V.R.M. Höfte

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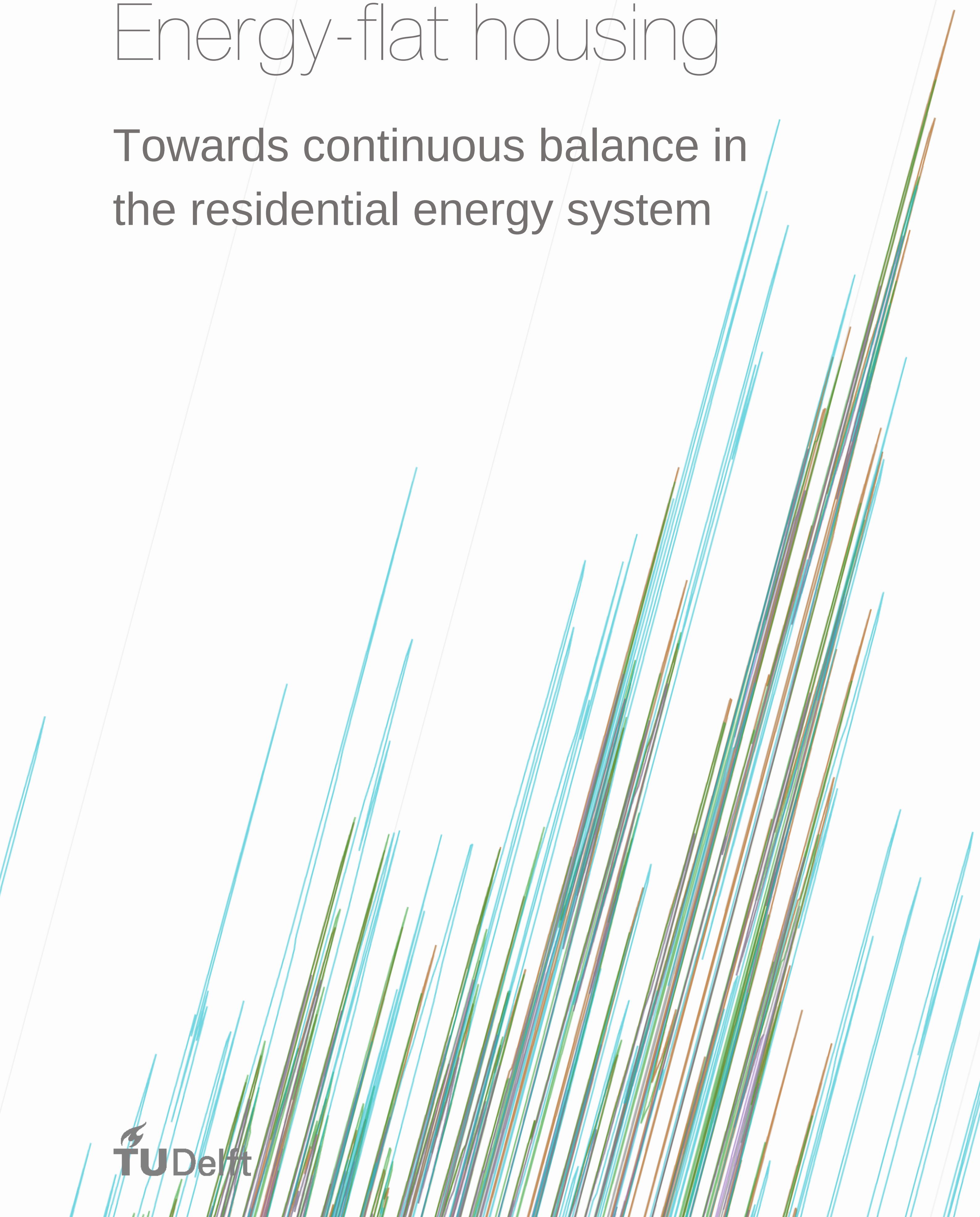
Towards continuous balance in the residential energy system



Energy-flat housing

Towards continuous energy balance in the residential energy system

By

V.R.M. (Vincent) Höfte

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Supervisors:	Prof. dr. ir. A.A.J.F. van den Dobbelsteen
	Dr. ir. S.C. Jansen
Thesis committee:	Dr. N.E.T. Nieboer
Company supervisor:	Ing. H.G.H.F. van Hauwe (*DPA Cauberg-Huygen)*

TU Delft
Faculty of Architecture
Julianalaan 134
2628 BL Delft
Tel: +31 15 27 89805

Contact information
v.r.m.hofte@gmail.com
Tel: +31 6 57 58 96 93

Preface

It was back in August 2016 when, together with two fellow students, I co-founded the design-studio Walden, a studio for small, self-sufficient architecture. I had the chance the bring radical sustainable-building ideas into practice and be inspired by fellow pioneers. One year later, when business went very well, I made the decision to quit the start-up and first focus on finishing my studies. Regardless my parting at Walden, the urge to continue in the practice of sustainable architecture was strong.

In the nine months between quitting Walden and starting graduation, I took the time to explore a graduation topic. It started with the idea of a technology-resilient tiny home, went to energy-balancing districts and also touched the optimization of Prêt-à-loger. After lots of meetings with professionals in both the academic and commercial discipline, I ended up with the idea of energy-flat buildings; buildings in which energy demand and local energy supply are matched by architecture.

I will confess right away; *energy-flatness* is a definition I conceived myself. The topic of energy balancing is not new, but achieving it in a single building with merely architectural features is new. Hence, it deserved this new definition in my opinion. The anticipatory nature of this topic, combined with the simple goal of matching supply and demand for which broad research is required, were my biggest motivation to fulfil this project.

In April 2017 I started my research, supported by two well-educated and motivated academics, Andy and Sabine, to be my mentors and by DPA Cauberg-Huygen, as the company whereat I could do my graduation internship. Now that my project is finished, in January 2018, I can honestly conclude that these were the most informative but tough months of my studies. The project illuminated me in academical, professional and personal ways. I learned more about building physics, energy systems, innovative software, business, relations, expectations, self-discipline, and so on. I am happy with my final result and the process I have experienced.

I would like to thank some people who have been important to me in this project. I would like to thank **Andy van den Dobbelsteen** and **Sabine Jansen** for greatly broadening my knowledge and providing me constructive feedback to improve my research. I want to thank **Hans van Hauwe** and **Anne-marije Scheffe** as my two mentors at DPA Cauberg-Huygen, for giving broader insights in the relevance of the topic and making my time at DPA an enervating experience.

Also, I want to thank **Tom**, for being the best roommate a graduation student could have with his constructive criticism, extremely tasteful dinners and our unstringing talks. A thanks to all my friends of the *Dikke V* and my fellow building technology graduate students for their interest in my project and for giving leisure and fun in the free hours.

Last, but most important, thanks to my love **Maël**, who has always been there for me and gives me all the joy, support and love I could wish for.

Vincent Höfte
Delft, January 2018

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Nomenclature

Abbr.	Meaning	Translation
(N)ZEB	(Nearly) Zero Energy Building	
AC	Alternating current	
BENG	Bijna Energieneutraal Gebouw	Nearly Zero Energy Building
CHP	Combined heat and power	
COP	Coefficient of performance	
CSP	Concentrated Solar Power	
DC	Direct current	
DHW	Domestic Hot Water	
DSM	Demand-side management	
EPC	Energie Prestatie Coefficient	Energy performance coefficient
EPV	Energieprestatievergoeding	Energy performance compensation
ETC	Evacuated tube collector (solar)	
EU	European Union	
FIX	Flexibility index (IEA, 2011)	
FPC	Flat plate collector (solar)	
HR++	Hoog rendement (glas)	High-efficiency (glass)
HVAC	Heating, ventilation and air-conditioning	
KPI	Key performance indicator	
LPG	Liquified petroleum gas	
NCSP	Non-concentrated Solar Power	
NOM	Nul-op-de-meter	Zero energy (building)
NSS	Nieuwe stappen strategie (Van den Dobbelsteen, 2008)	New Stepped Strategy
PCM	Phase change material	
PMV	Predicted Mean Vote (Fanger, 1970)	
PV	Photovoltaic (electricity production)	
PVT	Photovoltaic thermal collector	
REAP	Rotterdam energy approach planning (Tilly et al., 2009)	
RES	Renewable energy sources	
RMOT	Running mean outdoor temperature	
SPF	Seasonal performance factor	
TES	Thermal Energy Storage	
VOC	Volatile organic particles	
ZEN	Zeer energiezuinige nieuwbouw	Very energy-efficient new buildings

Abstract

The global energy demand is increasing as a result of population growth and increased wealth standards. In Europe, buildings are responsible for 37% of the final energy demand. The share of local renewable energy supply is also increasing, driven by the urge to mitigate climate problems.

Residential energy demand and renewable energy supply are both intermittent; the demand profile depends on several aspects like the inhabitants, the physical properties of a building and the outdoor climate. Renewable energy supply is intermittent because it can only occur when the intermittent renewable energy source, e.g. the sun, is present. So, the intermittencies of supply and demand depend on different aspects, hence causing a mismatch. This mismatch must be solved.

Energy-flat buildings are a potential solution to this problem. To diminish the problem of energy mismatch on a residential level, dwellings will have to be able to adapt the demand to supply and vice versa. The research presented in this thesis explores the potential of architectural design in eliminating the on-site energy mismatch. In other words, the potential of energy-flat buildings.

First, three key-performance indicators for energy-flatness are defined and a dynamic energy simulation model is set-up using Grasshopper Honeybee software. With this tool, the energy-flat performance of several designs can be quantified and analysed. Then, the current mismatch of residential energy in a reference design is determined. Thereafter, the effect of building parameters on the energy-flat performance of a design is researched. The results of this parameter study are then used to design an energy-flat building in three design steps; a design in which demand adapts to supply, a design in which supply adapts to demand and finally an optimized design in which both supply and demand are adapted. The knowledge gained by this design-by-research approach is bundled in a toolbox, which serves as a guide for architectural designers.

It is found that the heat balance should be considered first when aiming for energy-flatness, rather than the electricity balance. Moreover, heating demand, cooling demand and renewable supply should be considered separately. The nine building parameters that are researched, all significantly influence the energy-flatness by affecting different elements of the heat balance. An adaptive approach in terms of daily and seasonal differences is required for almost all parameters to achieve the best energy-flat performance.
It is also concluded that the largest challenges for energy-flatness are the lack of supply potential at night, lower solar power in winter combined with lower outdoor temperatures and the unpredictability of both energy demand and energy supply in short time intervals. The toolbox that is created provides effective energy-flat design principles. However, the effect of the individual principles cannot be quantified, because the principles influence each other. So, only complete designs can be evaluated in terms of energy-flatness.

Moreover, it is concluded that architectural design can greatly contribute to minimizing the mismatch between residential energy demand and supply, but it cannot create energy-flatness by itself. The performance of building installations is essential for achieving energy-flatness, but it is only partly researched in this thesis because these building installations lie beyond its scope.
Lastly, it is concluded that energy-flat buildings theoretically can be the solution to the (inter)national energy balancing challenge, but achieving this by taking only the most effective measures on every level of the system is preferable. The relevance of energy-flat buildings will change in the future, depending on the development of energy storage technologies and the share of renewable energy production.

Altogether, the architecture of a building can significantly influence its energy-flatness and the concept of energy-flatness will contribute to effective use of local renewable energy.

1 INTRODUCTION

1.1 RESEARCH OUTLINE

1.1.1 Background and problem statement

The global population and wealth growth result in an increase of energy demand. While renewable and clean energy technologies are rising, the amount of CO_2 produced yearly is still increasing. These emissions, combined with other sources of pollution, make the world subject to problems as climate change and global warming.

