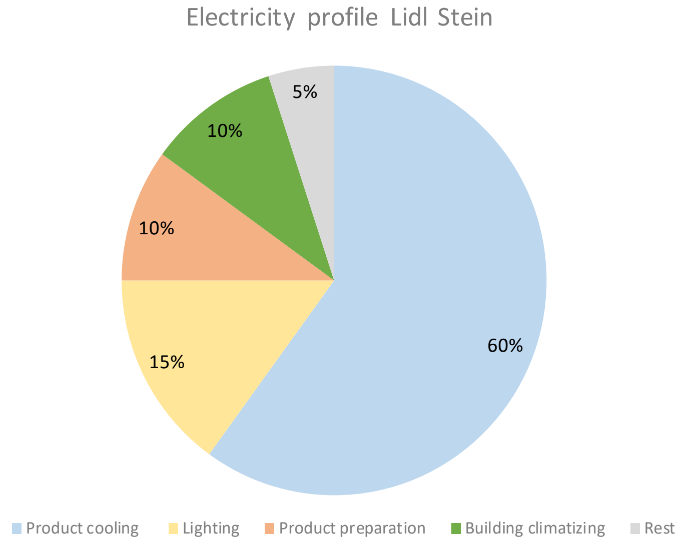

Figure A1.1: Estimation of the electricity distribution for the Lidl Stein.

(1) Product cooling

The calculation of the percentage of *product cooling* -the largest electricity post in a standard Lidl supermarket- is based on the idea that outside opening hours this post is the only active electricity consumer. Small 24/7 devices like CCTV systems and security lights are not taken into account. We also assume that the climate system of the supermarket is kept on an minimum when the shop is closed.

By calculating the energy use outside opening hours and by assuming this use is fully consumed by the product cooling units, we can subsequently determine what the energy use by the cooling displays should be for the full day. For this we use Figure A1.2.

Figure A1.2 is based on figure 4.9 in chapter 4. The green curve represents the average value of each first day of the month. Table 10.4 in Figure A1.3 displays the values from the graph.

Through calculations we find that about 60% of the electricity demand is consumed by the cooling displays on the sales floor and the freezing cell.

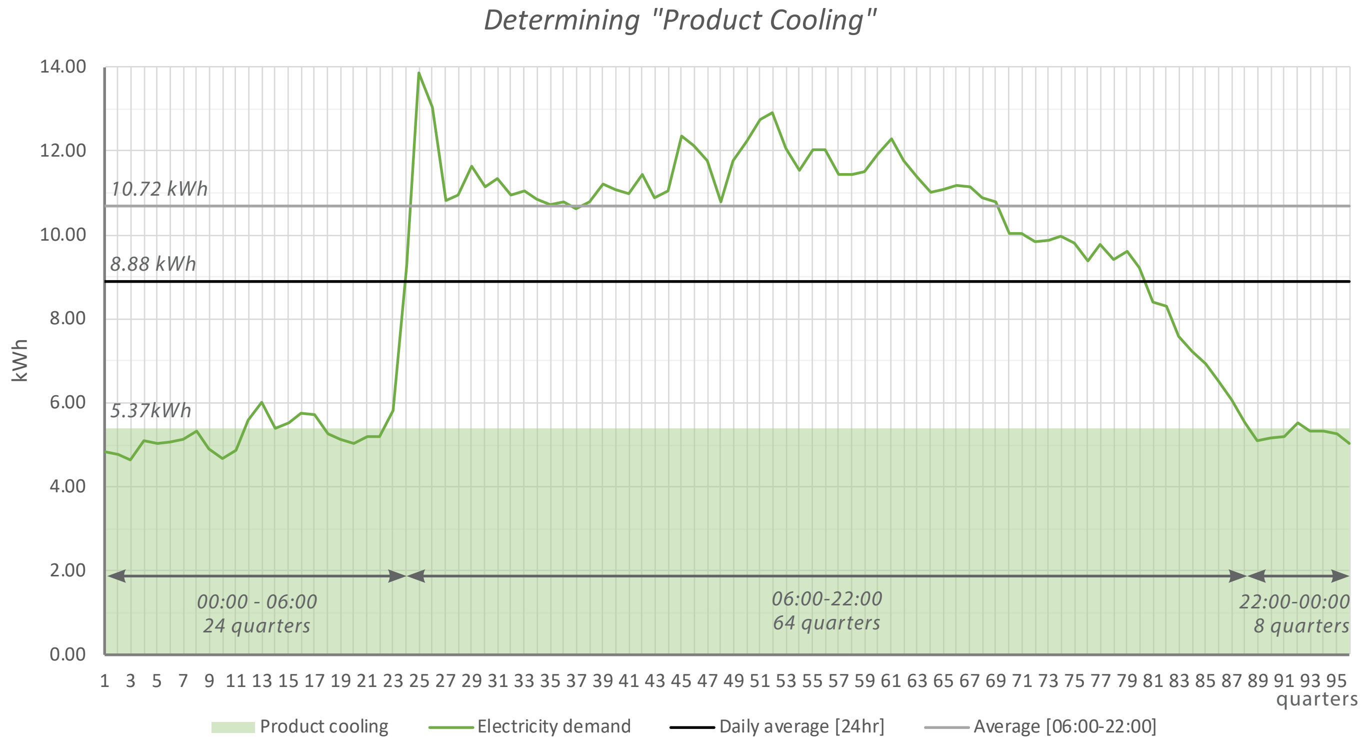

Figure A1.2: Development of the eledtricity demand during the day

Table 10.4	time slot		# quarters	x̄ kWh/15min *(from graph)*	tot. kWh / day *(from graph)*	Δx̄ kWh	Post	#quarters x Δ kWh	%
Open	06:00	22:00	64	10.72	675	5.37	Other	343	40%
Closed	22:00	06:00	32	5.35	177		Product cooling	514	60%
Daily average/tot.	00:00	24:00:00	96	**8.88**	**852.10**			**857.46**	**100%**

Figure A1.3: Table 10.4: Determining the electricty demand by product cooling

| Appendix I: Decomposing the electricity demand

Chapter 4

(2) Lighting

The electricity consumption by the LED lighting system of the supermarket can be calculated from the infographic that the supermarket has made to promote their sustainable flagship.

In the highlighted square you can see that the 100% LED system saves this Lidl about 31% electricity relative to conventional lighting system (in Dutch). They also mention this equals about six households. Through a quick calculation the total electricity consumption by *lighting* can be determined:

- 1 household in the Netherlands = 3500 kWh;
- 31% = 6 households = 21.000 kWh;
- 100% = (100/31) x 21.000 = 67.750 kWh;
- 67.750 - 21.000 = 46.750 kWh;
- Total electricity use Lidl Stein = 318 MWh;
- 47MWh / 318MWh = ~15%

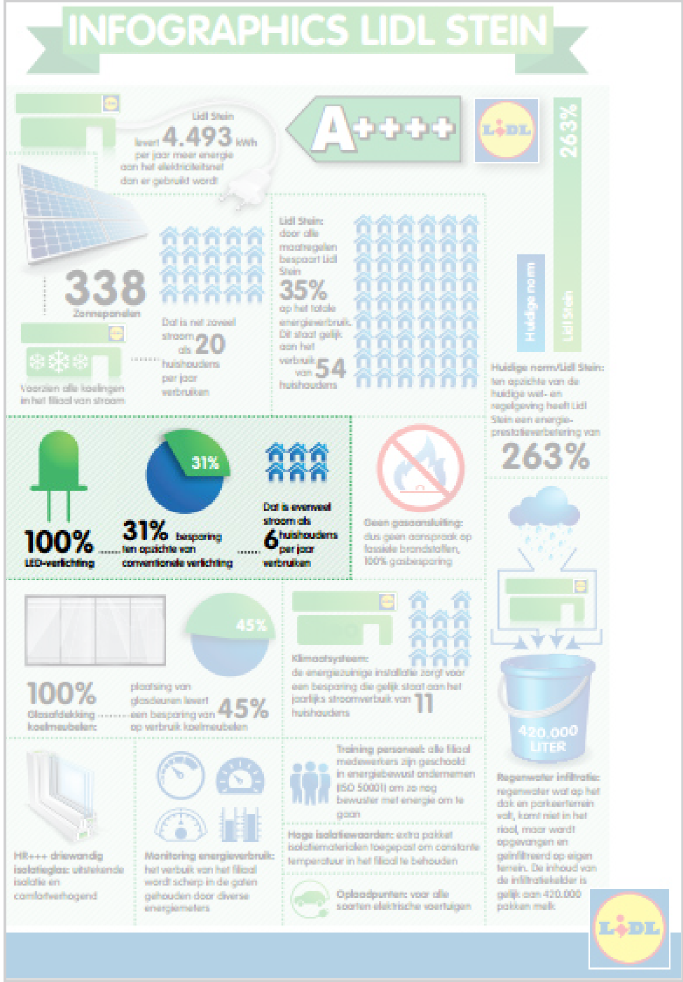

Figure A1.4: Lidl Stein Infographic. From ENERGIEvastgoed.nl[1]

(3) Product preparation, Building climatising and Rest.

Without additional energy data, it is not possible to give a calculated indication of the percentages for Product *preparation, Building climatising* and *Rest*. That is why these final 3 posts are estimated based on literature survey.

Product preparation. Literature gives 14% and 8%. Since Lidl Stein is a recently built and modern supermarket, we assume the electrical ovens have better electrical performance. We assume a lower value and stick with 10%.

Rest. This value is directly adapted from Meijer (2009) and is set on 5%.

Building climatising. What remains is building climatising: Roughly 10%.

Other sources

Calculated values are validated with literature survey. For *product cooling* we find comparable values. For *lighting* we find 18% & 26%, this is lower than 15%. This can be explained by the fact that the sources date from 2009. The Lidl A^{++++} in Stein dates from 2014 and uses 100% LED lighting, thus resulting in a lower percentage. Both sources do not give a value for *building climatising (BE)*, One probability is that Jans included BE in the rest post. In the overview by Meijer, BE was 100% gas based and therefore not comparable with this supermarket, leaving the post blanc (-).

The values by Meijer are gives per m^2. The values by Jans are based on a supermarket with a GFA of 1350Mm^2 and a sales floor area of 950m^2. Both sources can therefore be compared with the Lidl in Stein.

row	Table 10.3	*SenterNovem - Jans [1] (2009)*	*Meijer [2] (2009)*	Lidl Stein
1	Product cooling	*52%*	*61%*	60%
2	Lighting system	*18%*	*26%*	15%
3	Product preparation / bake-off	*14%*	*8%*	10%
4	Building climatising	-	-	10%
5	Rest	*16%*	*5%*	5%
6	Total	*100%*	*100%*	100%

1) Jans, R. (2009). Wat is hot en not bij koeling supermarketen [presentation]. Retrieved from http://www.coolsultancy.nl/wp-content/uploads/Wat_is_hot_en_not_bij_supermarkten.pdf

2) SenterNovem. (2007). Cijfers en tabellen 2007 (2KPGE-07.05). Retrieved from https://www.rijksoverheid.nl/documenten/brochures/2010/08/23/cijfers-en-tabellen-2007

Figure A1.5: Table 10.3: Energy profiles retrieved from literature.

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[1] *http://www.energievastgoed.nl/2014/09/16/supermarktketen-lidl-scoort-eerste-a4-label-en-realiseert-35-energiereductie/*

| APPENDIX II: Energy balance Supermarket - §5.3.1

Overview

Overview energy fluxes

The energy balance in the supermarket is represented by the following equation (Figure 4.11):

$$q_{LIGHT}+q_{PERSON}+q_{EQUIP}+q_{BAKE}+q_{TRANS}+q_{INF}+q_{VENT}+q_{COOL}=0 \quad [5.2]$$

where

q_{LIGHT}	Represents the interior heat load by the lighting system;
q_{PERSON}	Represents the interior heat load emitted by the customers and staff;
q_{EQUIP}	Interior heat gain by operational equipment and thermal energy emitted by the product cooling machines;
q_{BAKE}	Heat gain by the bake-off section (ovens);
q_{TRANS}	Heat transfer through the facade, floor and roof construction based on the temperature difference between the interior and exterior;
q_{INF}	Cooling load by the air infiltration due to main entrance door openings;
q_{VENT}	Represents the heat exhausted by the ventilation system;
q_{COOL}	Represents the surplus heat extracted from the greenhouse by means of a cooling system, this can be either thourgh floor cooling (q_{FLOOR}) or by HVAC system (q_{HVAC}).