In Europe, buildings are responsible for 37% of the final energy demand. Energy consumption of buildings has increased with 1,5% per year in Europe since 1994 (Pérez-Lombard, Ortiz, & Pout, 2008, pp. 395-396). The U.S. Energy Information Administration (IEA, 2016) expects that an average annual increase of 0.6% proceeds in the future in the OECD-countries, which results in a growth of energy consumption in the residential sector of 18% within the projection period of 2012-2040. Simultaneously, the production of renewable energy is increasing as well, both on the (inter)national level as the residential level. Private and commercial investments in solar energy in the residential sector are gaining popularity and the expected average annual percent increase in solar energy is 4.6% per year in the OECD countries (IEA, 2016). In the Netherlands, the total solar electricity production power has increased with a factor 10 from 2010 to 2014 (CBS, 2017). These figures, however, are to some extent misleading since the Netherlands are still far behind in renewable energy production both compared to other EU-countries and compared to its own targets for 2020. The Netherlands currently have a renewable energy production share of 5.8%, whilst the goal for 2020 is 14%, and thereby is on the third-last place in the EU in share of renewable energy (Eurostat, 2017).

Background problem

Residential energy demand and renewable energy supply are depend on several factors. Energy demand is not constant; fluctuations occur from hourly to yearly time intervals, caused by varying user demands and climate conditions. In the conventional energy system, energy supply is adjusted to this demand by adapting energy production to predictions on the energy demand fluctuations. With the rise of renewable energy supply, the manageability of energy production decreases. Renewable energy supply is intermittent by nature for it is dependent of contextual phenomena like solar and wind. The intermittencies of demand and supply result in an energy mismatch (Figure 1). An energy system always should be in balance and thus the mismatch must be solved.

Existing solutions

Solutions to this problem are to be found at different levels of the energy system; from housing appliances to the (inter)national (industrial) energy use and distribution. In the residential context, currently two solutions are elaborately researched, namely smart grids and batteries. Smart grids help turn home appliances on and off at times of respectively energy surplus and energy shortage. Residential batteries are used to ‘postpone’ renewable energy production by temporary storing energy. Smart grids, however, only solve the electricity use of home appliances, whilst more than half of the energy used by a building is for space heating (Itard & Meijer, 2008). Batteries can help to shift building energy, but batteries will always imply energy losses and environmental impact because of their cycle efficiency and embodied energy.

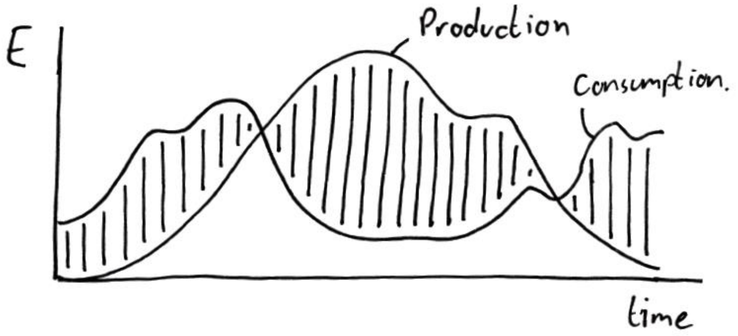


Figure 1: The local energy mismatch resulting in the aim for energy-flatness

Problem statement

Existing solutions focus on compensating the effects of the mismatch of residential energy demand and renewable energy supply. However, solving the mismatch directly by architectural design might be a more effective solution. Research on the energy system of buildings mainly focuses on reducing the energy demand or increasing the renewable energy production annually. The problem statement is that too little is known on the potential of solving the residential energy mismatch by architecture.

Proposed solution

To diminish the problem of energy mismatch on a residential level, dwellings will have to be able to adapt the demand to supply and vice versa. This research focuses on buildings that eliminate the on-site energy mismatch by architectural design; **energy-flat buildings**. Energy-flat buildings stimulate on-site renewable energy production by making it more cost-effective and reducing conversion losses caused by temporary storage. In addition, the national utility grid could benefit from more stable connections with fewer and smaller peaks and house owners could benefit from lower energy costs.

1.1.2 Research questions and objectives

This research aims to solve the residential energy mismatch by providing a definition of energy-flatness in the residential context in terms of performance indicators. Moreover, it aims to explore design principles that stimulate energy-flat buildings and to make an example design that is fully focussed on energy-flatness. To fulfil these aims, the main question of this research is:

> *How can the residential mismatch of the supply and demand of energy be solved by architectural design?*

To find the answer to this question, the following sub-questions are defined:

- What is energy-flatness and what are its key performance indicators?
- How should the energy-flat performance of a design be simulated?
- What is the current residential energy mismatch between supply and demand?
- To what extent can supply and demand profiles be adapted by building parameters?
- What could an energy-flat design look like?
- How do energy-flat buildings relate to solving the mismatch in the energy system that the building is part of?

The corresponding objectives of the research are:

- Defining the key performance indicators both graphically and mathematically and setting the energy-flatness framework
- Setting up an energy-flatness model that is able to evaluate the energy-flat performance of a design
- Analysing the residential energy supply and demand profiles to determine the current mismatch
- Measuring the effect of changing individual building parameters on the demand and supply profiles
- Designing an example design solution for a completely energy-flat house
- Positioning the results in the energy system that a building is part of

Hypothesis

It is expected that energy-flat buildings are a solution for solving the residential energy mismatch. It is not expected that energy-flat buildings are the best solution for the total energy system (i.e. nationally). The simplified energy mismatch consists of two profiles; the demand profile, the sum of a heat demand and a cool demand, and the supply profile. To design an energy-flat building, the profiles have to be mutually adapted by architectural design. It is expected that design-principles that affect the demand and supply will be found, partly based on architectural precedents. Furthermore, it is expected that a perfect energy-flat house design is theoretical rather than realistic and practically feasible. The theoretical design, however, will show the possibilities for energy-flat design that contribute to the improvement of the energy system as a whole and the model that is set-up is expected to be useful to evaluate energy-flatness of future designs.

Scope

The scope of the research is extensively defined in *3.2 Scope of the energy-flat building*, though shortly explained here. The research focusses on a modern, representative detached Dutch dwelling with an average consumer. Both heat balance energy-flatness and electricity balance energy-flatness are the aim, although heat balance is the primary goal for it is the most primary form for energy-flatness. The research is of a theoretical nature; the aim of pure energy-flatness is theoretical and not practically realistic. It is assumed that exploring this extreme theoretical ambition, new insights on sustainable building design might be found. The products that are delivered by this research, might be useful as well when changing the parts of the scope (e.g. other climate, other household).

1.2 METHODOLOGY

The six sub-questions and their related objectives serve as the structure of the overall methodology. Figure 2 shows how the combination of research questions will lead to answer the main question. The vertical location of the blocks suggests a certain chronology; however, the research will have an iterative nature and the flow therefore is not too strict.

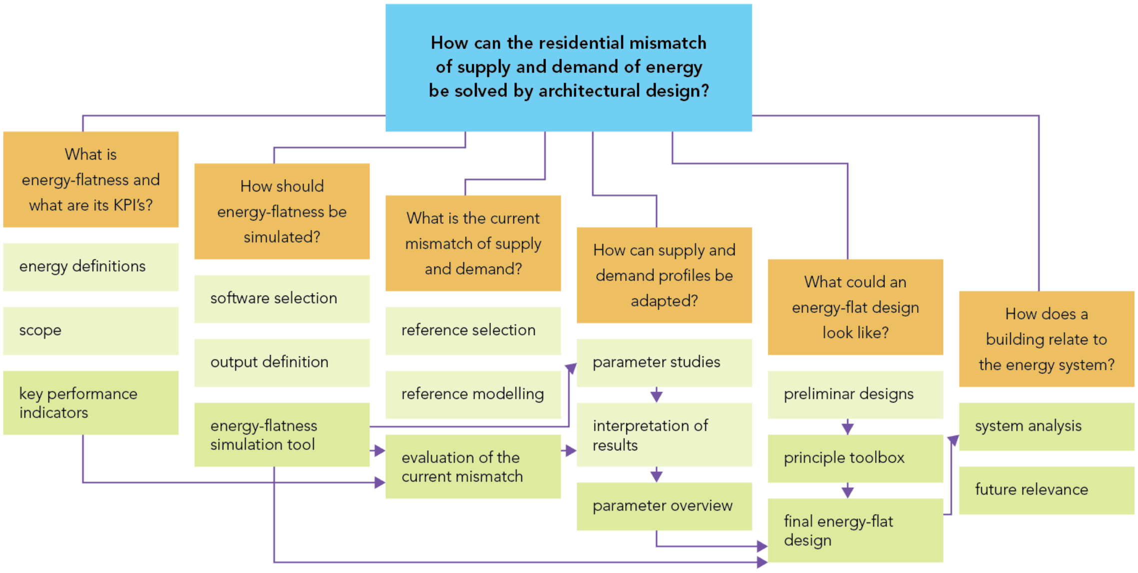


Figure 2: Overview of main question, sub questions and the main products per question

All questions and their related objectives are explained in the next section. The last section will show how the answers to the questions relate to each other.

What is energy-flatness and what are its key performance indicators?

In order to answer this question the following three objectives are achieved:

- Clarify energy definitions
- Set the scope
- Define the key performance indicators

To clarify the energy definitions, a literature study is done on definitions in building energy systems. Lots of research is done in the subject of building energy, so it is important that the definitions used in the study are in line with the commonly accepted definitions.

The scope of energy-flatness is refined by considering some elements of the framework for zero-energy buildings (ZEB) as set up by Sartori, Napolitano, and Voss (2012). The physical boundary, balance boundary and balancing period are discussed. Other literature is used to substantiate the scope-related decisions.

The key performance indicators (KPI) are defined by myself, based on meetings with tutors at the Delft University of Technology and inspired by literature. Peer-reviewed papers have been used to explore other performance indicators, e.g. Salom et al. (2011) and Widén, Wäckelgård, and Lund (2009), but it is concluded that the simplicity of the initially designed performance indicators suits the need for to-the-point validation the best. The KPI's are graphically and mathematically defined and are used to evaluate the energy-flatness of a design based on its supply and demand profiles.

How should the energy-flat performance of a design be simulated?

The energy-flatness of a design is determined by the values of the KPI's resulting from the demand and supply profiles of a design. These profiles consist of hourly values, which are generated by a dynamic energy model, using the software package Honeybee, as part of Ladybug Tools (Ladybug Tools, 2017). This is an open-source plug-in for Grasshopper, which is in turn a plug-in for Rhinoceros. For the dynamic energy calculations Honeybee makes use of EnergyPlus, a renowned building energy simulation program (EnergyPlus, 2017). Since Honeybee and Grasshopper are open-source software, they have large online community in which new ideas, questions and bugs are shared and solved. Hence, its quality is constantly improved by the trial and error of thousands of users.

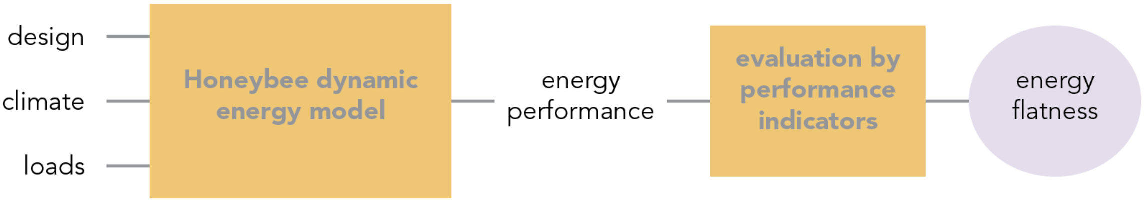


Figure 3: The role of the TRNSYS energy model to provide the energy-flatness of a design

The input and output of the Honeybee model can be highly customized. The input will be provided by the designs that are made, as well as the user-profile consumption data as discussed in ''*What is the mismatch between supply and demand?".* The initial output will be the energy demand and supply profiles, which will be translated into the key performance indicators. Figure 3 shows the role of the Honeybee model.