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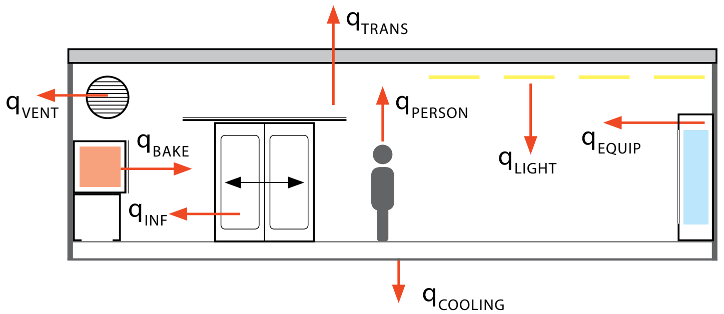

Figure A2.1: Fluxes in the supermarket

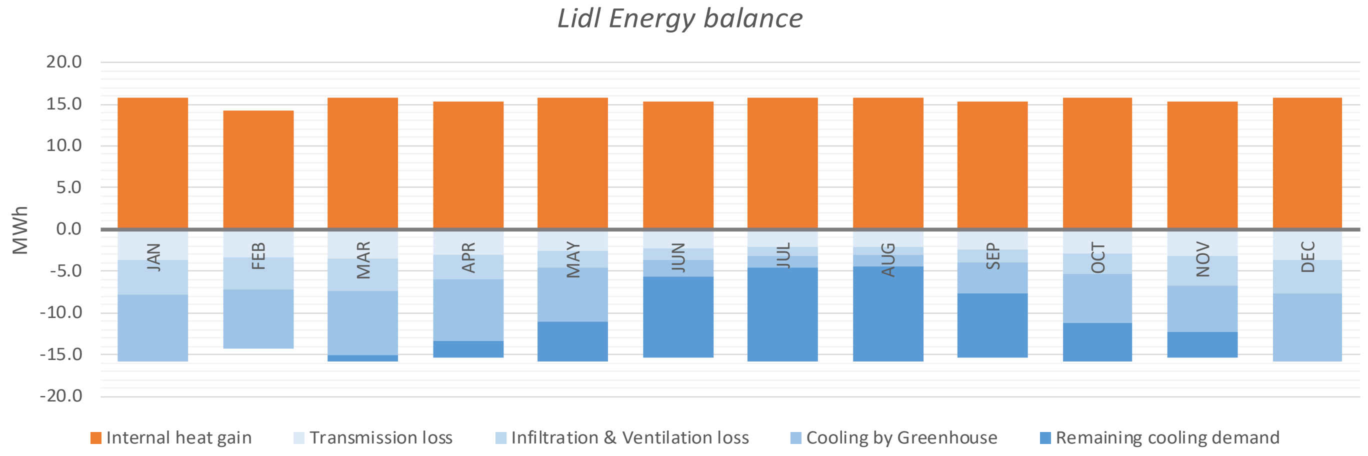

Figure A2.2: 12month energy balance supermarket

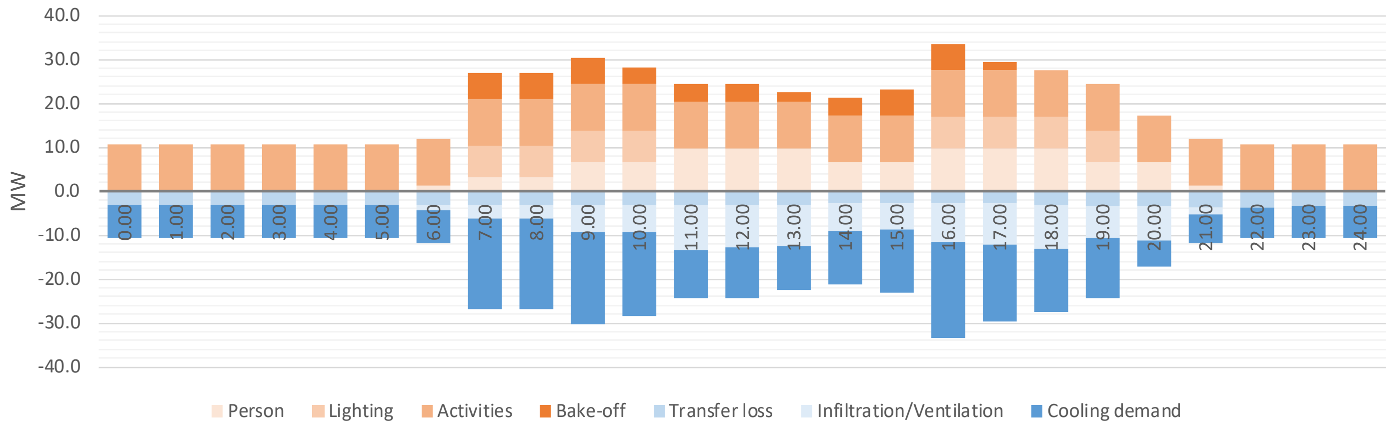

Figure A2.3: 24hr energy balance supermarket

row	Table 10.2	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	[-]
1	Global Horizontal irridiance[1]	79	143	212	248	309	310	308	282	219	151	96	61	W/m2
2	Percentual difference from qsun max. (July)	26%	46%	69%	81%	100%	101%	100%	92%	71%	49%	31%	20%	%
3	Average outside dry buld temperature[2]	4.2	3.7	5.3	8.4	12.7	15.2	16.9	17.1	14.4	10.9	6.5	4.4	°C
4	Calculation tempere T_{IN} GH[3]	18.5	18.5	20.8	20.8	20.8	22.0	22.0	22.0	21.3	21.3	21.3	18.5	°C
5	Full sun hours (2016 data)	20.9	40.7	80.0	123.7	162.5	160.0	159.0	139.0	103.0	60.0	25.0	16.0	hrs

1) Source: Climate consultant - Amsterdam Weather station

2) Source: Climate consultant - Amsterdam Weather station

3) Temperatures applied to calculate the heat loss through the floor of the greenhouse

Figure A2.4: Climate parameters used for determining monthly energy balances

| Appendix II: Energy balance Supermarket

Customer occupancy and climate values

Customer occupancy

According to the Dutch building code, the occupancy rate for a building with a retail function is 0.05 person/ m^2, or $20m^2$/person. For the calculation we apprehend the total floor surface and not only the sales floor. This results in:

$993m^2$ / $20m^2$ = 50 persons.

For the Lidl Helmersbuurt we include a safety factor of 1.5:

44 * 1.5 = 75 persons.

During the course of the opening hours, we assume the customer occupancy to proceed according to the curve below. To simplify the calculation we assume that there are 10, 25, 50 or 75 people in the supermarket. We assume occupancy peaks between 10:00 - 13:00 and 15:00-18:00. Before and after opening hours, there are 10 members of the staff present in the store.

Infiltration rate, ventilation rate and heat gain by people are 1-on-1 linked to the amount of customers that are present in the supermarket. For these calculations, the numbers in the graph are used.

To calculate q_{INF}, q_{VENT} & q_{PEOPLE} for the 12month energy balance, we take the average 24hour customer occupancy: which is 33 persons. This equals 44% (33/75=0.44) of the maximum customer occupancy and this reduction factor is included in the calculations.

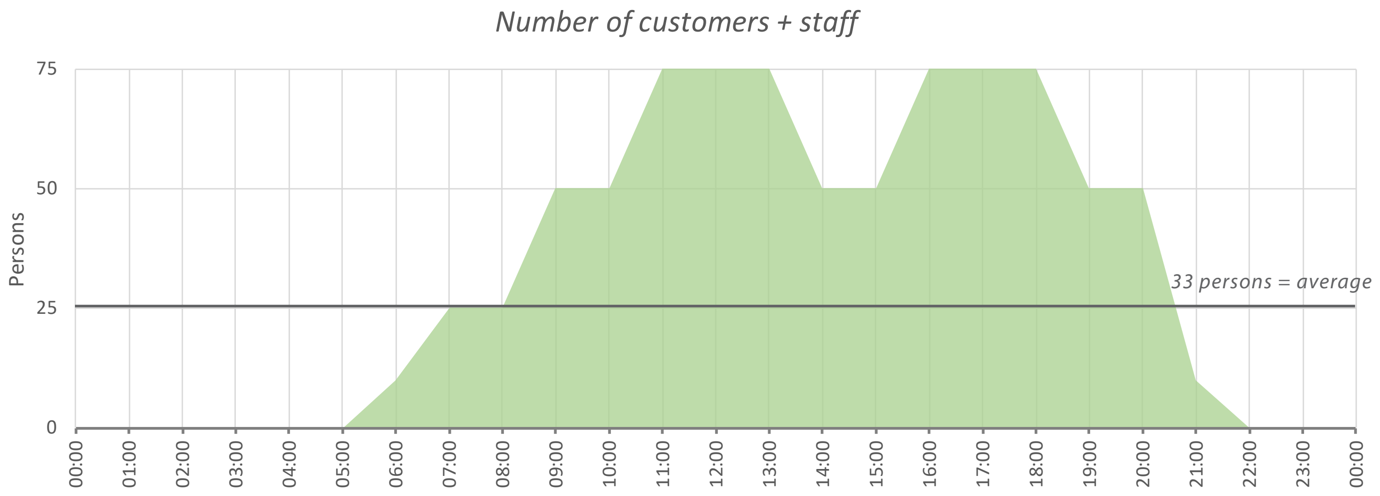

Figure A2.5: Customer occupancy during the day

| Appendix II: Energy balance Supermarket

External fluxes

Transmission loss

Heat transfer through the facade, floor and roof based on the temperature difference between the interior and exterior. Calculated according to equation 10.1:

$$q_{TRANS} = U*A*(T_{IN} - T_{OUT}) \qquad [10.1]$$

where

q_{TRANS}	Heat loss through facade [Watt]
U	Heat transfer coefficient [W/m^2.K];
A	Surface of facade (roof, walls or floor) [m^2];
T_{IN}	Interior air temperature of the supermarket. For the calculations in the study a T_{IN} of 21°C is apprehended [K].
T_{OUT}	Ambient dry bulb air temperature [K]. Value depends on season. See table x.

U-values apprehended:

- Floor - 0.25W/m^2.K
- Walls - 0.22 W/m^2.K
- Roof - 0.17 W/m^2.K

Supermarket facade:

- Length - 46.0m
- Width - 15.4m
- Height - 2.9m

Also:

- This supermarket does not have any windows.

Infiltration loss

Cooling load by the air infiltration due to main entrance door openings. Calculated according to equation 10.2:

$$q_{INF} = r *q_v * c * n * (T_{IN} - T_{OUT}) \qquad [10.2]$$

where

q_{INF}	heat loss though cold air infiltration [Watt]
q_v	infiltration rate [m^3/s]. In this study, a standard value of 0.625dm^3/s/m^2 is used (value provided by the Lidl). For this supermarket (708.4m^2), this value equals 0.43m^3/s or 1548m^3/hr.
r	density air, 1.21 kg/m^3
c	specific heat capacity, 1005 kJ/kg.K
n	reduction factor, average occupancy in 24hr = 0.44. For the determination see page 242.
T_{IN}	Interior air temperature of the supermarket. For the calculations in the study a T_{IN} of 21°C is apprehended [K].
T_{OUT}	Ambient dry bulb air temperature [K]. Value depends on season. See table 10.2.

Also:

- The infiltration rate is not necessary a negative flux since the outside temperature can periodically be above 21°C.

Ventilation loss

Represents the heat exhausted by the ventilation system. A large part of the ventilation demand is already covered by th infiltration rate, what remains is covered by mechanical ventilation.

Ventilation demand
According to SenterNovem (2007, p.62), the ventilation demand in a supermarket is 8dm^3/s/person. The maximum number of customers in the store is 66 (including safety factor of 1.5), this gives:

$8 * 75 = 600$dm^3/s (max.)
600dm^3/s = 2160m^3/hr

This gives,
ventilation by infiltration = 1548m^3/hr
ventilation demand = 2160m^3/hr
remaining ventilation demand = 612m^3/hr
(= 0.17m^3/s & n=0.3)

The energy loss through ventilation is calculated according to equation 10.3:

$$q_{VENT} = n* r* c *(N*(1/3600)* V)* (T_{IN} - T_{AIR}) \quad [10.3]$$

where

q_{VENT}	Thermal energy loss due to ventilation [Watt];
r	Density air = 1.21 kg/m^3;
c	Specific heat capacity air = 1000 kJ/kg.K;
N	Ventilation rate [-]
V	Volume of the supermarket space = 2054m^3;
T_{IN}	Interior air temperature of the supermarket. For the calculations in the study a T_{IN} of 21°C is apprehended [K].
T_{OUT}	Ambient dry bulb air temperature [K]. Value depends on season. See table 10.2;
n	reduction factor, average occupancy in 24hr = 0.44. For the determination see page 236.

Also:

- The ventilation demand of 0.1m^3/s is only applicable if the occupancy of the supermarket is at it's maximum (66 persons).

| Appendix II: Energy balance Supermarket

Internal fluxes

Lighting

Represents the interior heat load by the lighting system of the supermarket. Calculated according to equation 10.4:

$$q_{LIGHT} = q_{lamp/m2} * A_{FLOOR} * n_{LIGHT} \qquad [10.4]$$

where

q_{LIGHT}	Thermal heat gain [Watt]
$q_{lamp/m2}$	Thermal heat gain per square meter.
A_{FLOOR}	Total floor surface [m^2]. For the energy calculations, the sales floor surface is used.
n_{LIGHT}	On average, the lights in a supermarket are switched on from the moment the first staff arrives in the morning until the last one leaves late at night. We assume the time slot 06:00-22:00 for the energetic calculations, this equals a activation factor of n = 16/24 = 0.66.

Modern-day supermarkets use LED lighting to illuminate their shelves and isles to minimize electrical energy consumption. The heat load of LED lighting is lower then standard light bulbs or fluorescent beams. In the energy balance a heat load of 10W/m^2 is retained.

Customers

Represents the interior heat load emitted by the customers and staff. This heat flux is calculated according to equation 10.5:

$$q_{PERSON} = q_{1\ PERSON} * \#p \qquad [10.5]$$

where

q_{PERSON}	*Total heat emitted by the customers + staff [Watt]*
$q_{1\ PERSON}$	*Heat emitted by 1 person [Watt/person]*
$\#p$	*Number of people in the store [-]*

The amount of customers and staff present in the supermarket at a certain moment is determined on page 242.

According to NEN5067 (p.27, table 1 and 1a), the heat emitted from 1 person is 131 Watt. (light work, clo = 0.8, sensible heat at 22^{0}C). For the calculations in this study we hold on to 131W/person.

Equipment & product cooling

Interior heat gain by operational equipment and thermal energy emitted by the product cooling machines, calculated according to equation 10.6:

$$q_{EQUIP} = q_{equip\_m2} * A_{FLOOR} \qquad [10.6]$$

where

q_{EQUIP}	Total heat gain [Watt];
q_{equip}	Heat emitted per square meter = 15W/m^2;
A_{FLOOR}	Total surface of the floor [m^2].

For the calculation of the internal heat gain by operational processes, machines and equipment, a standard value of 15W/m^2 is applied. Heat emitted by the product cooling displays on the sales floor is also included in this heat value. This standard value is suggested by the Lidl. No reduction factors are included outside supermarket opening hours. This value does NOT included the heat gain by the bake-off section in the supermarket, see the next column.

Bake off section

Heat gain by the ovens is according to the following principles / values:

- 1 standard oven has a heat emission of 2.0kW. This value is suggested by the Lidl;
- Ovens are not turned on 24/7, their use throughout the day is according to figure A2.6. This diagram is based on logical assumptions. At any time of the day, 1, 2, 3 or no ovens are in use;
- The Lidl in Amsterdam has 3 ovens installed.
- To simplify the calculation, we assume this pattern can be applied on each day of the year, regardless of Christmas or Easter periods;
- The average hourly heat gain by ovens is 2000W, or 48kWh/day, see figure A2.6. This value is applied in the monthly energy balance.

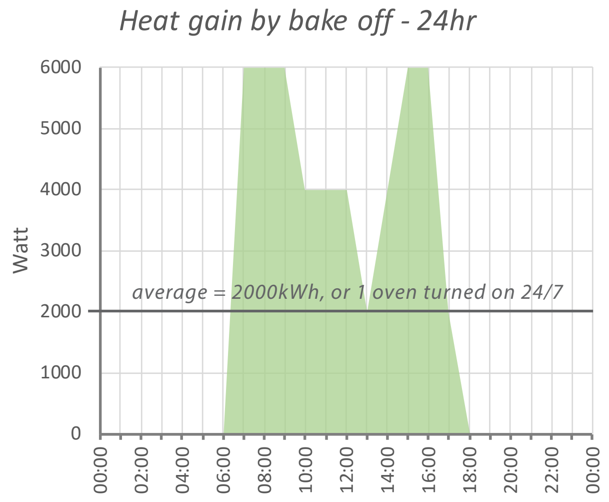

Figure A2.6: Heat gain by bake-off

| Appendix II: Energy balance Supermarket

Greenhouse <> Lidl energy exchange

General

The supermarket is kept on a temperature that revolves around 21°C. The greenhouse indoor temperature is maintained between 11°C and 27°C. The supermarket requires constant cooling due to the large internal heat gains. In a Dutch climate, the greenhouse requires a lot of heating to remain above 11°C. These two functions can support each other through energy exchange, which can be activated the moment the indoor temperature of the greenhouse drops below 21°C. Through this, the greenhouse profits from the heat surplus of the supermarket and visa-versa.

Greenhouse and supermarket air is circulated along a heat exchanger. For the calculations, an air circulation rate of 3 and an exchanger efficiency of 75% is apprehended. This cooling+heating method reduces this Lidl supermarket cooling demand by 54%.

Calculations

Temperature return air

Assume the efficiency of the heat exchanger on 75%. The air temperature of the return air is calculated with equation 10.7:

$$T_{RETURN} = T_{LIDL} - ((T_{LIDL} - T_{GH}) * 75\%) \qquad [10.7]$$

where

T_{RETURN}	Return temperature of the air [°C];
T_{LIDL}	Indoor air temperature Lidl = 21°C;
T_{GH}	Indoor temperature of the greenhouse [°C]. Temperature depends on ambient temperature but is always >11°C.

The cooling capacity of this energy exchange method is calculated with equation 10.x.

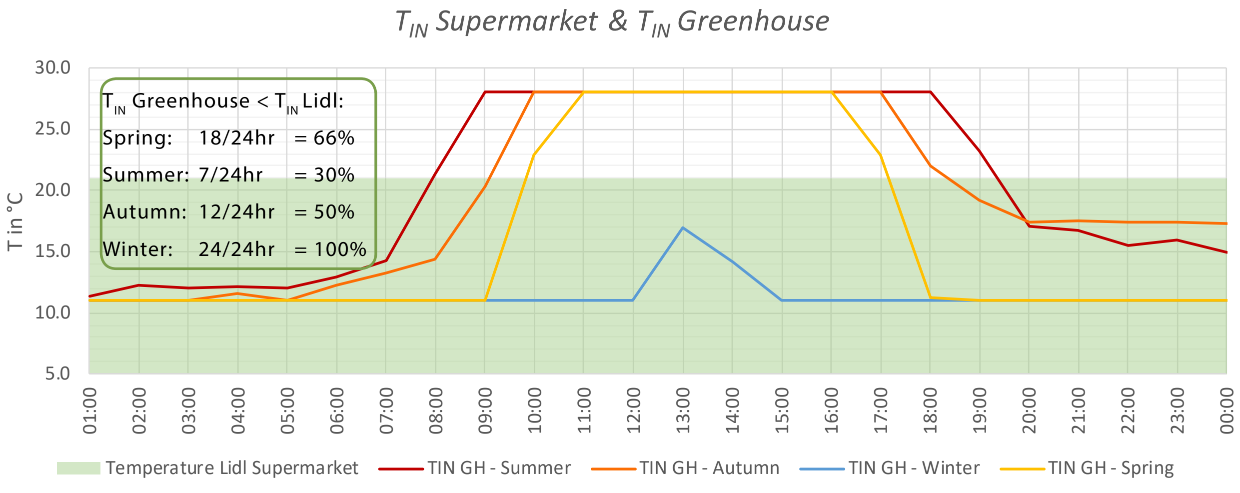

Figure A2.7: Estimated proceeding of the indoor greenhouse temperature during 4 seasons

Cooling capacity

Cooling capacity by greenhouse energy exchange

Equation 10.8:

$$q_{C.EX} = r * c * (N * (1/3600)*V)* ((T_{IN} - T_{RETURN}) \; [10.8]$$

where

$q_{C.EX}$	Cooling capacity system [Watt];
r	Density air = 1.21 kg/m³;
c	Specific heat capacity air = 1000 kJ/kg.K;
N	Ventilation rate = 3. This equals 1.72m³/s;
V	Volume of the supermarket space = 2054m³;
T_{IN}	Interior air temperature of the supermarket. For the calculations in the study a T_{IN} of 21°C is apprehended [K].
T_{RETURN}	Return air temperature [K]. Value depends on ambient dry bulb temperature and is calculated with equation 10.x.

Monthly cooling capacity

The monthly cooling capacity is calculated through equation 10.x:

$$q_{C.EX.M} = q_{C\_EX} * 24 * d * n \qquad [10.9]$$

where

$q_{C.EX.M}$	Monthly cooling demand [Watt]
$q_{C.EX}$	Static cooling demand [Watt]
24	24 hours [-]
d	Number of days in a month [-]
n	Reduction factor [-]. Based on graph 10.x. Here you can see -based on 4 different data throughout the 4 seasons- how many hours per day the T_{IN} Greenhouse < T_{IN} Supermarket.

Example: January

Parameters: efficiency heat exchanger = 75%, air exchange rate supermarket = 3, $T_{IN\_GH\_JAN}$ = 11°C, V_{LIDL} = 2053m³, n=100% (see Figure xx), T_{LIDL} = 21°C.

Equation 10.7:
T_{RETURN} = 21°C - ((21°C-11°C)*75%)
= 13.5 °C

Equation 10.8:
$q_{C.EX}$ = 1.21 * 1005 * (3 * (1/3600) * 2054)* (294-286.5)
= 15.614 W

Equation 10.9
$q_{C.EX.M}$ = 15614 * 24 * 31 * 100%
= 11.6 MWh

In the month January, the supermarket has a cooling demand of just 8.1MWh. All the demand is therefore covered by retrieving the cold energy from the Greenhouse, see the Figure below.

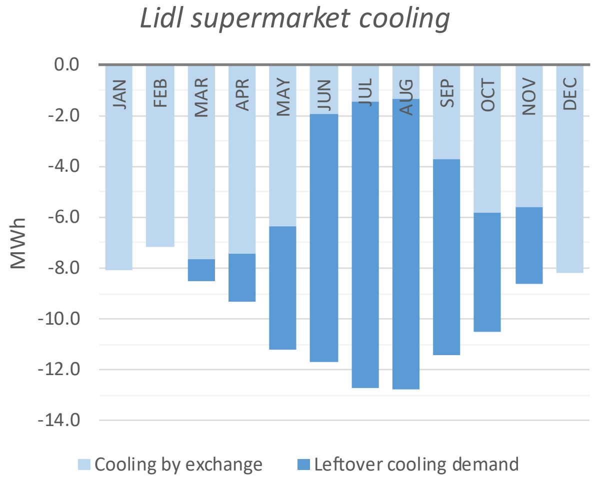

Figure A2.8: Lidl cooling demand

| APPENDIX III: Energy balance Greenhouse - §5.2.5

Overview

Overview energy fluxes

The energy balance in the greenhouse is represented by the following equation:

$$q_{LIGHT} + q_{PERSON} + q_{EQUIP} + q_{SUN} + q_{TRANS} + q_{COOL} + q_{HEAT} = 0 \qquad [5.1]$$

where

q_{LIGHT}	Represents the interior heat load by the lighting system;
q_{PERSON}	Represents the interior heat load emitted by the greenhouse caretakers / farmers;
q_{EQUIP}	Interior heat gain by operational equipment;
q_{SUN}	Solar heat gain. This flux covers both the direct solar heat gain as the diffuse solar heat gain* (Global horizontal irradiance);
q_{TRANS}	Heat transfer through the facade, floor and roof construction based on the temperature difference between the interior and exterior;
q_{COOL}	Represents the surplus heat extracted from the greenhouse by means of a cooling system. In the greenhouse, this can be either through floor cooling (q_{FLOOR}), by evaporative cooling (q_{EVAP}) or by natural ventilation (q_{NAT});
q_{HEAT}	The energy balance is closed by q_{HEAT} during colder periods. Heating is achieved by floor heating (q_{FLOOR}) and ventilation (q_{VENT}).