What is the mismatch between supply and demand?

The current mismatch of residential energy supply and demand is based on the SenterNovem Reference design. This design is created by DGMR (2016), on behalf of the Rijksdienst voor Ondernemend Nederland. It is part of a collection of BENG referentiegebouwen, which by the Dutch government is assumed to be representative for the Dutch building stock, designed to fit recent standards. The reference design consists of a short building description, some building construction and installation properties, and the energy performance.

The mismatch will be defined by determining the supply profile and the demand profile, and then mutually comparing them using the KPI's as explained in the first section. Moreover, the mismatch will be analysed on a more qualitative level by analysing exceptions and determining the distribution of the different energy flows in the demand and supply profiles.

All the user-dependent energy flows (i.e. plug-loads, lighting, domestic hot water) are set by taking Dutch averages, derived from online databases. The building-dependent demand flows (i.e. heating, cooling and ventilation) and all energy supply flows (i.e. solar radiation) are determined using the energy model from the previous section. The user-dependent flows are, regardless their fixed nature, integrated in the energy model. This way, there will be one overview of outputs of the energy model that can be used for analysis directly.

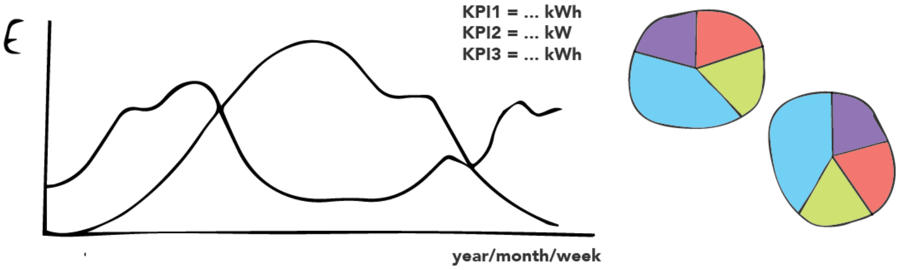


Figure 4: The mismatch is determined by KPI's and qualitative analysis of the energy flows

The KPI analysis and the qualitative analysis of the mismatch result in an overview of the characteristics and potentials of the mismatch, which is used as a starting point for the designs combined with the parameter overview.

How can the supply and demand profiles be adapted?

The product of this sub-question is an overview of the effect of building parameters on the supply and demand profiles. The effect of changing parameters on the energy-flat performance of a design is studied using the simulation tool as described by the second sub-question. Nine building parameters are studied, they are shown in Figure 5 below.

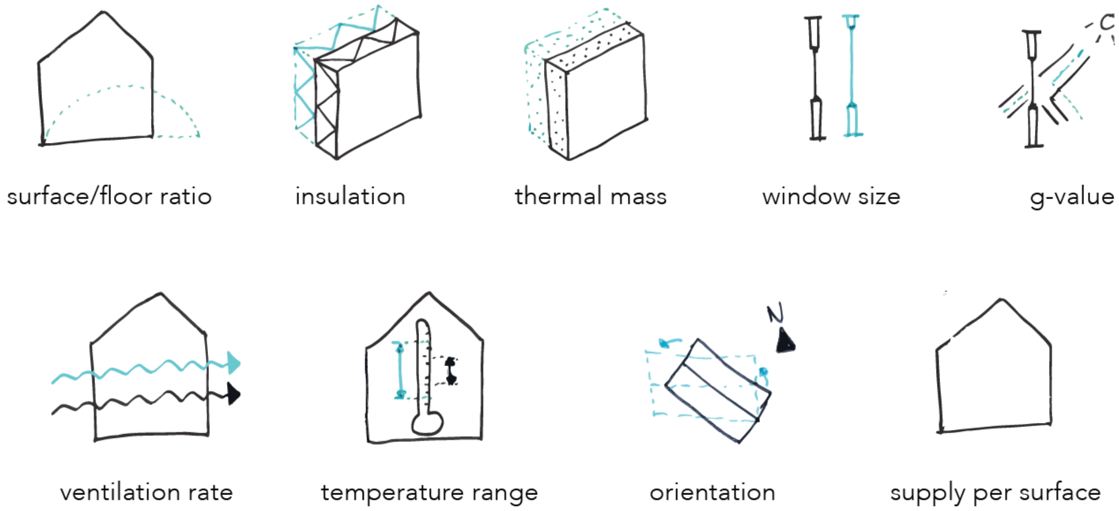


Figure 5: An overview of the nine building parameters that are studied individually

All design parameters are quantitative, linear parameters, in favour of the scalability and the applicability of their effects on all future designs. The parameter study variables are chosen such that, for every parameter, the lowest and highest value are as broad as possible (to show the effects more clearly), though within realistic limits. Moreover, all other building properties are kept constant relative to the reference, unless indicated otherwise. For every parameter study, some short background information is given. Then is explained what the variants of the parameters are and why they are chosen. The results are provided in graphs and text, which is then interpreted. Then, a conclusion is given that answers the questions of what the most energy-flat solution would be for that specific parameter and if or how it should be achieved in architecture.

This parameter study results in the eventual parameter overview, in which per parameter is shown which is the best possible solution in terms of energy-flatness. Moreover, the parameter-study is reflected upon, to assure how the results should or should not be used.

What could an energy-flat design look like?

An energy-flat design has the goal to have a perfect match between supply and demand at all times. The earlier defined design principles will be the inspiration for the designs. Energy-flatness is achieved by adapting the profiles of supply and demand. However, since there are two different profiles (i.e. supply and demand), it is undetermined how they should adapt to each other. Three different designs are made to optimize the mutual adaptation. The designs are made using a design by research approach, which means the design is adjusted in an iterative process in which the effect on energy-flatness of all design steps is constantly checked. In the first design, the demand profile will be adapted to the (fixed) supply profile. In the second design, the supply profile will be adapted to the (fixed) demand profile.

These two preliminary designs provide knowledge on the effect of combining several parameters, hence giving suggestions for more design principles. These principles are summarized in a toolbox, which is an overview of ideas that could be implemented in an architectural design to improve its energy-flatness. Per principle, the effect on the demand or supply profile is shown. The toolbox also consists of two sketch designs in which multiple principles are combined.

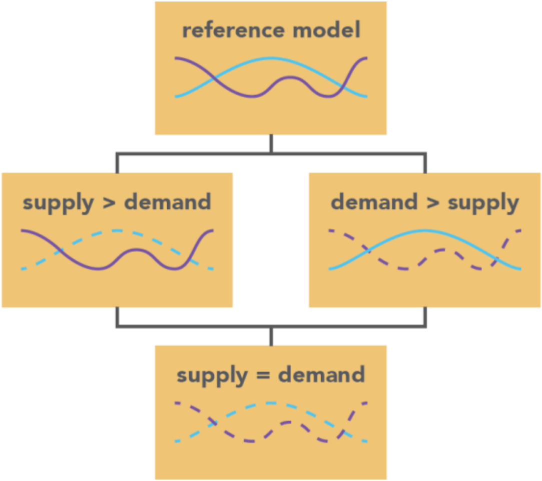


Figure 6: Researching the two profiles separately at first, results in an optimal balance in the end

The third design is the final design, and it will combine the knowledge of the former two designs by mutually adapting the profiles in the most efficient way. The set-up is shown in Figure 6. The final design is elaborated upon. Its energy-flat performance is analysed and the design is documented in a way that can be properly expected from an architectural design, taken into account the focus of the research. Plans, elevations and sections will be provided in scale 1:100. Some more detailed drawings of details are added to explain critical cornerstones of the designs.

How do energy-flat buildings relate to solving the mismatch in the energy system that the building is part of?

Solving the mismatch of supply and demand completely on the residential level, might not be the most favourable solution depending on the context. Lund, Marszal, and Heiselberg (2011), for example, conclude that for a national energy system, the mismatch of supply and demand can have both a positive or negative effect on the bigger system. In this final sub-question of the research, the question to how the energy-flatness in the residential setting relates to bigger systems is answered. It provides a critical reflection on the results and gives direction to successive research. The answer to this question is provided partly by literature research from peer-reviewed papers, my own reflections on the research and discussion with my tutors and other scientists.

1.3 ORGANISATION OF THE DOCUMENT

Chapter 2 consists of a literature study that goes into the background of the energy mismatch and the relevance of solving it on the residential scale. It describes the global changing energy system and its effect on the residential sector. The problem of intermittency of supply and demand is shown and Dutch regulations towards sustainable housing are explained. Solutions for matching supply and demand in other disciplines and other levels of the energy system are given. The energy balance, which is the foundation of supply and demand adaptation is explained. It is proven that a solution in terms of decreasing a mismatch is desired.

Chapter 3 answers the first sub-question *“What is energy-flatness and what are its key performance indicators”*. Definitions on a residential energy system are given and the scope for energy-flatness in this research is set. Moreover, the key performance indicators, which quantify the energy-flatness performance of a building, are defined.

Chapter 4 goes into the set-up of the simulation model. It provides information on the approach to energy-flat design modelling, the selection of software and the input variables and expected output of the model.

Chapter 5 describes the current residential energy mismatch by analysing the energy-performance of the reference design. The mismatch is described in different time-intervals and the basic characteristics of the mismatch are explained. This summarizes the focus for energy-flat design.

Chapter 6 explains the parameter study, in which the effect of changing individual building parameters on the energy mismatch is studied. The results are summarized in an overview that forms the foundation for the first energy-flat design optimisation.

Chapter 7 describes the iterative process towards the final energy-flat design. It describes three steps of design and eventually the energy-performance of the final design. It also consists of the design principle toolbox, which could serve as a tool for designers to improve the energy-flatness of their designs. Moreover, considerations concerning building services are made and the challenges to achieve even better energy-flat performance are described.

Chapter 8 goes into the role of energy-flat buildings in the bigger energy system as a whole. It reflects on how energy-flat buildings might contribute to energy balance on the highest level of the grid, and equally reflects on which aspects should not be solved by energy-flat buildings.

Chapter 9 provides the conclusion to this research by summarizing the results and answering the main research question. Also, recommendations for future research are given.

Chapter 10 is an academic, personal and societal reflection on both the graduation process and the results. It elaborates more on the authors personal opinion on the relevance of energy-flat building design in the energy transition.

2 LITERATURE RESEARCH

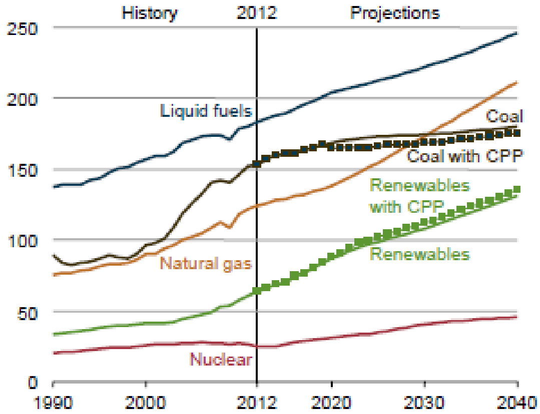
This chapter goes into the background information and the relevance of the topic. It describes the transition to sustainability and its effect on the energy system. Energy consumption and production are increasing, and so is the dependency on electricity. The problem of intermittency and the Dutch regulations that are aiming for sustainable buildings are discussed. Moreover, the building physical heat balance is explained and a precedent study is done.