*In the 24hr energy balances, the GHI is split up in two separate posts: q_{SUN_DIR} & q_{SUN_DIFF}, or direct solar gain and diffuse solar gain.

Index

Internal fluxes

External fluxes

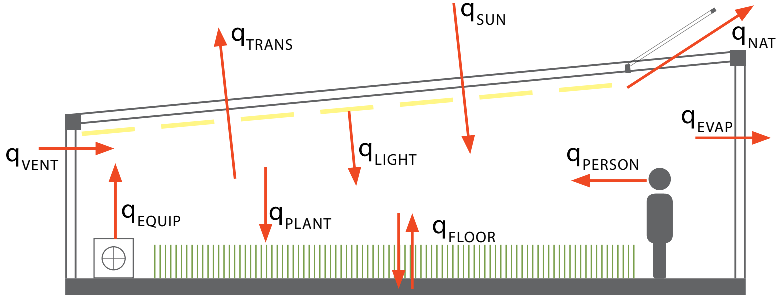

Figure A3.1: Fluxes in the greenhouse

Energy balances

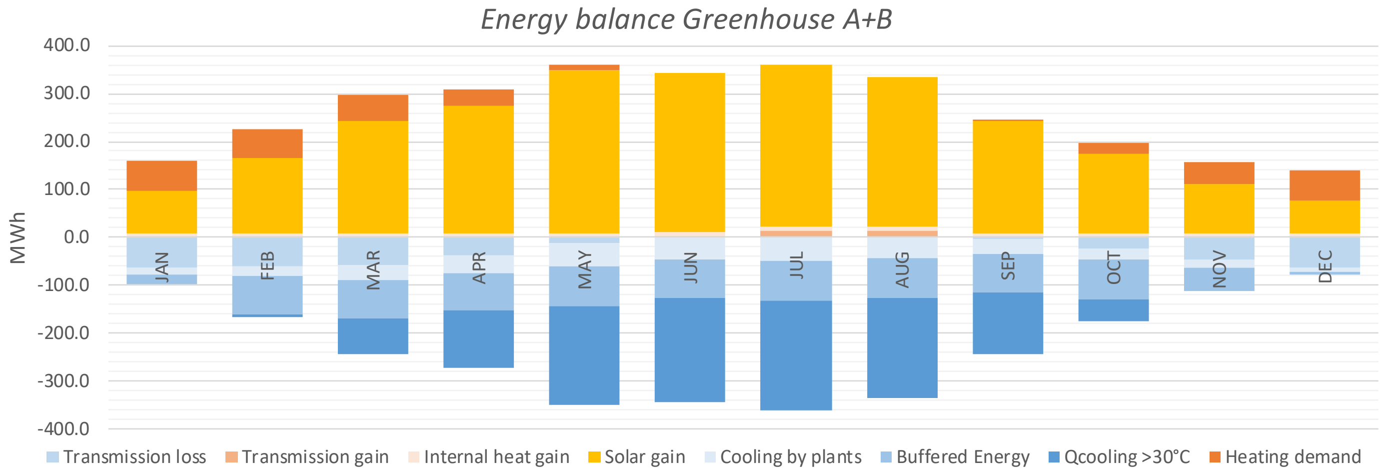

Figure A3.2: 12month energy balance

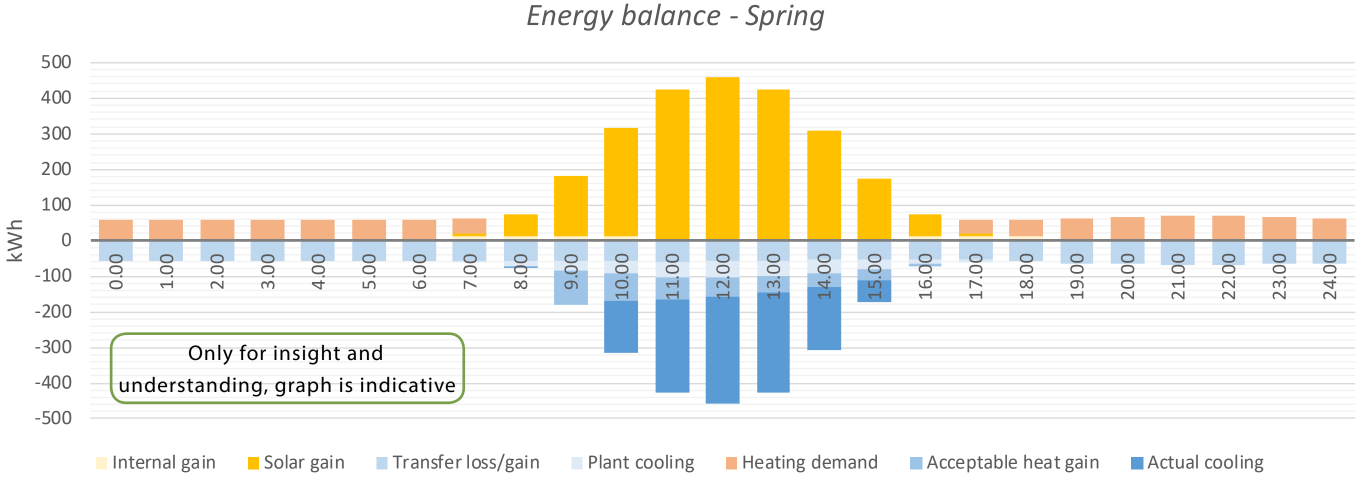

Figure A3.3: 24hr energy balance supermarket

| Appendix III: Energy balance Greenhouse

Internal fluxes

Lighting

q_{LIGHT} represents the interior heat load by the lighting system, calculated with equation 10.10:

$$Q_{LIGHTS} = q_{M2} * A_{FLOOR} * n_{LIGHT} \qquad [10.10]$$

where

Q_{LIGHTS}	Heat load by lights [Watt];
q_{M2}	Heat load per square meter [Watt/m^2];
A_{FLOOR}	Total floor surface [m^2].
n_{LIGHT}	Reduction factor in monthly energy balance calculations to account for the hours the lights are not turned on, n=0.2.

Due the case's inner city location in the middle of a high density residential area, it is not possible to opt for additional night time lighting to enhance plant growth.

During the early morning hours and late afternoon, additional lighting is required to make working in the greenhouse possible.

For this greenhouse we assume a thermal heat gain of 10W/m^2 in the time slots 07:00-10:00 and 16:00-19:00.

Persons

q_{PERSON} represents the interior heat load emitted by the greenhouse caretakers / farmers. Calculated with equation 10.11:

$$Q_{PEOPLE} = q_{PERSON} * \#person * n_{WORK} \qquad [10.11]$$

where

Q_{PEOPLE}	Heat load by people [Watt]
q_{PERSON}	Heat load per person [Watt/person]
n_{WORK}	Reduction factor added to the monthly energy balance calculations to account for the hours there are no persons present in the greenhouse. n=0.5 since we assume there are people present 12hrs a day & 7 days a week.

Thermal gain by the people working in the greenhouse is relative to the solar gain and transmission loss a neglectable post. However, for the sake of completeness, this flux is included in the energy balance.

For this greenhouse we assume 4 adult persons working 7 days a week during the time slot 07:00-18:00. Agricultural work is intensive and therefore we apply a high load: 180W/person.

Equipment

Interior heat gain by operational equipment, represented by equation 10.12:

$$Q_{EQUIP} = q_{M2} * A_{FLOOR} \qquad [10.12]$$

where

Q_{EQUIP}	Heat load by equipment [Watt]
q_{M2}	Heat load per square meter [W/m^2]
A_{FLOOR}	Total floor surface [m^2].

Heat gain by equipment is the umbrella term for heat gain by machines in the production area and the activities performed by those machines.

For this greenhouse we assume a 24/7 heat gain by equipment of 5W/m^2.

There is no reduction factor for the equipment internal heat gain. We assume that the flux is present 24/7.

| Appendix III: Energy balance Greenhouse

external fluxes

Solar gain

Thermal energy gain by the solar radiation, represented by the following equation [10.13]

$$Q_{SUN\_DIR} = q_{SUN\_M2} * A * g * n \qquad [10.13]$$

where

Q_{SUN_DIR}	Solar gain [Watt]
q_{SUN}	Direct solar intensity [Watt/m²]. The the energy calculations, the global horizontal orientation is used. For an overview see page 257;
A_{GLASS}	Surface of individual facade [m²]. Surfaces are according to the construction dimensions in figure A3.4.;
g	Solar heat transmittance coefficient. g=0.60 (Double glazing);
n_{ORT}	Orientation reduction factor [0>1] Horizontal surface n=1*; South-West + South-East facade n=0.7; North-West + North-East facade n=0.5.

Solar gains are calculated separately for each glass facade. Reduction factor *n* tunes the solar gain according to the facade orientation where a facade facing North has a much lower thermal gain compared to the South facade. The greenhouse is fitted with standard double glazing to reduce the transmission loss. This goes at the cost of the solar transmittance and the g-value is settled on 0.6.

Solar data for the monthly greenhouse energy balance is retrieved from climate consultant software. See table 10.2 on page 242.

To establish the 24hr energy balances, the direct solar radiation and the diffuse solar radiation are calculated separate. The calculation of the energy gain by diffuse solar radiation is according to equation 10.13, where q_{SUN_M2} is replaced by q_{SUN_DIF} and q_{SUN_DIR}.

Solar data for the 24hr energy balance is retrieved from TU Delft data[1] (Trübungsfactor T=4).

*Even though the roof is technically not horizontal (small inclination), for the energy calculations a horizontal surface is apprehended.

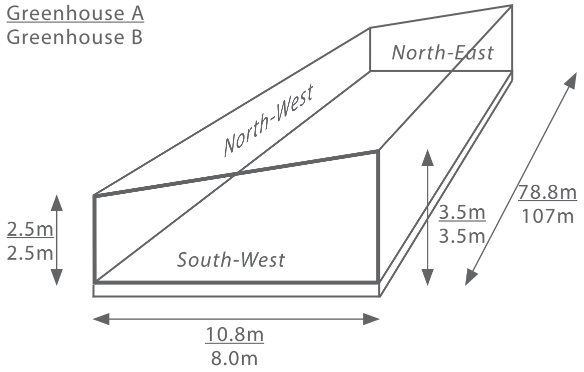

Figure A3.4: Global dimensions greenhouse A & B

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[1] *http://wiki.bk.tudelft.nl/bk-wiki/Zonnestralingsintensiteit*

Solar gain - 24hr energy balance

The average hourly solar intensity is determined from figure A3.5a & A3.5b (both Figures are retrieved from the TU Delft Wiki). For 4 distinctive days, in each of the 4 seasons, the direct horizontal intensity and the diffuse horizontal intensity are given. For each hour, the solar intensity is taken and the percentage of that intensity relative to the maximum value. For example, during a summer day, at 10:00 in the morning, the direct horizontal intensity is 656W/m², or 88% of the maximum value of 745W/m², see figure A3.5a. An overview of all the energy values and percentages is given in table 10.1. The percentages are later used to determine the cooling capacity of the plants.

For the 12month energy balance, the Global Horizontal Intensity (GHI) is applied and there is no distinction between diffuse and direct sunlight necessary. There is no average hourly GHI available, hence the distinction between diffuse and direct for the 24hr balances.

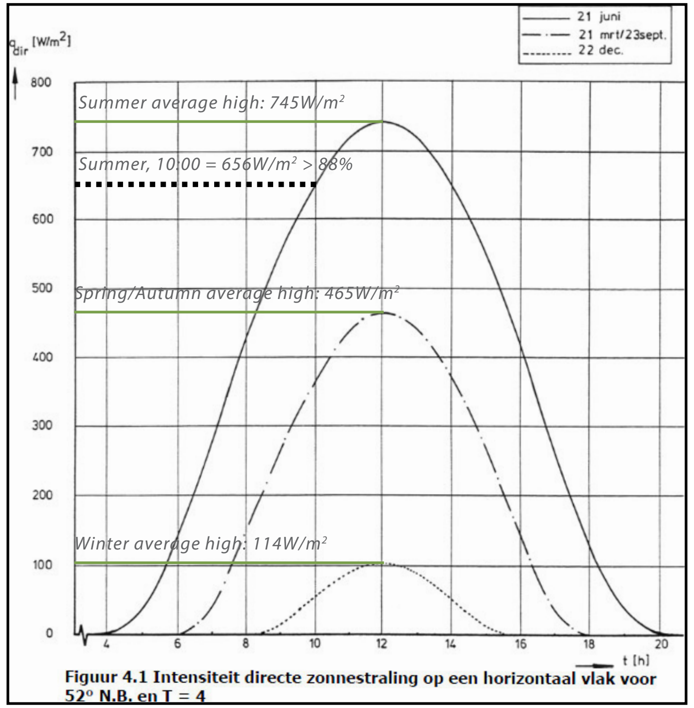


Figure A3.5a : Average hourly direct solar intensity on a horizontal surface throughout the day. (adapted from the TU Delft[1])

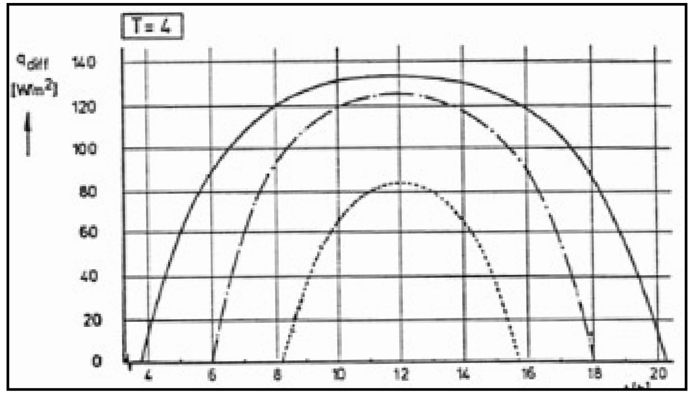


Figure A3.5b : Average hourly diffuce solar intensity on a horizontal surface throughout the day. (adapted from the TU Delft[1])

Transmission loss

Heat transfer through the facade and roof glazing based on the temperature difference between the interior and exterior, calculated with equation 10.14:

$$q_{TRANS} = U * A * (T_{IN}\,[K] - T_{OUT}\,[K]) \qquad [10.14]$$

where

q_{TRANS}	Energy transfer through the glazing [Watt];
U	Transmission coefficient [W/m K]. Double glazing is applied in this greenhouse. We assume a standard U-value of 2.7 W/m².K;
A	Total surface of glass facade in [m²];
T_{IN}	Indoor temperature greenhouse [K]. For the energy calculations, the minimum set point temperature is used;
T_{OUT}	Ambient dry bulb temperature [K]. See the overview on page 242 & 257 (table 10.2 & 10.1).

- q_{TRANS} can also be positive, depending on the ambient dry bulb temperature (if >15°C).

Transmission loss - floor

Heat transfer across the floor construction for both convection and conduction. This flux is calculated with equation 10.15:

$$q_{TRANS\_F} = U * A * (T_{IN}\,[K] - T_{ADJ}\,[K]) \qquad [10.15]$$

where

q_{TRANS_F}	Energy transfer through the floor [Watt];
U	Transmission coefficient through the floor construction. An U-value of 0.2 is apprehended;
A	Total surface of the floor [m²];
T_{IN}	Indoor temperature greenhouse [K];
T_{ADJ}	Standard temperature value for directly adjacent (adj) construction. T_{ADJ} = 15°C.

row	Table 10.1		00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00	Av.	[-]
1	Direct sunlight[1]	Summer	0%	0%	0%	0%	0%	5%	19%	38%	58%	75%	88%	97%	100%	97%	88%	75%	58%	38%	19%	5%	0%	0%	0%	0%	0%		%
2			0	0	0	0	0	37	142	283	432	559	656	723	745	723	656	559	432	283	142	37	0	0	0	0	0	256	W/m2
3		Spring + Autumn	0%	0%	0%	0%	0%	0%	0%	10%	32%	58%	80%	96%	100%	96%	80%	58%	32%	10%	0%	0%	0%	0%	0%	0%	0%		%
4			0	0	0	0	0	0	0	47	149	270	372	446	465	446	372	270	149	47	0	0	0	0	0	0	0	121	W/m2
5		Winter	0%	0%	0%	0%	0%	0%	0%	0%	0%	13%	48%	79%	100%	79%	48%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%		%
6			0	0	0	0	0	0	0	0	0	15	55	90	114	90	55	15	0	0	0	0	0	0	0	0	0	17	W/m2
7	Diffuse sunlight[1]	Summer	0%	0%	0%	0%	0%	5%	19%	38%	58%	75%	88%	97%	100%	97%	88%	75%	58%	38%	19%	5%	0%	0%	0%	0%	0%		%
8			0	0	0	0	10	60	86	108	120	127	133	135	136	135	133	127	120	108	86	60	10	0	0	0	0	68	W/m2
9		Spring + Autumn	0%	0%	0%	0%	0%	0%	0%	10%	32%	58%	80%	96%	100%	96%	80%	58%	32%	10%	0%	0%	0%	0%	0%	0%	0%		%
10			0	0	0	0	0	0	0	59	95	108	119	123	125	123	119	108	95	59	0	0	0	0	0	0	0	45	W/m2
11		Winter	0%	0%	0%	0%	0%	0%	0%	0%	0%	13%	48%	79%	100%	79%	48%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%		%
12			0	0	0	0	0	0	0	0	0	38	66	80	83	80	66	38	0	0	0	0	0	0	0	0	0	18	W/m2
13	Outside dry bulb temperature[1]	19-Jun	11.4	12.2	12	12.1	12	12.8	13.2	14	16.1	18.2	19.3	17.3	17.5	17.5	15.8	16.7	17.3	16.2	17.4	16.4	15.8	14.6	15	14	14	15.2	Tout -°C
14		21-Mar	5.2	5.3	5.2	5.2	5.2	5.4	5.4	5.7	5.9	6.2	6.1	5.1	5.7	6.1	6.6	7.1	7.2	6.4	5.6	4.1	3.2	2.6	2.4	3.8	4	5.2	Tout -°C
15		22-Sep	10.9	11.0	10.8	11.6	10.8	12.2	13.3	13.6	15.1	16.8	18.4	19.7	20.2	20.6	19.6	19.3	17.7	16.9	16.6	16.5	16.6	16.5	16.5	16.4	17.0	15.8	Tout -°C
16		22-Dec	-0.4	-0.4	-0.7	-0.6	-0.7	-0.7	-0.6	-0.6	-0.5	-0.3	-0.1	0.2	0.3	0.4	0.8	1.4	1.8	2.1	0.9	0.8	1.4	3.4	2.1	3.2	3.0	0.6	Tout -°C
17	Cooling by plants	19/06	0%	0%	0%	0%	0%	5%	19%	38%	58%	75%	88%	97%	100%	97%	88%	75%	58%	38%	19%	5%	0%	0%	0%	0%	0%		%
18		n=1	0	0	0	0	0	6	21	42	64	83	97	107	110	107	97	83	64	42	21	6	0	0	0	0	0	37.8	W/m2
19		21/03	0%	0%	0%	0%	0%	0%	0%	10%	32%	58%	80%	96%	100%	96%	80%	58%	32%	10%	0%	0%	0%	0%	0%	0%	0%		%
20		n=0.51	0	0	0	0	0	0	0	6	18	33	45	54	56	54	45	33	18	6	0	0	0	0	0	0	0	14.6	W/m2
21		21/03	0%	0%	0%	0%	0%	0%	0%	10%	32%	58%	80%	96%	100%	96%	80%	58%	32%	10%	0%	0%	0%	0%	0%	0%	0%		%
22		n=0.51	0	0	0	0	0	0	0	6	18	33	45	54	56	54	45	33	18	6	0	0	0	0	0	0	0	14.6	W/m2
23		22/12	0%	0%	0%	0%	0%	0%	0%	0%	0%	13%	48%	79%	100%	79%	48%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%		%
24		n=0.11	0	0	0	0	0	0	0	0	0	2	6	10	12	10	6	2	0	0	0	0	0	0	0	0	0	1.8	W/m2

1) Source: Climate consultant - Amsterdam weather station

Figure A3.6: Climate parameters used for setting up the 24hr energy balances.

row	Table 10.2	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	[-]
1	Global Horizontal irridiance[1]	79	143	212	248	309	310	308	282	219	151	96	61	W/m2
2	Percentual difference from qsun max. (July)	26%	46%	69%	81%	100%	101%	100%	92%	71%	49%	31%	20%	%
3	Average outside dry buld temperature[2]	4.2	3.7	5.3	8.4	12.7	15.2	16.9	17.1	14.4	10.9	6.5	4.4	°C
4	Calculation tempere T_{IN} GH[3]	18.5	18.5	20.8	20.8	20.8	22.0	22.0	22.0	21.3	21.3	21.3	18.5	°C
5	Full sun hours (2016 data)	20.9	40.7	80.0	123.7	162.5	160.0	159.0	139.0	103.0	60.0	25.0	16.0	hrs

1) Source: Climate consultant - Amsterdam Weather station

2) Source: Climate consultant - Amsterdam Weather station

3) Temperatures applied to calculate the heat loss through the floor of the greenhouse

Figure A3.7: Climate parameters used in setting up the monthly energy balance

| Appendix III: Energy balance Greenhouse

external fluxes

Plant cooling - Estimation

According to Engel et al (2017), plants can have a cooling capacity higher than $400W/m^2$ (10L of water evaporation / m^2 / day). Due to this, the indoor greenhouse temperature can remain ~4°C below the outside temperature during warm days. According to Graamans (2015, table A2.3- p. 184), Tomato crops evaporate $2.77L^{-1}$ of water per square meter per day. If we combine the numbers, we get the following cooling capacity of plants:

$$\begin{array}{c|c} 2.77L^{-1} & q_{TOMATO} \\ \hline 10.0L^{-1} & 400W/m^2 \end{array} \quad \text{>>>} \; q_{TOMATO} = 110W/m^2$$

Secondly, we can safely assume this cooling capacity is only achieved when the q_{SUN} is peaking. In other words, the evaporation rate of the plants is directly affected by the intensity of the sun. For this, we set the cooling capacity of the plant on $110W/m^2$ if the sun is at it's highest altitude (at 12:00). At any other hour before or after this peak, the cooling demand is a percentage of $110W/m^2$, gradually reducing to 0% after sunset and before sunrise. The percentages are given in table 10.1, row 1,3 & 5.

Thirdly, a reduction factor for Spring, Autumn and Winter should be included, as the solar intensity is does on average not reach the same high values as in Summer. To determine these reduction factors we look at the average hourly direct and diffuse solar intensities during the day. See table 10.1, row 2, 4, 6, 8, 10 & 12.

The seasonal reduction factors:
average dir. + average diff. = total average gain [W/m²]

Summer
256 + 68 = 324 $W/m^2/hr$ >>> 100% or 1.0
Spring & Autumn
121 + 45 = 166 $W/m^2/hr$ >>> 51% or 0.51
Winter
17 + 18 = 35 $W/m^2/hr$ >>> 11% or 0.11

Fourth and finally, we establish the cooling capacity of the plant for the monthly energy balance. For this we calculate the daily cooling capacity of the plant in the month with the highest solar intensity: June. We can assume - with the knowledge that plant cooling is directly affected by the solar intensity- that in June the maximum plant cooling is achieved. Cooling by plants in the other eleven months is a percentage of this maximum, see table 10.2 - row 2.

| Appendix III: Energy balance Greenhouse

cooling demand greenhouse

Heating / cooling: closing the balance

If all other energy fluxes are defined, $Q_{HEATING}$ or $Q_{COOLING}$ can be derived from formula 5.1

$$q_{LIGHT} + q_{PERSON} + q_{EQUIP} + q_{SUN} + q_{TRANS} + q_{COOL} + q_{HEAT} = 0 \qquad [5.1]$$

However, this formula is based on a minimum indoor temperature of T_{IN} = 11°C, which means that the calculated cooling demand is based this temperature as well. The indoor air temperature in the greenhouse should be kept in the range of 11°C-27°C. The cooling demand calculated with formula 5.1 shows therefore values that are to high and in addition to that indicates there is a cooling demand where there should not be one, see figure A3.8. The dark red colour is the actual cooling demand, the light red colour indicates that there is a internal temperature rise due to the heat surplus, but is still within the desired temperature range.

To differentiate between where the heat surplus is still acceptable and where actual cooling is required, the indoor temperature should first be calculated. For this we apply formula 4.12, which includes both the time and the effect of the thermal mass and is proven to be a reliable formula to find the T_{IN}. Due to the absence of ventilation, the indoor temperature shows high and unrealistic values. Nevertheless, based on these temperatures can now be calculated which part of the total cooling load is actual cooling load. For this we apply formula 4.18 and 4.19.