2.1 GLOBAL AND RESIDENTIAL ENERGY TRENDS

The consciousness on climate change related problems in the world is rising, the importance of renewable energy sources is acknowledged and the transition towards renewable energy has started. Fossil fuels are still dominant in the energy system and cause a lot of CO_2 emissions that negatively affect global warming and other climate changes.

2.1.1 Global energy demand and supply increase

As the economy keeps growing and wealth is increasing, the world's total energy consumption will rise with 48% from 2012 to 2040 (IEA, 2016). Figure 7 shows that renewable energy is the fastest growing energy source in the world, with an average increase of 2.6% per year from 2012-2040. Disregard its high growing rate, the share of renewable energy in the total energy consumption is expected to be 22% in 2040 (IEA, 2016, p. 4). All other energy sources, apart from nuclear, are responsible for a total of 32.2 billion metric tons CO_2 emissions in 2012. This amount is expected to be increased with 34% in 2040 on a global scale (IEA, 2016, p. 5) and contribute to the commonly known climate change effects.



Note: Dotted lines for coal and renewables show projected effects of the U.S. Clean Power Plan.

Figure 7: Total world energy consumption by energy source, 1990-2040 (quadrillion Btu) (IEA, 2016, p. 1)

2.1.2 Shift towards electricity

Electricity is the world's fastest growing form of energy consumption, with an expected total global increase of 69% from 2012 to 2040. This increase partly relates to improved living standards that imply more and better home appliances as well as commercial services (IEA, 2016, p. 4). In Europe, electricity consumption increases with 1.4% per year from 2012 to 2040 whilst natural gas consumption grows at a rate of 1.0% per year. The IEA (2016, p. 101) expects that in 2025 electricity will be the leading source of residential energy and thereby surpassing natural gas. The shift towards electricity as most used form of energy consumption is favourable when regarding that produced renewable energy mostly has the form of electricity (e.g. photo-voltaic panels, wind turbines).

2.1.3 Energy trends in the residential sector

The energy demand and supply in the residential sector show similar patterns as the global energy trends. Both energy demand and renewable energy supply are increasing.

Energy demand

The energy demand in the residential sector is increasing due to population growth, the increasing time spent inside buildings and the higher standards for indoor comfort (Pérez-Lombard, Ortiz, & Pout, 2008, p. 395). In Europe, buildings use 37% of the final energy demand. The residential sector is responsible for 26% points of this value (Pérez-Lombard et al., 2008, p. 396).

Building energy demand in Europe has increased with 1.5% per year since 1994. This is partly caused by the increasing demand for indoor comfort, resulting in an increased amount of heating, ventilation and HVAC (Pérez-Lombard et al., 2008, p. 395). Residential energy demand increases with 0.6% per year in OECD countries from 2012 to 2040 because of increasing economic growth and living standards, which results in a total increase over that period of 18% (IEA, 2016, p. 4).

Energy supply

The share of renewable energy supply is rising. Figure 8 shows the rise of renewable energy share in the Netherlands in the past 25 years, rising from 1.2% to 5.8%. Almost 67% of this is from biomass, 21% is produced by wind energy and solar energy is responsible for only 4.3% of the total renewable energy consumption. Remarkable is that the share of solar and wind energy is growing much faster than biomass, 30% and 19% from 2014 to 2015 respectively. (CBS, 2016)

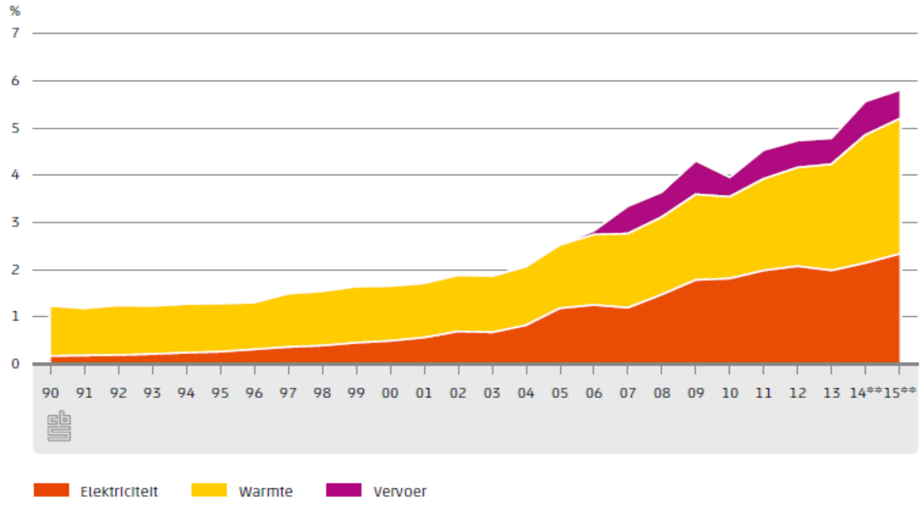


Figure 8: Share of renewable energy in gross final energy use in the Netherlands (CBS, 2016, p. 17)

For a dwelling, solar energy is the most common local renewable energy source. Solar energy can be distinguished in solar heat collection and solar electricity generation. In the Netherlands, solar energy has a share of 4% in the total renewable energy production.

Solar electricity has increased greatly the past few years, as shown in Figure 9. In the year of 2015 almost 440 MW is added to the system. CBS (2016, p. 48) predicts that the increase of solar electricity production is mostly caused by Dutch subsidies and the ‘salderingsregeling’ combined with high energy taxes for little-electricity users. Users do not have to pay taxes for their self-produced electricity. The total produced solar-electricity in the year 2015 was 1108 Mln kWh (CBS, 2016, p. 48).

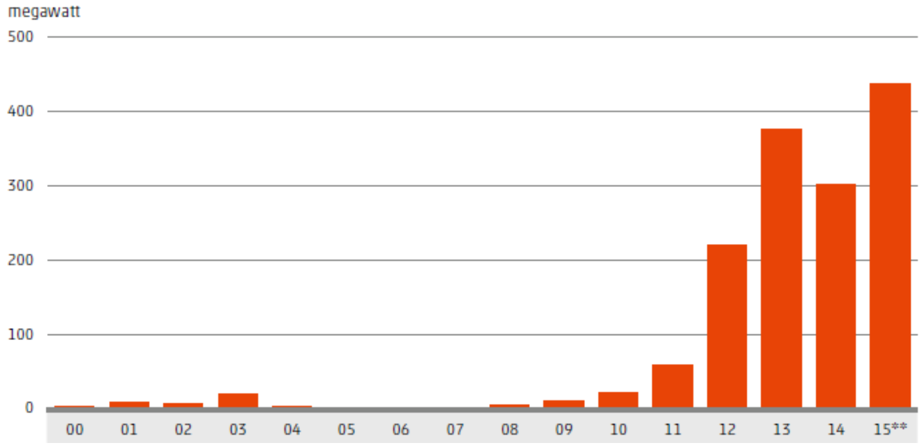


*Figure 9: Added solar-electricity power in the Netherland (CBS, 2016, p. 47), **provisional values at time of publishing*

In 2011, 52,572 kW of solar electricity power came from non-utility-provided, grid-coupled solar systems. This is almost a factor 10 compared to the solar systems controlled by electricity providers, which is 5,815 kW (CBS, 2013). It shows that solar panels are especially popular within the building sector, though it should be noted that for example farmers and big-land-owners who invest in PV-systems are also included in the former number. It is expected that costs for solar electricity production will fall and cost for conventional power (plants) will rise (Hafemeister, 2014, p. 434), resulting in an increase of solar energy production.

2.1.4 The energy mismatch in residential buildings in the Netherlands

The energy mismatch is determined by the size of demand and supply and the timing of demand and supply. The previous part showed the increase of energy demand and renewable energy supply. This section shows typical Dutch dwelling energy characteristics and considers the origins of the mismatch between supply and demand.

Energy demand characteristics

While every household has its unique demand and supply profiles, some typical characteristics of the energy profile of dwellings in the Netherlands can be described. Dwellings in the Netherlands, with their high latitude, are characterised by high heating loads in the winter and high energy generation in summer (in the case of PV production). On an annual basis, the heating has a high share compared to the low cooling loads resulting in a seasonal disbalance between heating demand and cooling demand. In a dwelling, there is a noticeable difference in energy consumption profiles between weekdays and weekend. During the working days, a short peak can be expected in the morning and a larger peak is to be expected in the late afternoon and early evening.

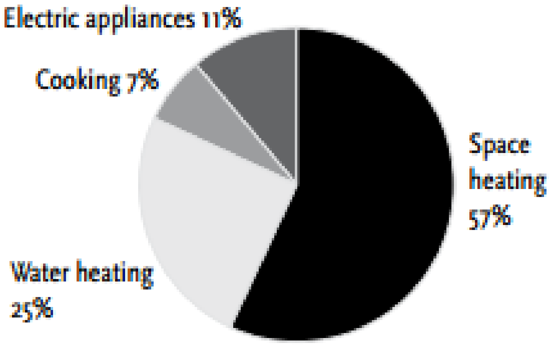


Figure 10: Final energy consumption in residential buildings in EU countries (Itard & Meijer, 2008, fig 2.8)

Figure 10 shows the energy consumption break down of a residential building in the EU. It can be derived that there is a need for focus on the making the primary energy of the building energy-flat. It should be noted though, that energy-flatness primarily regards modern, energy-neutral buildings. Energy regulations focus strongly on reducing the energy demand for space heating, by implementing insulation and having more efficient ventilation systems. It is to be expected that future households will have a relative lower share of energy for space heating. The higher insulation values can result in slightly higher cooling loads, due to heat accumulation. Figure 11 shows an illustrative future energy use for dwellings in Europe. (Kelly, 2012)

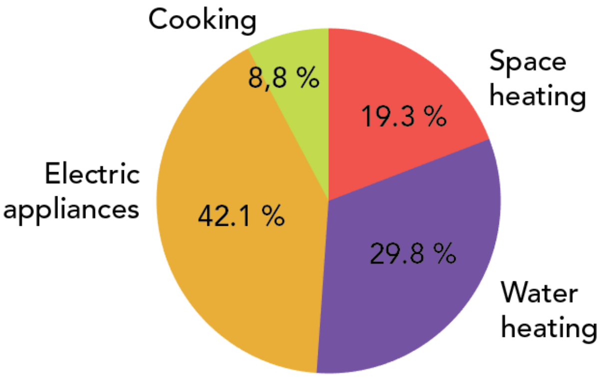


Figure 11: Illustrative energy use distribution of future dwellings in Europe, characterised by a lower share of space heating (adapted from Kelly, 2012, p. 24)

NEDU, a platform for the Dutch energy market, provides datasets of the consumption profiles as determined by the Dutch institution *Platform Verbruiksprofielen (Langen et al., 2017)*. The dataset *Profielen Elektriciteit 2017* provides the total electricity consumption of all E1A connections. This is the typical connection for a dwelling, although small utility buildings are likely to have a similar connection. This dataset thus not merely includes dwellings. The size of the dataset makes the set especially useful to show the typical patterns in the Netherlands, neglecting specific factors like location, size and specific user.

Figure 12 shows the electricity demand in a winter week and a summer week in the Netherlands. The daily pattern is clearly visible, with a valley during night-time, a lift in the morning, a small decrease during noon and a large peak at the beginning of the evening which gradually decreases till the valley of night-time.