Figure A3.8 shows both $Q_{COOL\_>30}$ as well as Q_{COOL_15-30}, of which only the latter one is the actual cooling demand.

Calculating T_{IN} - 24hr energy balance

$$T_{IN} = T_{OUT} + (W/H) * (1 - e^{-(H/M)*t}) \qquad [10.16]$$

$$W = q_{SUN} + q_{INT} + q_{PLANT} \qquad [10.17]$$

$$H = U*A\ (+ \rho*c*\eta*V_{AIR})* \qquad [10.18]$$

$$M = \rho_{AIR}*c_{AIR}*V_{AIR} + \rho_{CON}*c_{CON}*V_{CON} \qquad [10.19]$$

where

q_{SUN}	$Q_{SUN\_DIF} + Q_{SUN\_DIR}$	[10.20]
q_{INT}	$Q_{PERSON} + Q_{LIGHT} + Q_{EQUIP}$	[10.21]

T_{IN}	indoor air temperature [K]
ρ_{AIR}	density of air, 1.21kg/m³
c_{AIR}	specific heat capacity air, 1005 KJ/kg.K
V_{AIR}	total air volume [m³]
ρ_{CON}	density of concrete, 2400kg/m³
c_{CON}	specific heat capacity concrete, 840 KJ/kg.K
V_{CON}	total concrete volume [m³] (working thickness = 6cm!)
T	time after sun started shining [sec]
T_{OUT}	ambient air temperature [K]

** Primarily, ventilation is not applied in a semi-closed greenhouse system and is only activated for peak cooling. Therefore this part of the formula is left out in this phase of the calculation.*

$$Q_{COOL\_15-30} = Q_{COOLING} / (T_{IN} - T_{MIN}) * \Delta T \qquad [4.18]$$

$$Q_{COOLING} = Q_{COOL\_>27} + Q_{COOL\_11-27} \qquad [4.19]$$

where

T_{IN}	Indoor temperature according to 4.12;
T_{MIN}	set point minimum indoor temperature = 11°C
ΔT	T_{IN} - T_{MIN}, with a minimum of 0°C and a maximum of 16°C, above 16°C means T_{IN} = >27°C, which is the actual cooling part.

Calculating T_{IN} - monthly balance

Equation 4.12 is not suitable to calculate the average indoor temperature of the greenhouse on a monthly basis. For this, equation 4.20 is applied.

$$T_{IN} = ((q_{SUN} + q_{INT} + q_{PLANT}) + (U*A*T_{OUT})) / (U*A) \qquad [10.22]$$

where

q_{SUN}	$Q_{SUN\_DIF} + Q_{SUN\_DIR}$	[10.20]
q_{INT}	$Q_{PERSON} + Q_{LIGHT} + Q_{EQUIP}$	[10.21]

T_{IN}	indoor air temperature [K]
U	U-value glass, 2.7 W/m².K
A_{GLASS}	Total glass surface [m²]
T_{OUT}	ambient air temperature [K]

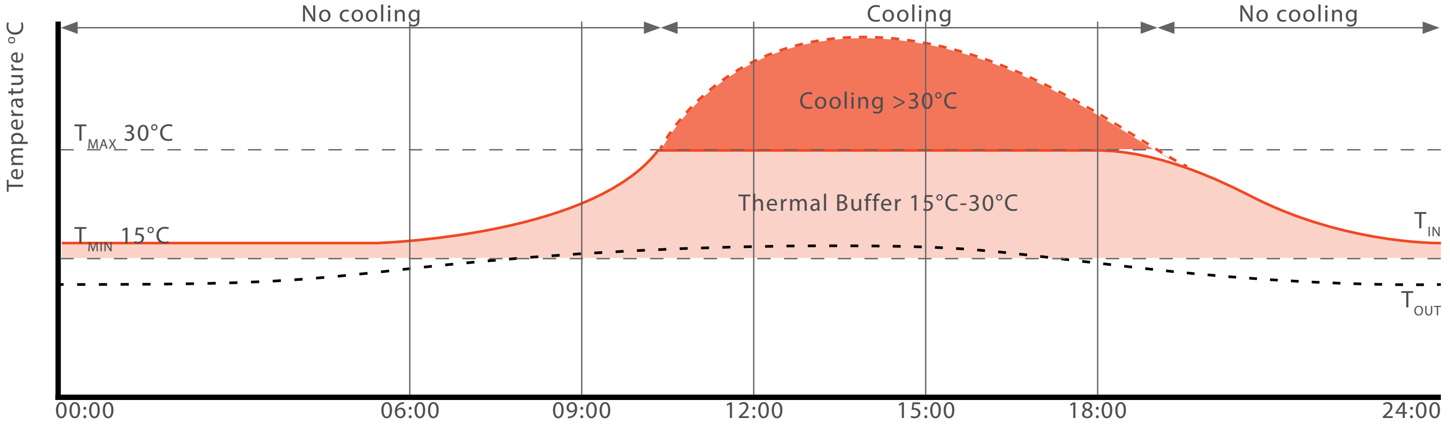


Figure A3.8: Range T_{IN} = 15-30°C. Relative to this range, not all cooling demand actual cooling demand.

| Appendix III: Energy balance Greenhouse

heating demand greenhouse

Greenhouse <> Lidl energy exchange

The greenhouse is heated through energy exchange with the supermarket. This is the same principle and mechanism as described on page 248, but now from the greenhouse perspective. The heat gain can be calculated with equation 10.7 & 10.23:

$$T_{RETURN} = T_{GH} - (T_{GH} - T_{LIDL}) * 75\%) \qquad [10.7]$$

and

$$q_{H.EX} = r * c * q_v * (T_{RETURN} - T_{IN}) \qquad [10.23]$$

where

$q_{H.EX}$	Heating capacity exchanger [Watt];
r	Density air = 1.21 kg/m³;
c	Specific heat capacity air = 1000 kJ/kg.K;
q_v	ventilation rate =1.72m³/s (see page 248)
T_{IN}	Interior air temperature of the greenhouse. Temperature depends on ambient dry bulb temperature but is never lower than T_{MIN_GH}.
T_{RETURN}	Return air temperature [K]. Value depends on ambient dry bulb temperature and is calculated with equation 10.7.

Assume the heat exchanger efficiency on 75%. In figure A3.9, all the monthly heat exchanged with the supermarket is shown. Thermal energy exchange with the supermarket results in a heating demand reduction of 46%. The remaining heat demand is covered by floor heating.

This reduced heat demand by energy exchange is also included in the rest of energetic calculations.

Table 10.4	Winter		Spring			Summer			Autumn			Winter	*Average / total*
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Average monthly ambient temperature [°C]	4.2	3.7	5.3	8.4	12.7	15.2	16.9	17.1	14.4	10.9	6.5	4.4	*10.0*
Design temperature Greenhouse [°C]	11.0	11.0	11.0	11.0	12.7	15.2	16.9	17.1	14.4	11.0	11.0	11.0	*12.8*
Time factor n: $T_{IN\_Greenhouse} < T_{IN\_Lidl}$	100%	100%	66%	66%	66%	30%	30%	30%	50%	50%	50%	100%	*0.6*
Original GH heating demand [MWh]	21.1	20.5	17.6	7.7	0.0	0.0	0.0	0.0	0.0	0.5	13.5	20.4	101.3
nr. of days in month	*31*	*28*	*31*	*30*	*31*	*30*	*31*	*31*	*30*	*31*	*30*	*31*	
Temperature approach air GH [°C]	18.5	18.5	18.5	18.5	18.9	19.5	20.0	20.0	19.4	18.5	18.5	18.5	*18.9*
q_{H_EX} [Watt]	15596	15596	15596	15596	12890	9049	6376	6018	10284	15596	15596	15596	*12816*
Monthly heating capacity [MWh]	11.6	10.5	7.7	7.4	0.0	0.0	0.0	0.0	0.0	0.5	5.6	11.6	54.9
new heating demand [MWh]	9.5	10.0	10.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	7.9	8.8	46.5
												Reduction of the heating demand	**46%**

Figure A3.9: Greenhouse heat demand reduction due to thermal energy exchange with the supermarket.

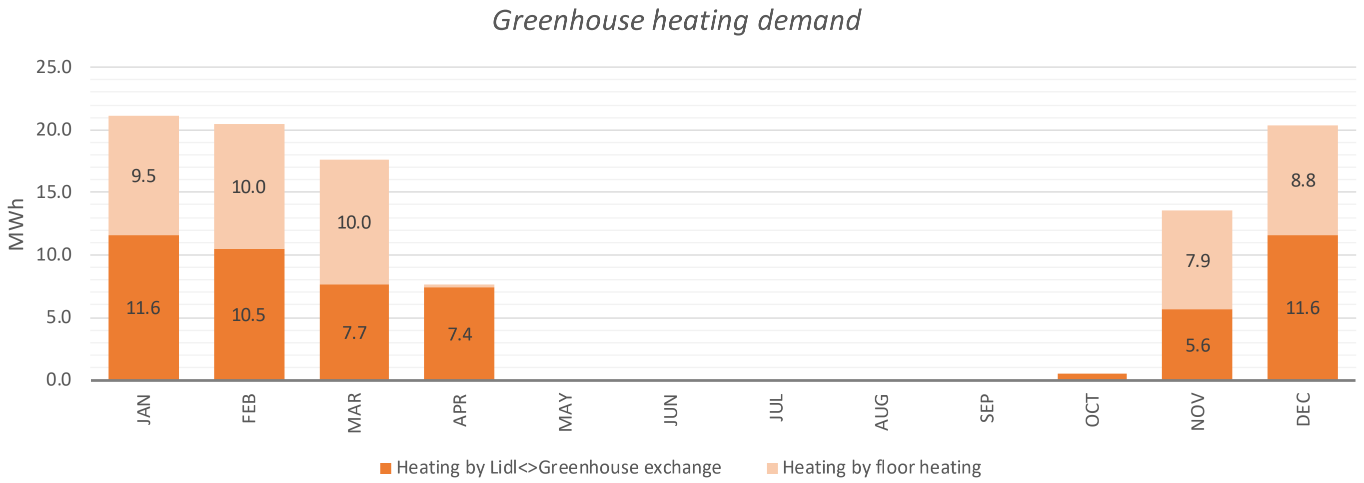
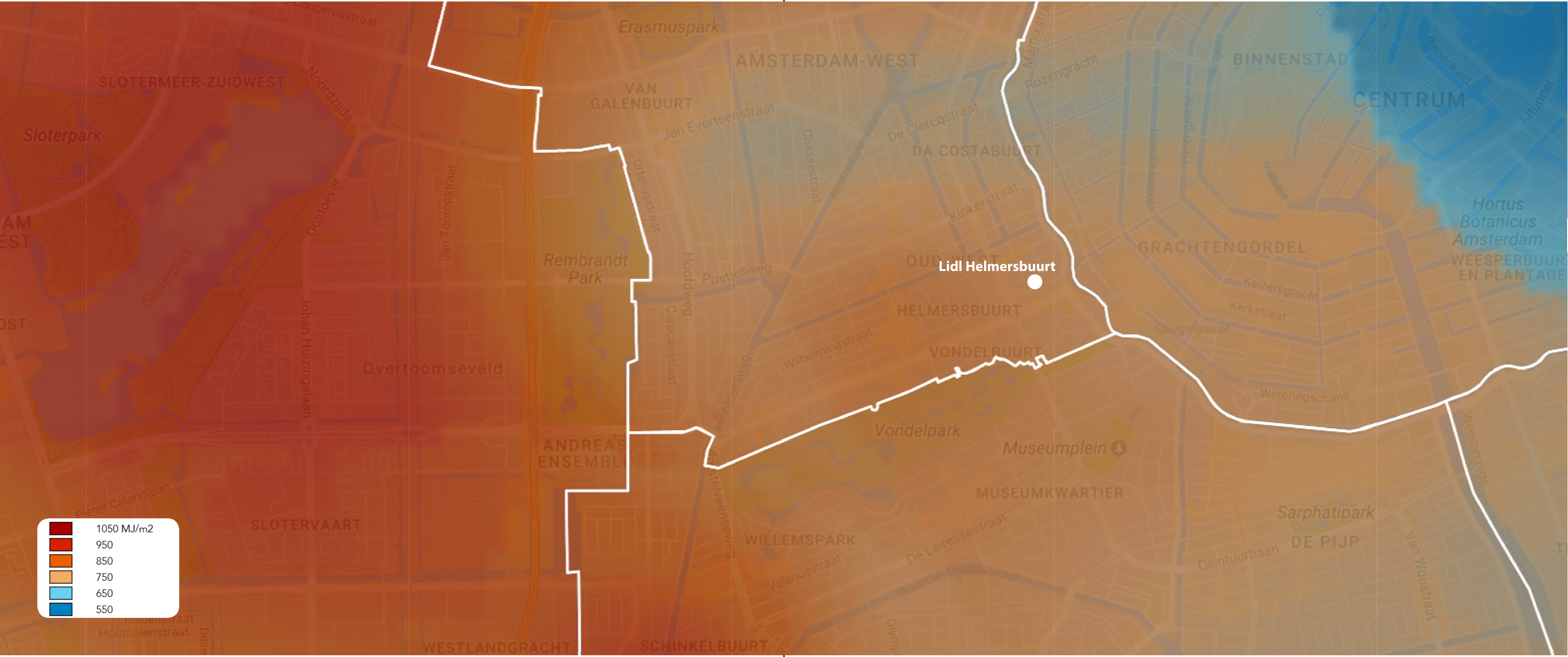


Figure A3.10: Greenhouse B heating demand (T_{IN} = 11°C-27°C).