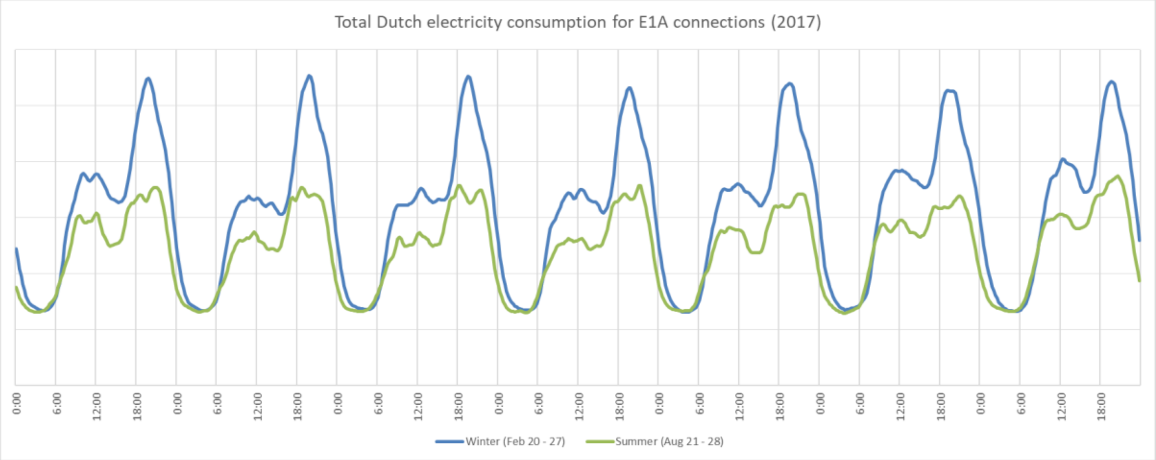


Figure 12: The total Dutch electricity consumption of E1A connections, which shows the typical characteristics of the demand (Langen et al., 2017)

The summer demand is lower than the winter demand, although the load at night is equal. The difference between the morning peak and the evening peak is relatively smaller in summer.

Lastly, a little difference between workdays and the weekend can be found in both summer and winter profiles. The morning peaks on Saturday and Sunday are higher than on workdays. The maximum peak of the evening is approximately like workdays though.

Renewable supply potential characteristics

In an energy-flat building, all the energy that is used, is locally produced renewable energy. Renewable energy is energy from sources that are not depleted by extraction. Renewable energy can be obtained from:

- Bio energy
- Hydropower
- Wind power
- Solar energy
- Geothermal energy

For the residential context, solar energy is the most easily achievable source of energy. The other forms of renewable energy are less (or not) feasible for a single household. In this research, solar energy is the only regarded source of renewable energy.

The Netherlands is located in the northern hemisphere at a latitude of 52°N. This results in the sun path diagram as shown in Figure 13. In the summer, at June 22nd, the sun has the longest path and the highest altitude which gradually decrease towards the winter, December 22nd.

Solar radiation can be divided into direct, indirect (diffuse) radiation and radiation from reflection by the earth surface. Solar radiation is a form of primary energy, which can be directly used in the form of heat absorption, or which can be transformed into distributable energy by photovoltaics (electrical energy) or solar collectors (thermal energy). The total solar power is the sum of the direct and diffuse solar power and the reflections by the earth surface:

$$Q_{sun} = Q_{direct} + Q_{diffuse} + Q_{reflection}$$

The solar power by reflection is always a share of the sum of Qdirect and Qdiffuse, influenced by the reflection coefficient of the surface and the geometrical factor. With an increase of sky coverage (N.B. by clouds) the direct solar radiation decreases, but the diffuse radiation increases because of a higher scattering. The total solar absorption by the horizontal plane diminishes. Figure 14 shows the values for direct normal radiation for the 15th day of every month of the year.

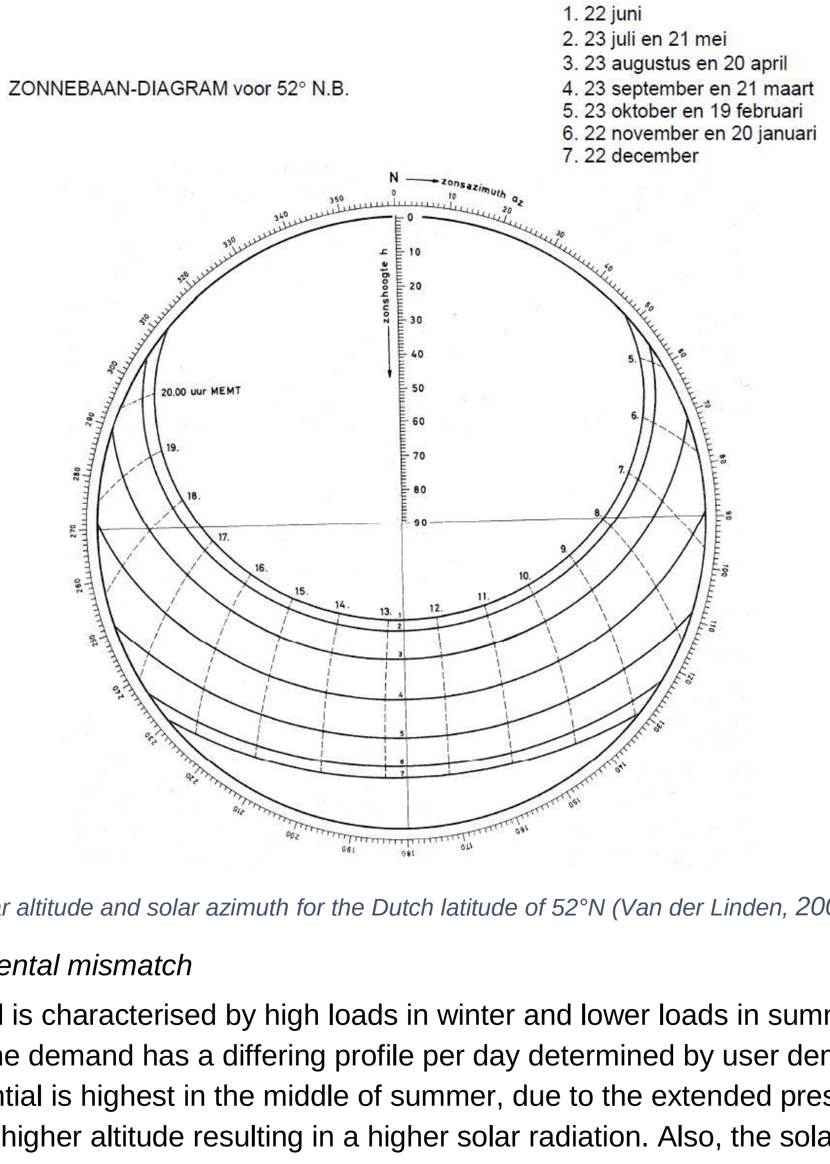
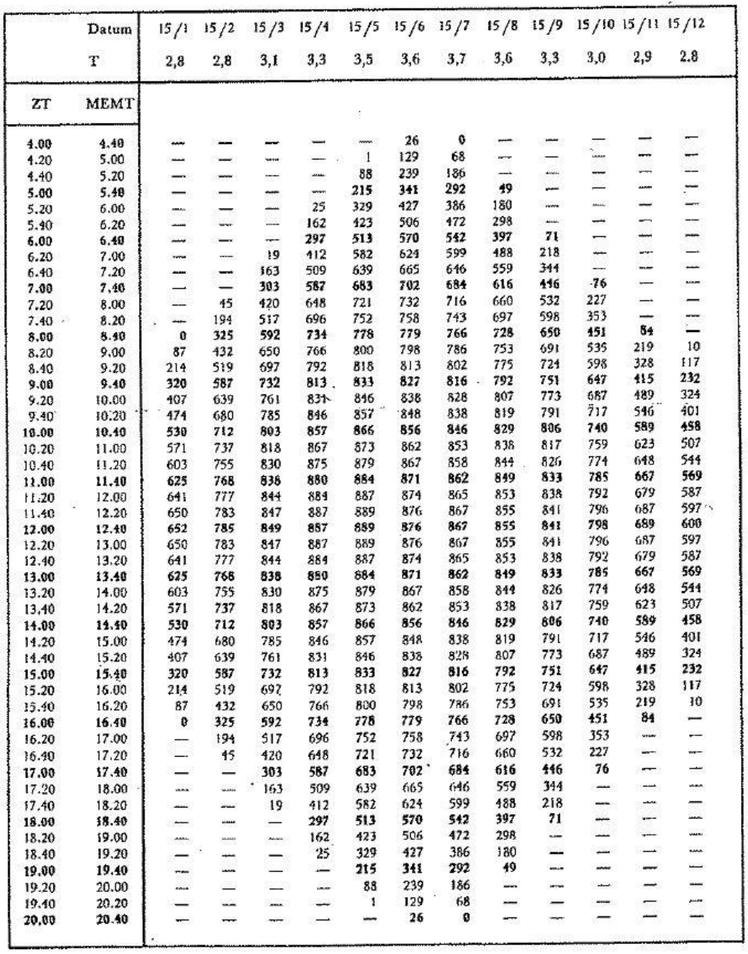


Figure 13: Solar altitude and solar azimuth for the Dutch latitude of 52°N (Van der Linden, 2005)

The fundamental mismatch

The demand is characterised by high loads in winter and lower loads in summer. Moreover, the demand has a differing profile per day determined by user demands. The supply potential is highest in the middle of summer, due to the extended presence of the sun and the higher altitude resulting in a higher solar radiation. Also, the solar power is highest during the middle of the day and the logically there is no solar supply during the night time. The solar supply potential depends on astronomical and meteorological aspects. The demand mostly depends on the user and meteorological aspects. In this, there is the fundamental mismatch.



	Datum	15/1	15/2	15/3	15/4	15/5	15/6	15/7	15/8	15/9	15/10	15/11	15/12
	T	2,8	2,8	3,1	3,3	3,5	3,6	3,7	3,6	3,3	3,0	2,9	2.8
ZT	MEMT												
4.00	4.40	—	—	—	—	—	26	0	—	—	—	—	—
4.20	5.00	—	—	—	—	1	129	68	—	—	—	—	—
4.40	5.20	—	—	—	—	88	239	186	—	—	—	—	—
5.00	5.40	—	—	—	—	215	341	292	49	—	—	—	—
5.20	6.00	—	—	—	25	329	427	386	180	—	—	—	—
5.40	6.20	—	—	—	162	423	506	472	298	—	—	—	—
6.00	6.40	—	—	—	297	513	570	542	397	71	—	—	—
6.20	7.00	—	—	19	412	582	624	599	488	218	—	—	—
6.40	7.20	—	—	163	509	639	665	646	559	344	—	—	—
7.00	7.40	—	—	303	587	683	702	684	616	446	76	—	—
7.20	8.00	—	45	420	648	721	732	716	660	532	227	—	—
7.40	8.20	—	194	517	696	752	758	743	697	598	353	—	—
8.00	8.40	0	325	592	734	778	779	766	728	650	451	84	—
8.20	9.00	87	432	650	766	800	798	786	753	691	535	219	10
8.40	9.20	214	519	697	792	818	813	802	775	724	598	328	117
9.00	9.40	320	587	732	813	833	827	816	792	751	647	415	232
9.20	10.00	407	639	761	831	846	838	828	807	773	687	489	324
9.40	10.20	474	680	785	846	857	848	838	819	791	717	546	401
10.00	10.40	530	712	803	857	866	856	846	829	806	740	589	458
10.20	11.00	571	737	818	867	873	862	853	838	817	759	623	507
10.40	11.20	603	755	830	875	879	867	858	844	826	774	648	544
11.00	11.40	625	768	838	880	884	871	862	849	833	785	667	569
11.20	12.00	641	777	844	884	887	874	865	853	838	792	679	587
11.40	12.20	650	783	847	887	889	876	867	855	841	796	687	597
12.00	12.40	652	785	849	887	889	876	867	855	841	798	689	600
12.20	13.00	650	783	847	887	889	876	867	855	841	796	687	597
12.40	13.20	641	777	844	884	887	874	865	853	838	792	679	587
13.00	13.40	625	768	838	880	884	871	862	849	833	785	667	569
13.20	14.00	603	755	830	875	879	867	858	844	826	774	648	544
13.40	14.20	571	737	818	867	873	862	853	838	817	759	623	507
14.00	14.40	530	712	803	857	866	856	846	829	806	740	589	458
14.20	15.00	474	680	785	846	857	848	838	819	791	717	546	401
14.40	15.20	407	639	761	831	846	838	828	807	773	687	489	324
15.00	15.40	320	587	732	813	833	827	816	792	751	647	415	232
15.20	16.00	214	519	697	792	818	813	802	775	724	598	328	117
15.40	16.20	87	432	650	766	800	798	786	753	691	535	219	10
16.00	16.40	0	325	592	734	778	779	766	728	650	451	84	—
16.20	17.00	—	194	517	696	752	758	743	697	598	353	—	—
16.40	17.20	—	45	420	648	721	732	716	660	532	227	—	—
17.00	17.40	—	—	303	587	683	702	684	616	446	76	—	—
17.20	18.00	—	—	163	509	639	665	646	559	344	—	—	—
17.40	18.20	—	—	19	412	582	624	599	488	218	—	—	—
18.00	18.40	—	—	—	297	513	570	542	397	71	—	—	—
18.20	19.00	—	—	—	162	423	506	472	298	—	—	—	—
18.40	19.20	—	—	—	25	329	427	386	180	—	—	—	—
19.00	19.40	—	—	—	—	215	341	292	49	—	—	—	—
19.20	20.00	—	—	—	—	88	239	186	—	—	—	—	—
19.40	20.20	—	—	—	—	1	129	68	—	—	—	—	—
20.00	20.40	—	—	—	—	—	26	0	—	—	—	—	—