According to the municipality of Amsterdam[1]



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[1] *https://maps.amsterdam.nl/energie_bodemwater/*

| APPENDIX V: Final parameters & results - §8.6

Parameters used for final energy system design

Towards Energetic Circularity - Parameters energy system

Towards Energetic Circularity - System design tool

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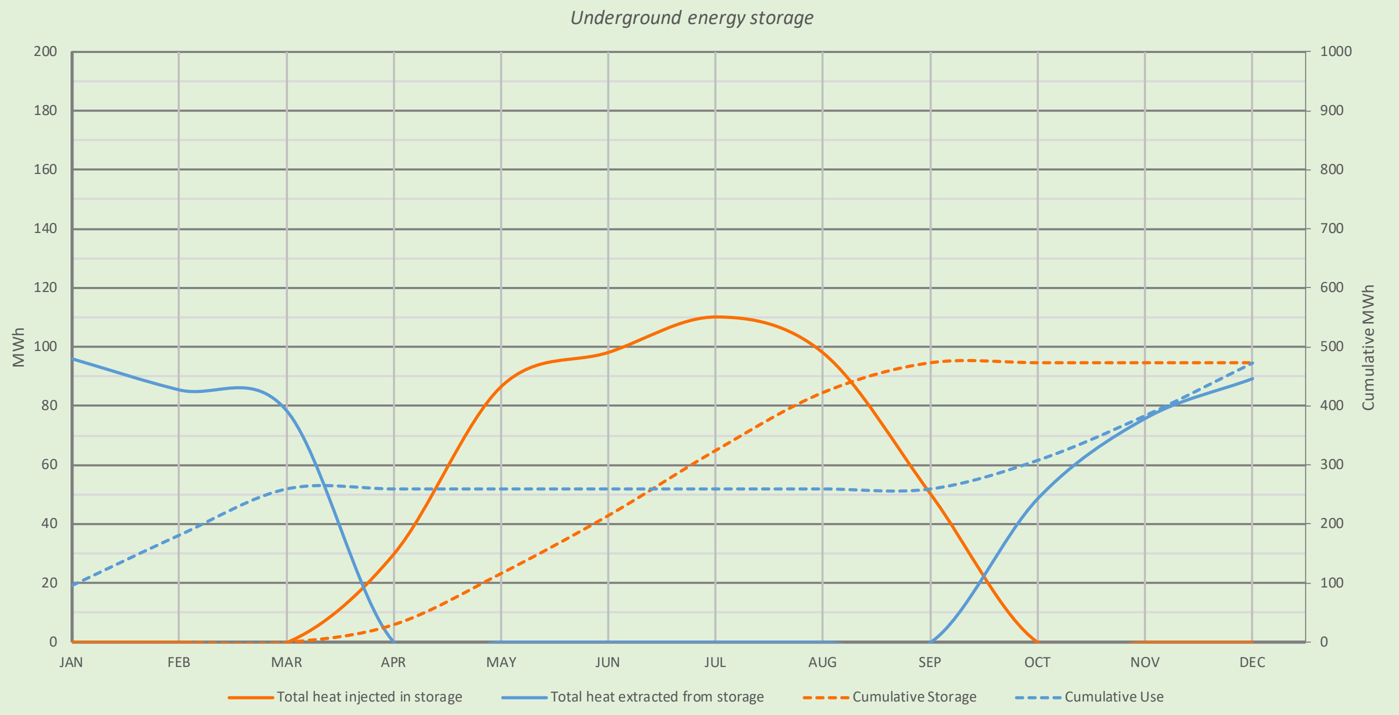
This tool can be used to design an balanced local energy system with a greenhouse and adjacent dwelling.

All the parameters that have influence on the performance of the greenhouses, supermarket or apartment buidlings can be found and changed in the dark green boxes. Most of the changes made to these parameters will first have a direct effect on the components and subsequently on the (un)balance of the underground energy storage. Changing parameters will finally affect the effect of the the total system in terms of CO2 containment. Some parameter changes (like the COP values) result in significant changes of the performance of the system where other changes (like # people in the greenhouse) have a neglectable effect. While setting up the integrated energy system, a balanced out underground energy storage should always be achieved. This means that the oversupply/undersupply should be as close to zero as possible (value I, II & IV). Tab B points out the (positive) effect of the energy system relative to a simular system that is climatised by conventional means. This tool quickly points out that in terms of CO2 emission, it is better to scale down the whole energy system than to remain with the maximum possible component sizes. Below, 3 system settings are given: one where only greenhouse A or B is used and one where both greenhouses are used (1,2 & 3). All settings are in balance.

(1) Settings only Greenhouse A:	*size: 78.8 x 10.8m*	*Tin = 11°C-27°C*	*Tin Lidl = 21°C*	*# Households included: 96*	Alternative: consider a lower gas demand per household = 424m^3 (-27%) allows for 124 hh
(2) Settings only Greenhouse B:	*size: 107 x 8m*	*Tin = 11°C-27°C*	*Tin Lidl = 21°C*	*# Households included: 94*	Alternative: consider a lower gas demand per household = 389m^3 (-33%) allows for 124 hh
(3) Settings both Greenhouses:	*size B: 78 x 8m, size A: Full*	*Tin = 15°-30°C*	*Tin Lidl = 21°C*	*# Households included: 124*	

A. Results

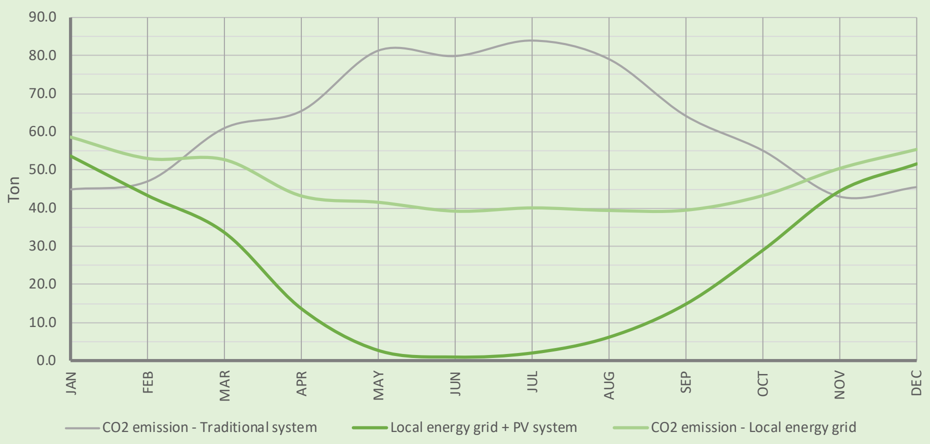
I. Cumulative storage	472	II. Cumulative use	473	III. Extra safety included	43



IV. Oversupply / under-supply	0

B. CO$_2$ Emission

CO2 emission gas [1GJp = kg]	56.60
kWhf > MJp	9.00
CO2 emission electricity [1kWhp = kg]	0.53
MJp > kWhp	3.60
Energy content natural gas [MJp / Nm3]	31.65
COP_Cooling greenhouse	3.50
CO2 improvement, excluding PV gain	26%
CO2 improvement, including PV gain	60%



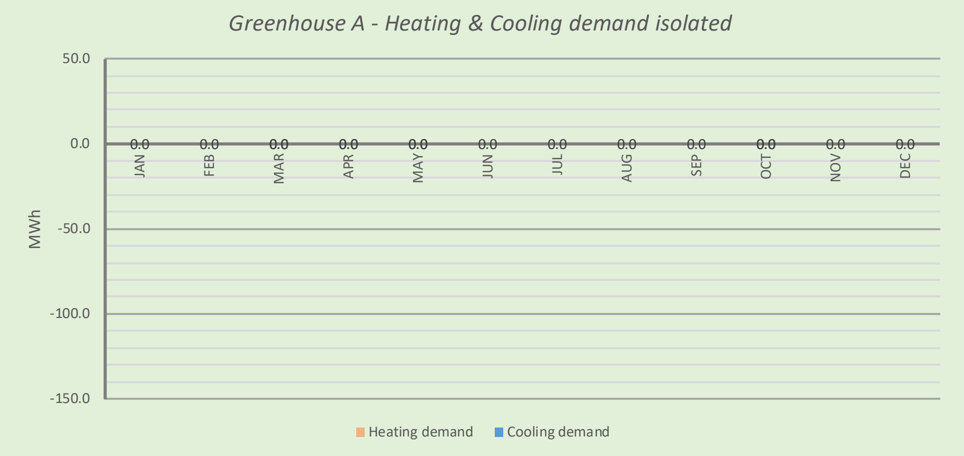
C. General & COP Heat pumps

		T_{LOW}	T_{HIGH}	SCOP	Invested elec. [kWh]		
Safety factor	1.1						
Heat pump A - Greenhouse heating	7.9	26	35	7.9	5806		
SCOP Hpump B1 - Dwelling | Space heating Sum.	4.5	26	50	4.5	21153		
SCOP Hpump B2 - Dwelling | Space heating Win.	4.4	25	50	4.4	85466		
SCOP Hpump B3 - Dwelling | Dom. water Sum.	3.5	25	60	3.5	39913		
SCOP Hpump B4 - Dwelling | Dom. water Win.	3.5	26	60	3.5	39694		
Heat pump C - 24hr buffer	7.4	20	30	7.4	38	Total electricity invested in heat pumps [MWh]	**192**

D. Components

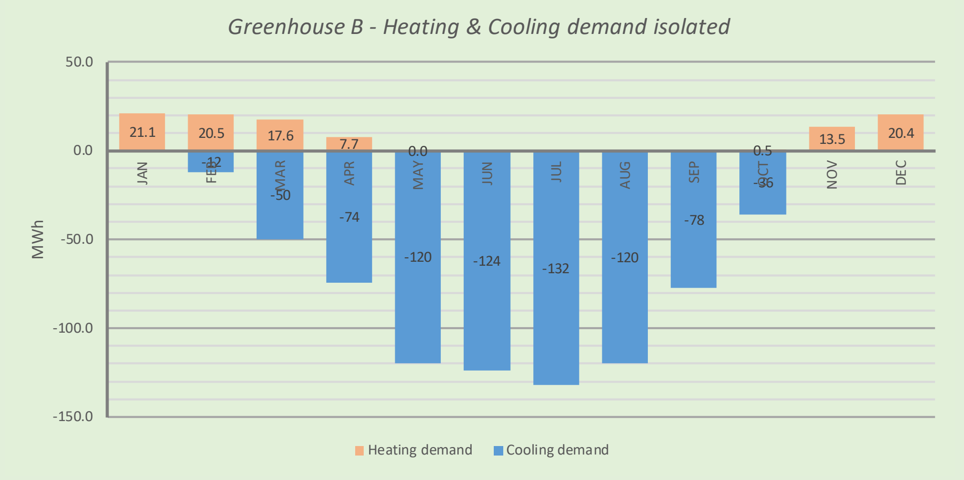
D1. Greenhouse A

Status	**not in use**
Length [m]	78.8
Width [m]	10.8
U-value glass [W/m2.K]	2.7
STC value [-]	0.6
Minimum indoor temperature [°C]	11
Maximum indoor temperature [°C]	24
q_{PERSON} [W/person]	180
q_{EQUIP} [W/m2]	5
q_{LIGHT} [W/m2]	10
Number of people [-]	5
Lights on factor (hours on / 24hr)	0.32
People occupancy factor (hours present/24hr)	0.2
Equipment on factor [hours on/24hr]	1.0