Figure 14: Direct normal solar radiation in W/m^2 for the Dutch latitude of 52°N (ISSO, 1976, publikatie 3)

2.1.5 Conclusion

On a global scale, both energy demand and renewable energy supply are rising as a result of increasing wealth and population. Residential buildings are responsible for a significant part of this energy demand. There is a shift towards electricity as main energy carrier, caused by the rise of renewable energy and the increased use of electric appliances.

On the residential level, the energy demand for heating and cooling is increasing due to higher living comfort demands. There is a large rise in on-site renewable energy supply, photovoltaics in particular for residential buildings. This implies a shift from centralized energy supply to decentralized, local renewable energy supply.

The demand by dwellings is characterised by high heating loads in winter and cooling loads in summer. Typical daily patterns are characterised by high peaks in the evening. The local renewable energy supply by solar is characterised by high peaks during the middle of the day, and a big difference in seasonal supply with low supply potential in winter and high supply potential in summer. These characteristic patterns of supply and demand, both influenced by different conditions, inherently result in a residential energy mismatch.

2.2 THE PROBLEM OF INTERMITTENCY

The increasing energy demand and renewable energy supply in the residential context provoke a balancing problem on the utility grid, the electricity grid in particular. In the existing energy system, the energy supply is adjusted to the fluctuating energy demand by making estimations on demand profiles. This is possible because the energy production is always, constantly available and adjustable. Renewable energy supply is intermittent and not constantly available, because it depends on the presence of solar, wind et cetera.

Another difference compared to the conventional system, is the decentralised energy production. In the case of a house, the grid used to be the energy source where an amount of energy equal to the fluctuating energy demand was taken from. In the case of the house with solar panels, the house has an energy surplus or energy shortage depending on the solar production and the energy demand, as shown in Figure 15. Then the grid, apart from being the energy source sometimes, also serves as an energy dump for the energy surplus produced by the local solar panels. This may be beneficial when there is a shortage somewhere else on the grid. It may also be detrimental, which is the case when there is a surplus on the grid. When there is a surplus of energy on the grid, the energy is stored. This system is called grid storage. Another name for grid storage is large-scale energy storage, which is less misleading for it states that it is about large energy storage systems that are connected to the grid. Another option to prevent energy-surplus on the grid is on-site energy storage in terms of batteries.

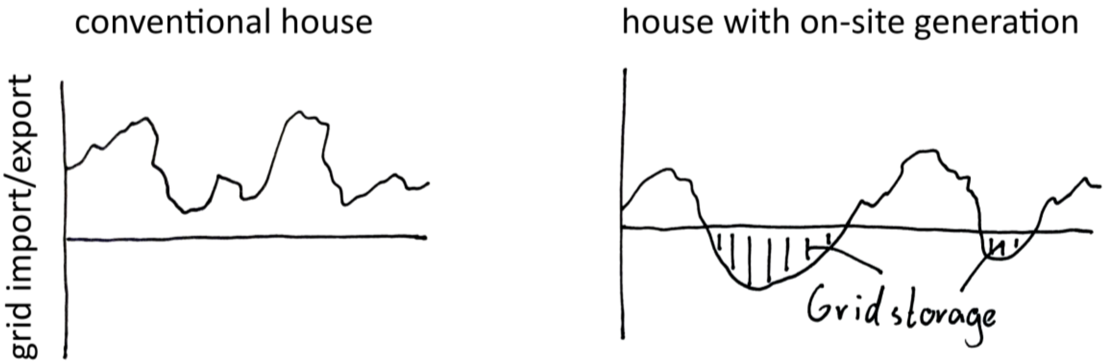


Figure 15: Relation to utility grid of a conventional house compared to house with renewable energy production

2.2.1 Potential benefits of a stable energy connection for both utility managers and house-owners

The increasing intermittency as described in the previous section implies greater unpredictability and uncontrollability of the utility grid. The problem is that the more renewable energy there will be, both locally and nationally produced, the bigger the problem of uncontrollability will become. In districts with similar functions and consumption/production profiles, the peaks of all the individual actors in the system add up, which results in even bigger peaks. The controllability of these fluctuations implies cost and thus for the utility grid it is economically interesting in most cases to have a more stable and predictable supply and demand.

Lund et al. (2011) are critical about solving the mismatch on the residential scale. They show that the residential mismatch can have, depending on the other actors in the system, both a positive or negative effect on the national energy balance. It proves that energy-flat housing is not the most efficient solution per se, although the need for controllability is not diminished.

Speaking from the house-owners point of view, a more self-consuming energy system could be beneficial as well. Nowadays in the Netherlands, there is a day-time and a night-time price. It is to be expected that, based on the increasing fluctuations in supply and demand, smart pricing will be introduced to the energy market sooner or later. The price of electricity is influenced both by industry and dwellings. In times of high-pricing, a higher self-consumption is favourable, although the high self-consumption might also be disadvantageous in times of lower energy-pricing.

Capacity of the utility grid

As energy demands, and its peaks, are increasing, the utility grid sooner or later will meet its maximum capacity. The capacity of the grid has to be dimensioned to the highest expected peak over a year. The bigger the difference is between the amount and size of the peaks compared to the base-load, the less optimally the grid capacity is used. It is favourable to have lower peaks on a national level, so that the base-load can increase and the capacity of the grid is used more efficiently, as shown in Figure 16 .

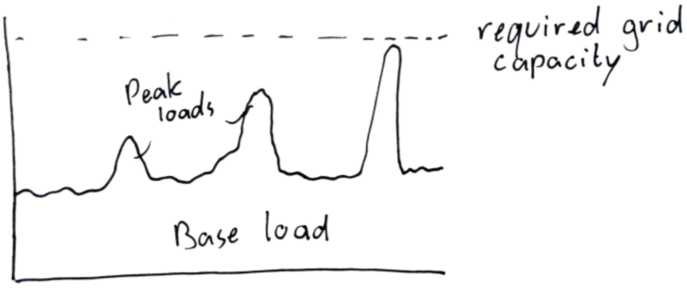


Figure 16: Peaks determine the required capacity of the grid. Lower peaks allow for more optimal use of the capacity

One way to diminish the national peaks is to limit the power give-or-take boundaries of the household. It is imaginable that this will happen in the future. This would probably result in higher pricing for houses that need a bigger power range. Then it is favourable to flatten out the load curve for the house-owner, which means that the size of the peak-load compared to the base-load is lower. This will allow for a higher share of the more efficient base-load production and lower energy costs for house-owners (Figure 17).

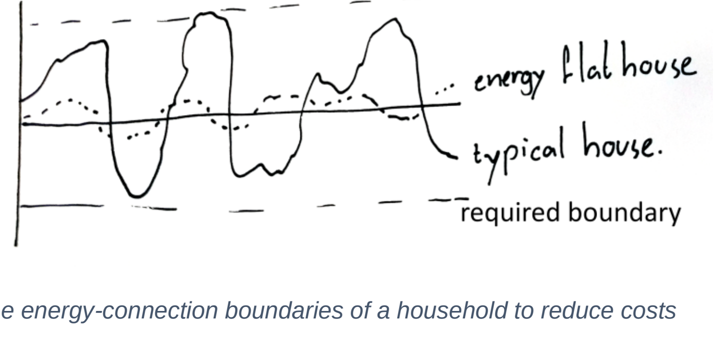


Figure 17: Limiting the energy-connection boundaries of a household to reduce costs

2.2.2 Dutch energy system balance predictions

The Dutch *Innovatieprogramma Intelligente Netwerken* (IPIN, 2015) compares several important references related to energy balancing and summarizes corresponding conclusions. They conclude that:

- Problems will occur in the controllability and quality of the energy balance if no changes are made
- Using different energy sources (e.g. electricity, gas, heat) may contribute to compensating supply and demand surpluses and shortages and provide flexibility
- Both central and decentralised generation power will remain important
- Energy storage provides a solution for flattening peaks in power supply and demand, but energy storage is (still) more expensive than controlling the pattern of demand.

Whereas the electricity grid has been one-way for more than a century, the role of the consumer in the grid is changing. With the rise of decentralised production, consumers now become the so-called prosumers; consumers that partly produce their own product. Kok (2013) describes that the customer, besides from become a producer for the electricity grid, also add value by adding flexibility to the grid. Improving the flexibility of end-users will improve the quality of the grid.

From this should be concluded that energy-flat buildings could improve the energy-system. Multiple different energy sources in a dwelling can decrease the mismatch. Energy storage is a solution for the mismatch though it is always more expensive and less efficient than having no mismatch.

2.2.3 Conclusion

With decentralised energy production, the role of the building compared to the utility grid changes. Apart from being the energy supply, the grid also becomes an energy dump. This affects the controllability of the energy balance on the grid. This problem increases as the share of decentralised renewable energy supply increases.

Several studies conclude that problems will occur in the controllability of the energy balance if no changes in the energy system approach are made. Energy storage provides a solution, but energy storage is probably more expensive than controlling the pattern of demand in the first place. Mitigating the mismatches on the grid by reducing peak surpluses and peak shortages can be beneficial for both house owners and utility grid managers. Modern energy pricing systems will stimulate these developments.

2.3 CURRENT SOLUTIONS FOR MATCHING SUPPLY & DEMAND

Matching demand and supply is a common challenge in multiple disciplines. Both in other levels of the energy system (i.e. not the on-site energy balance of a dwelling) and in other disciplines this concept is studied. The aim of this section is to gather information on potential principles for matching supply and demand in the dwelling, by looking at principles for matching supply and demand in other levels of the energy system and in other disciplines; economics and philosophy.

2.3.1 Energy flexibility in the energy system

Energy-flatness is a new definition created in this research, but the problem of energy mismatch as a result of an increase of demand and renewable supply is present at all levels of the energy system, as explained earlier. In most research, the solutions to the mismatch are summarised by the definition of ‘energy flexibility’. Energy flexibility describes the ability of a building or system to adapt to changing demands and supply. This section describes the definition and applications of energy flexibility.

The value of energy flexibility

Energy flexibility is important for similar reasons as energy-flatness. Looking from a more societal and economic point of view; the adaptation to the rising intermittency of energy supply becomes more important and will be stimulated by the energy market. In a well-functioning energy market – which requires for optimal transparency - the value of energy flexibility is determined by the price differences. The higher the price differences, the more value flexibility will get and the more it will provoke investments and innovations in energy flexibility. (Donker et al., 2015, p. 9). Higher mismatches will result in higher price differences and thus more value for flexibility. The need for flexibility in the new energy system is undisputed.

Flexibility resources

The IEA (2011) set up the Flexibility Assessment method to make the system-side measures for flexibility on the grid more insightful. Though it was designed for (inter)national grid balancing, the principles of this methodology can be used for assessing a dwelling as well. Flexibility resources can be divided in four categories according to this method, namely flexible generation, energy storage, interconnection and demand side management. They are summarized below.

Demand-side management	DSM implies that certain energy demanding processes are turned on (or off) based on a signal. The demand reacts to the production.
Flexible generation	Being able to turn off (renewable) energy production can be favourable for the balance, though in the residential context it probably is always better to temporarily be not energy-flat and have an energy surplus (to give that back to the grid).
Energy storage	Energy storage is a useful means to provide energy-flatness, though it is often better to prevent the initial mismatch than compensating a mismatch by storing energy.
Interconnection or inter-exchange	Interconnection or inter-exchange describes how the surplus of one actor in the system can be compensated by the shortage of another actor. Because the ‘power system’ of a household is usually limited to one system, inter-exchange is by definition not applicable in the residential context. Its principles, however, can be applied.

These categories provide a concise but complete base for the preliminary research on the possibility of buildings to adapt their demand and supply patterns. The four categories will be addressed in the next section, including examples of applications.

Flexibility index

In favour of the energy flexibility performance, it is important to know the energy-balancing quality of all the energy resources. This quality is based on factors like total amount of energy produced, power and response-time. The Flexibility Index (FIX), designed by (IEA, 2011), assesses the flexibility of energy resources by determining the amount of power that can be scaled up or down within a timescale of 15 min, 60 min, 6 hours or 36 hours. The index is then calculated by dividing the technical flexible resource by peak demand. This means is mostly used to compare the energy flexibility of different areas with different systems.

The above could be translated to the level of a buildings. Both on-site renewable energy sources and energy demand should be measured on respectively their increase and decrease in power within a set timescale. For instance, it should become clear how quick a heating appliance can be turned off to lower its demand power to match the supply power. Having a FIX of several measures could help in a design with deciding which design principle should be implemented, depending on the need of the system.

Demand side management

Demand-side management (DSM) can be translated into six load shape objectives, namely peak clipping, valley filling, load shifting, strategic conservation, strategic growth and flexible load shape (Gellings & Smith, 1989). These objectives are visualised in Figure 18.

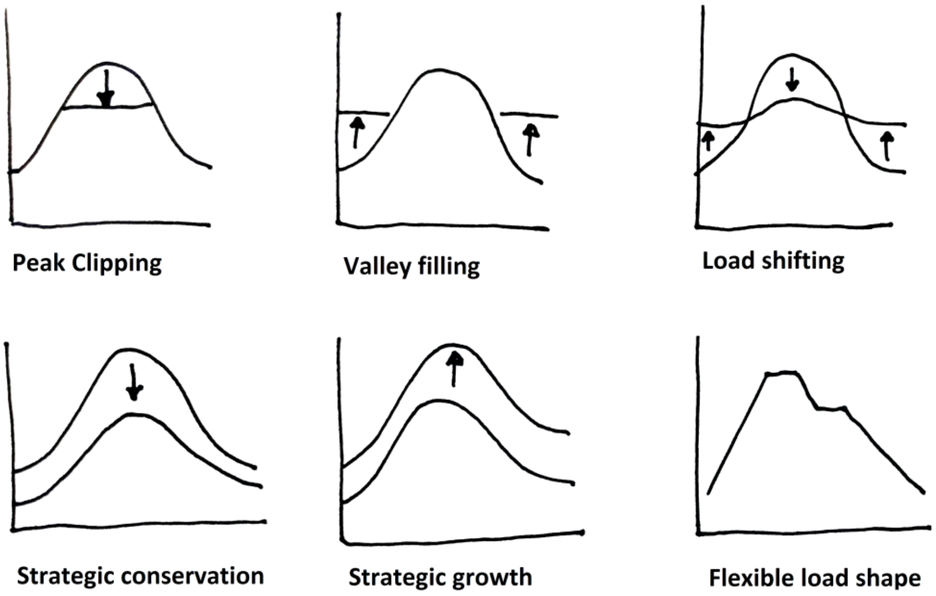


Figure 18: Load objectives visualised for demand-side management (inspired by "Integrating Demand-Side Management into Utility Planning" by Gellings & Smith, 1989, p. 910)

These figures provide, in a graphical way, an overview of the objectives that could be set to adapt the demand to the supply. They could be used in the final parameter overview of this research to categorize the design principles for energy-flatness as well as to rank them per category. When the request from the supply side is clear, the related demand-side solutions could be found by category.

Some papers (e.g. Gellings and Smith (1989)) assume energy storage as a key feature DSM, other papers (e.g. IEA (2011)) see storage as a different aspect than DSM. In this case, energy storage is considered separately, because the initial idea of this research is that storage should be prevented. This means that the changes of the demand-side profile should be approached by changes in the building envelope, and not by storage.

2.3.2 Flexible generation

Flexible generation describes the potential of adaptability of the supply of renewable energy. It could also be defined as supply-side management, which shows more clearly the similarities with demand-side management definition. Flexible generation is different from demand-side management in the sense that generation (in the case of photovoltaic electricity production) strongly depends on the presence and power of the sun, which cannot be influenced. Nevertheless, the graphs as shown in *Figure 18* also provide a useful approach for flexible generation. Principles for flexible generation could be categorized with the same graphs, and the aim to reach the effect of a certain graph may introduce new inspiration for approaching flexible generation.

Because the generation of renewable energy depends on climatic context, solutions are assumed to be found in the generation installations, the use of different energy sources and dynamic elements in the resources. Two examples of flexible generation are shortly described.

Flexible generation with solar systems

Solar energy production depends on the availability of the sun, which cannot be influenced. In that sense, creating flexible generation is only possible by increasing the maximum capacity and turning part of the system off sometimes. The orientation of the PV systems however, influences the production. Also, the capacity could be increased by increasing PV area and in times of smaller demand the generation could be cut off. Salpakari and Lund (2016, p. 434) show that the grid feed-in could be limited to zero using this technique, although this would only be favourable in times of surplus both on in the on-site energy systems as well as the national energy system.

Flexible generation using biogas

Other renewable energy carriers are easier to use in a flexible way. An example is biogas in combination with a combined heat and power (CHP) generator, often used by farmers. By turning on CHP appliances, they provide themselves with heat and sell the electricity in peak-price hours. To facilitate this system, tools like heat buffers, energy control systems and back-up systems are required. In other words, elements of storage are introduced. In this system, the heat demand is decoupled from energy production by thermal buffering, which allows the farmers to produce electricity whenever it is effective and still make optimal use of all the heat produced at the same time. This favourable flattening of the consumption peak, is a nice example of a self-balancing system caused by economic regulations (i.e. the price of energy) made possible by thermal buffering.

The example shows how flexible generation is implemented. However, it shows the need for storage to fulfil the flexibility. Storage is assumed separately in this research.

2.3.3 Electrical energy storage

In most research on demand-side management and load-matching, energy storage is assumed to be a legitimate solution. In this research, the aim is to provide energy-flatness without energy storage to reduce conversion losses and embodied energy. However, it should be noted that in some cases it might be in favour of the energy-flatness of the total energy system of the building to temporary store energy. In other words, the conversion losses could be compensated by the benefit of having energy available in times of energy shortage.

Some energy storage solutions are shortly discussed, to gain insight in the advantages and disadvantages of storage. Storage is avoided in the design of an energy-flat building in this research, but eventually ending up with more realistic design, it is to be expected that storage solutions will have to be implemented.

Local energy storage in batteries

A rising solution for the problems mentioned in the previous paragraph is the storage of electrical energy in batteries. Batteries provide a solution for peaks in the energy demand and supply by shifting the production. Energy produced in times of surplus is stored in the battery and used at another desired time.

Extensive research is done on batteries for they are used in a high number of sectors. Both the energy density and the lifetime of batteries are constantly increasing. Recently, battery-packs for households, like the Tesla Powerwall, have become more popular. The storage capacity of these kind of (lithium-ion) batteries can reach up to 400 kWh/m^3 (Wang et al., 2013, p. 264). Nevertheless, batteries are known to have short lifetimes and have cycle efficiencies ranging from 75-97% (Luo et al., 2015). Storage of energy thus has an impact on the environment in terms of materials and in energy lost by storing energy. Moreover, stored energy in battery vanishes over a relatively short time, resulting in an extra loss in energy for long-term storage. For lithium-ion, this self-discharge is such that these batteries are not suitable for seasonal storage. Though future improvements on batteries are to be expected, it is in favour of the efficiency of the total energy system of a household to reduce the need for batteries.

Grid storage

Grid storage is an alternative to peak-power plants, to provide extra energy in times of excessive demand. A big difference is that grid storage may also store a surplus of energy production (e.g. caused by the intermittency of renewables) so that a surplus is not lost.

The term grid-storage is misleading in the sense that the energy is not actually stored on the grid itself. Another name for grid storage is large-scale energy storage, which is less misleading for it states that it is about large energy storage systems that are connected to the grid. In most cases, grid storage refers to pumped-storage hydroelectricity, in which gravitational potential energy by pumping water up a reservoir in times of energy surplus and turbines are used to transform the potential energy to electricity in times of shortage.

As is the case with household batteries, grid storage could co-exist with energy-flat buildings. Both principles have a positive effect on the stability of the utility grid and together they contribute to a stable system.

2.3.4 Inter-exchange

Inter-exchange is the fourth element of energy flexibility which describes how the shortage of an actor in the energy system can be compensated by the surplus of another. The REAP, as set-up by Tillie et al. (2009) shows how a sustainable energy system can be created by inter-exchanging waste flows between different levels (i.e. building, cluster, district and city) and different functions (e.g. swimming pool, dwelling). In this research, the system boundary is limited to one dwelling and so inter-exchange is assumed to be out of scope.

2.3.5 Smart grids

An overall development that facilitates and optimizes the measures of DSM, inter-exchange and storage, are smart grids. Smart grids control an electricity system in which supply and demand are balanced out based on information communication between all elements of the system. Smart grids are a recent development, made possible by improvements of data communication. They provide a solution for the need for smarter and quicker adaption of supply and demand to prevent black-outs on the electricity grid.

Smart grids inside the physical boundary of a dwelling exist, and are more familiarly known as energy management tools; systems that turn house appliances on and off based on the availability of energy. This is the first step of balancing out supply and demand. The next step is the communication of all the individual systems with the larger power system. By having this decentralized system, the complexity remains limited. The intelligence of a bigger system can be very high, while the complexity of individual systems can be low (Kok, 2013, p. 46). However, to integrate individual systems in a bigger system effectively, Kok (2013) defines four requirements:

Scalability	it is important that a big number of individual systems are involved in the bigger system. Similarly, the bigger system should be able to manage the rising number of actors.
Openness	information communication should be transparent and uniform to allow the connection and disconnection of individual system without changing the functionality of the system.
Multi-level stakes	the information system must allow for the stakes to be balanced both an a global and a local level.
Autonomy and privacy	because different actors will be involved, the information system should be suitable to go beyond the boundaries of private ownership. Furthermore, all users should keep the right to make individual, autonomous decisions.