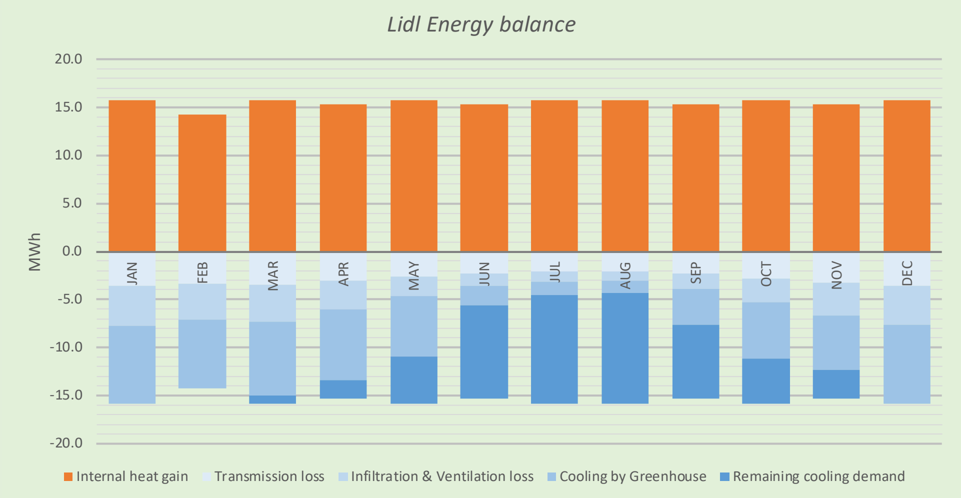
D2. Greenhouse B

Status	**active**
Length [m]	107
Width [m]	8
U-value glass [W/m2.K]	2.7
STC value [-]	0.6
Minimum indoor temperature [°C]	11
Maximum indoor temperature [°C]	27
q_{PERSON} [W/person]	180
q_{EQUIP} [W/m2]	5
q_{LIGHT} [W/m2]	10
Number of people [-]	5
Lights on factor (hours on / 24hr)	0.2
People occupancy factor (hours present/24hr)	0.5
Equipment on factor [hours on/24hr]	1.0



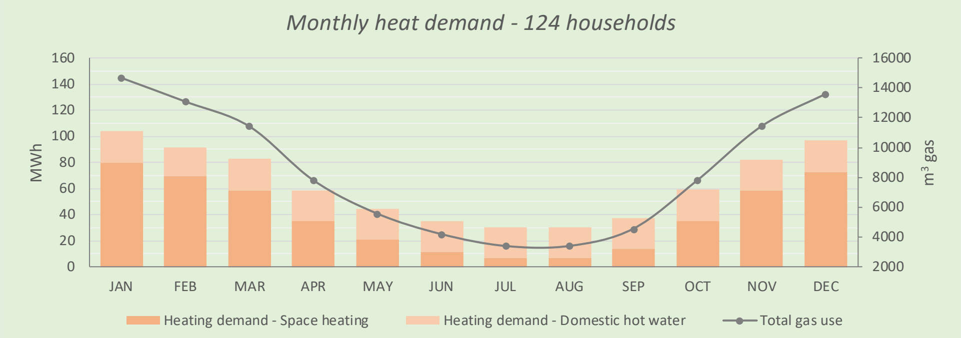
D3. Supermarket

Length [m]	46.00
Widt [m]	15.40
Height [m]	2.900
U-value roof [W/m2.K]	0.170
U-value floor [W/m2.K]	0.250
U-value wall [W/m2.K]	0.220
Indoor temperature [°C]	21.00
Infiltration rate [m3/s]	0.443
Ventilation rate [m3/s]	0.170
Heat emitted by one customer [Watt]	131
Greenhouse<> Lidl heat exchange rate	3



D4. Dwelling

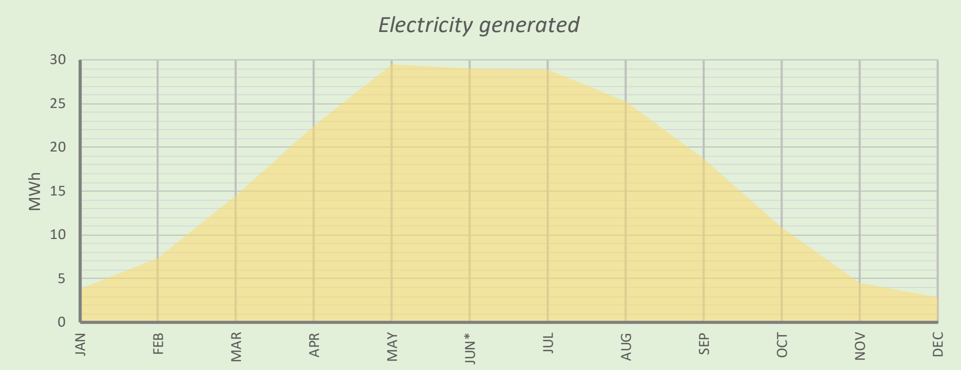
Number of households	124
Gas use for space heating [m3]	389
Gas use for domestic hot water [m3]	230
1 m^3 gas equals MJ	35.17
Gas use for space heating [m3] - Current situation	580
Gas use for domestic hot water [m3] - Current situation	230



D5. PV production

Gross roof area [m2]	1649
Effective roof area reduction factor [-]	0.6
WP per panel [Wp]	350
Length panel [m]	1.70
Width panel [m]	1.01
Efficiency [%]	90%

Rooftop A = 851m2
Rooftop B = 856m2
Rest rooftops = 798m2
Rest + A = 1649m2
Rest + B = 1654m2



APPENDIX VI: Lidl cooling: cooling by the fresh water supply - §7.4

[extra] only for inspirational purposes. Method not included in further energetic calculations

'Free' cold source

There are 124 households, a supermarket and two greenhouses connected to the energy system. All these functions together use large amounts of tap water every day. This water has an approach temperature of 10-15 degrees, depending on the season. All this cold water is an 'infinite' large cold source that could be used for space cooling, especially if the cooled space is a stable and relative cold environment: like the supermarket.

Legionella bacteria

The first concern that arises is the increased risk on the development of Legionella in the pipes after the water has passed through the supermarket floor. This hesitation is understandable and should be considered. Legionella bacteria multiply only in an environment between 25°C and 50°, below 25°C the bacteria can't reproduce, above 50°C they extinguish. Dutch law[2] states that the approach temperature of the water should not extend above 25°C

Total water use.

According to *Waternet*, the water supplier of the city of Amsterdam and adjacent districts, the daily water consumption per person is 133.4 litres[1]. There are 126 households connected to the system and for this calculation we take the Dutch average household size of 2013: 2.19 (Centraal Bureau voor de Statestiek).

$$133.4 \times 124 \times 2.19 = 36.200 \text{ L/day.}$$

This number is round up to <u>40.000 L/day</u> to include the water consumption of the greenhouse and the supermarket as well.

In operation.

The total water use of the block is 40.000L and this water temperature should not reach the 25°C lower limit. For safety, we state that the supply water should not stay in the system longer then one day and that the temperature of the water should not exceed 20°C. The demand for fresh water and the cooling demand of the Lidl do not follow the same curve. The water consumption peaks in the evening and the cooling demand peaks during opening hours (08:00-20:00). A 20.000L storage tank is installed to buffer this offset of demand. The quantity is rather low compared to the total use, but it makes sure the water does not remain in the tank longer than one night. Cold water is pumped through the floor in large quantities at the time, where it cools down the mass of the floor before it is collected in the buffer tank. A bypass is installed in case both the water demand and cooling align for a short period.

The cooling capacity would be:

$$q_{COOL} = \alpha * A * (T_{IN} - T_{WATER}) \qquad [5.1]$$

where

q_{COOL}	Floor cooling [Joule]
α	thermal conductivity floor, 6W/m^2.K $_{COOL}$
A	Total floor surface (sales area), 851m^2
T_{IN}	Indoor temperature Lidl: 19°C (all year)
T_{WATER}	Calculation temperature tap water, 13°C (average of 10°C and 15°C)

This makes:

$$q_{COOL} = 6 * 851 * (19\text{-}13) = 30.600 \text{ Watt}$$

Theoretical maximum cooling capacity:

$$Q = 4185 * 40.000 \text{ L} * (19\text{-}13) = 1000 \text{ MJ} = 279 \text{ kWh/day}$$

More one the effect of this cooling method in chapter 8.7.

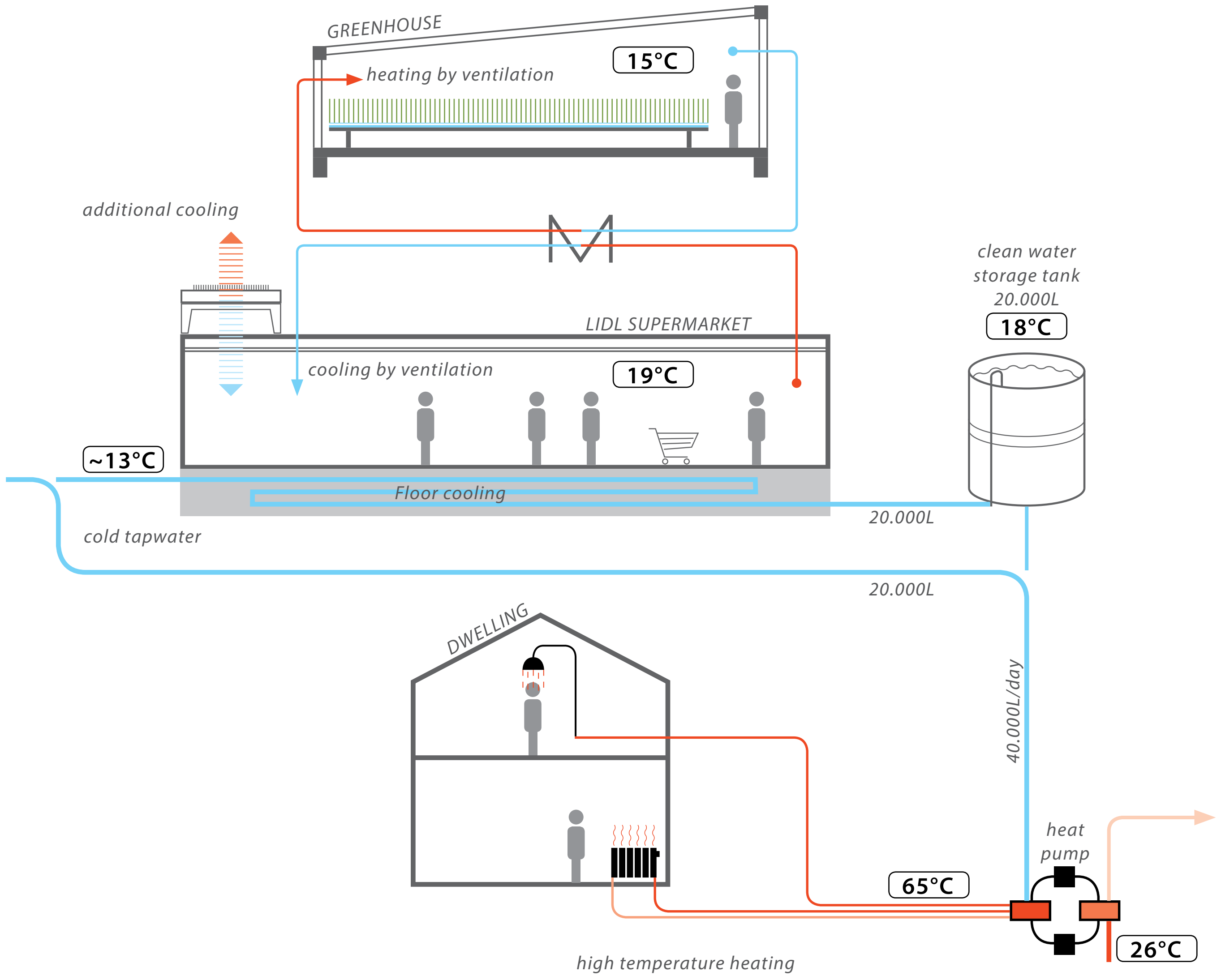


Figure 7.10: Scheme of the three cooling methods in the Lidl supermarket and how they are connected to other elements in the grid.

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1) https://www.waternet.nl/ons-water/drinkwater/gemiddeld-waterverbruik/ , 2) http://wetten.overheid.nl/BWBR0030166/2011-07-01#Artikel8


2,49
0,90