In relation to energy-flat housing, this shows the need for openness in information communication if (nearly) energy-flat buildings should be integrated in the global energy system. Moreover, it shows that users should always keep the right to make autonomous decisions. This means that an energy profile will never be completely predictable or fixed, so an energy-flat house should be able to instantly adapt its supply or demand if the users wishes to, or elements that allow a shift of demand and supply should be integrated.

Kok (2013) also shows that scalability of the smart grid system is one of the biggest challenges. The enormous amount of small and medium-sized prosumers that will enter the electricity grid greatly challenges the coordination of the system. In that sense, it might be favourable if the separate actors are more autonomous by themselves.

2.3.6 Economics

The terms of supply and demand are not merely dedicated to energy. In fact, almost all disciplines use the basic principles of supply and demand. In this section and the following two, a short review is done on theories on supply and demand in other disciplines to serve as inspiration for solving the mismatch in the discipline of the built environment.

Supply and demand relationship

Basic economics show that the supply and quantity of a certain good, relate to the price of it. The demand relationship shows that if the quantity of a good increases, the price of that good drops. The supply relationship shows that if the price of a good increases, the quantity of supply will as well.

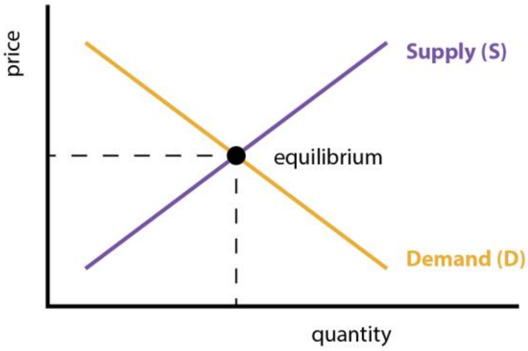


Figure 19: Supply and demand curves in basic economic theory

The economy is in equilibrium when the supply and demand are equal. This means that the available quantity of a good is exactly equal to the demanded quantity and thus both the suppliers and consumers are satisfied. The economy tends to find equilibrium by definition. If, for example, the quantity of supplied goods is too high compared to its price, the demand will automatically drop which leads to a lower price (see Figure 19). In the theory of free market economics, the principle of supply and demand will always result in the most efficient way of obtaining resources.

The supply curve, however, has a certain delay. Most often, suppliers are not able to and will not react directly to the demand curve. Based on estimations of the consistency of the demand change, suppliers will adjust their production. This leads to price fluctuations, resulting in changes in the equilibrium.

Economics distinguish two types of changes in the supply and demand relationships; movement and shifts. Movement along the curve of demand or supply means that the quantity is changing due to a change in price and vice versa. A shift means that the quantity or price is changing by other factors; a quantity could increase while the price remains the same.

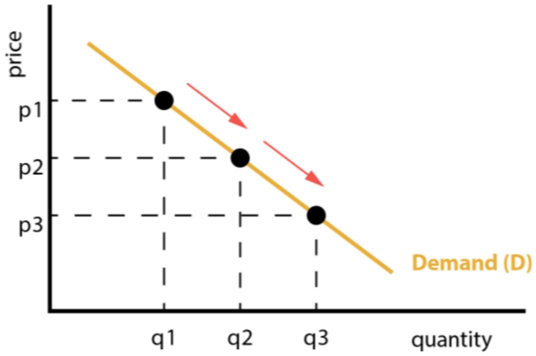


Figure 20: Movement along the demand curve

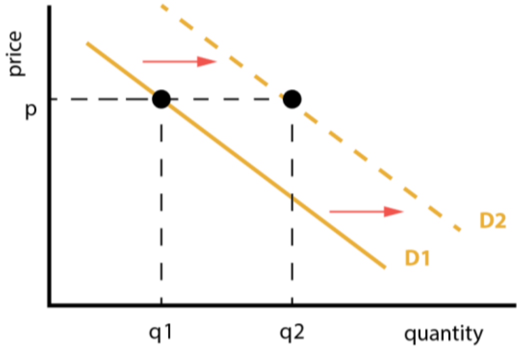


Figure 21: Shift of the demand curve

Elasticity

Elasticity is the degree of which the demand of a good responds to the price of that good. The elasticity varies from good to good because of varying dependency of consumers to that good. A good is highly elastic when the demand of it changes extremely due to a change in price. Most often, this is the case when there are substitutes available. For example, if one brand of sweets would increase its price, the demand for it would drop quickly since consumers can easily go for another brand. Goods that are more or less a necessity to people tend to be inelastic; an increase in price would not lead to a big decrease in consumption. The following factors affect the elasticity

Availability of substitutes	When a substitute is directly available, an increase in price of one product would result in consumers buying the substitute. The demand for the more expensive good would drop quickly. The availability of substitutes results in a higher elasticity.
Necessity	When a good is an essential product for consumers, they will keep buying it no matter the increase in price. A high necessity result in a lower elasticity.
Possibility of postponement	If the moment of buying a product can be delayed, the elasticity is higher. After all, why buy a cookie today for a high price if you can buy it cheaper tomorrow?
Habits	If some product has become a habit for a customer, the price might be less elastic. One does not want to change its habit and thus is willing to pay a higher price for it.

The aim for increased price elasticity in the built environment

The system of energy supply and demand aims for the same equilibrium as the economic supply and demand. In the Netherlands, the balance on the main electricity grid should be kept around 50Hz to prevent black-outs. Currently, the price of electricity for consumers are fixed over a longer period. The price of energy for consumers does not change, even if the quantity of it is changing and vice versa. For consumers, electricity pricing in the short run is very inelastic. A higher price elasticity in the energy market would lead to (Kok, 2013, p. 36):

- A lower electricity price, for peak-power is the mostly costly and a slight reduction of peak-demand results in a big reduction of costs
- Direct reduction of energy demand in times of energy shortage, based on the basic economic principles of supply and demand
- Lower need for (inefficient and environmental unfriendly) peak power suppliers, because peaks are flattened out more often by prices
- Lower market power of producers, because the monopoly position is reducing by the vast amount of decentralised suppliers.

The changes stated above are in favour of the overall energy system and thus a higher price elasticity should be pursued. The economic factors that affect the price elasticity of a system are translated to residential context below.

The need for energy is a **necessity** in buildings to assure comfort and a liveable context. The pattern of energy use for most people has become a habit. The necessity of energy and the **habitual** patterns cause a lower elasticity of energy. The necessity of energy seems unchangeable in the current society, though the total demand could be decreased. A large share of energy consumption is driven by habits and requires change in societal, cultural and institutional to be adapted (Maréchal, 2009).

The single electricity grid connection tends to be seen as if there is no **substitute**. However, in a household there is almost never a need for electricity itself, but there is a need for comfort or change in environment. Furthermore, multiple energy carriers are used in the house. Electricity for light might be substituted by daylight and electricity for heating might be substituted by passive solar power.

In terms of energy, the possibility of **postponement** in a building might have the most obvious solution. It can be introduced by buffering energy. Thermal buffering by thermal mass or ground storage or shifting electricity production by battery storage and lots of other storage options allow for postponement, as explained in *2.3.3 Electrical energy storage*.

2.3.7 The tragedy of the commons

Another relevant theory that is not directly related to the energy grid nor the discipline of architecture, is the Tragedy of the Commons by Garett Hardin (1968).

The tragedy of the commons shows one is willing to harm the environment (i.e. 'the commons') if their individual benefit is big enough. Hardin (1968) describes the effect with a short example, in which he refers to the situation of a herdsman within a shared pasture:

> *"As a rational being, each herdsman seeks to maximize his gain. Explicitly, or implicitly, more or less consciously, he asks: "What is the utility to me of adding one more animal to my herd?" This utility has one negative and one positive component.*
>
> *1) The positive component is the function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly +1.*
>
> *2) The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of -1.*
>
> *Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd."*
>
> *Hardin (1968)*

Currently, our energy system works this way as well. House owners with renewable energy production use the grid as the common storage battery. Increasing your solar panel production is beneficial, for it saves you a lot of money and improves your *'level of sustainability',* although unfortunately the latter is not often really experienced as a direct benefit for the average individual. The negative effects of fluctuations on the electricity grid caused by the intermittency of the local solar energy production is shared by the commons, thus the user has no reason not to buy the solar panels for that reason.

Hardin states that there is no technical solution to this problem. In the case of the herdsman, the reliance on the shared pasture is unchangeable; the commons are a necessity. In the case of the energy grid, diminishing the need for the commons could be a solution. This would translate to reducing the dependency on the shared energy grid by increasing self-sufficiency. An optimal energy-flat building, is completely self-sufficient.

The solution gets even better if the individual benefit, also is beneficial for the commons. This could be the case in buildings that are completely energy-flexible; being more energy-flat is profitable for the user, for he increases self-sufficiency and thereby reducing costs and increasing renewable energy efficiency. Similarly, the energy grid (i.e. 'the commons') benefits from the more stable, predictable connection.

Hardin (1968) would not agree with me, for he states that there is no technical solution. If he is right, regulation should be the solution. Regulation in this situation could be in terms of a maximum boundaries of give or take of the grid. By doing this, people are economically stimulated to improve their energy-flatness and thereby reducing the harmful effects on the shared energy grid.

2.3.8 Conclusion

The solutions and approaches to creating energy-flatness on larger levels than the individual building are broad. The solutions are mostly driven around the concept of energy flexibility, which is the ability of an actor in an energy system to adapt to the desires of the energy system. Energy flexibility can be achieved by demand-side management (DSM), flexible generation, electrical energy storage and interconnection.

DSM describes to what extent the demand profile can be adapted, based on the supply. Flexible generation is similar to DSM, but focusses on the supply-side. Flexible generation is hard to achieve, due to the unchangeable context (i.e. sun) on which it depends. Energy storage knows several forms, though in this research it is avoided to limit the disadvantageous effect of losing energy by cycle efficiency and discharge-rates and having an environmental impact in their use. Inter-exchange is an effective approach that is only relevant in an energy-system with multiple actors, where surpluses and shortages balance each other out. Hence, inter-exchange is not regarded in this research.

Theories from other disciplines (i.e. economy and philosophy) have shown to be relevant for the supply and demand problem of a dwelling. Economics show that demand and supply tend to find equilibrium most efficiently in an open and accessible energy market. The degree in which demand responds to changes in supply or vice versa, is defined with the elasticity. Elasticity is dependent on the availability of substitutes, the necessity, the possibility of postponement and habits. Increasing the elasticity benefits the energy market.

The commonly known Tragedy of the Commons by Hardin (1968) explains why the commons suffer from its individual users. One solution is to diminish the dependency on the commons by every user, which could be reached by an increased self-consumption in terms of the residential context. The next level would be to create individual benefit that is also beneficial for the commons, which would be the case if a building is completely energy-flexible.

2.4 POLICIES ON SUSTAINABLE BUILDINGS IN THE NETHERLANDS

Sustainability principles tell us to reduce energy use and then provide the remaining need in a sustainable way. In the Netherlands, there are regulations that aim to stimulate designers, builders, house owners and tenants to design and use more sustainable buildings. Analysing the requirements of these regulations provides information on the focus of the building improvement policies. Three different regulations are discussed. All policies focus on reducing energy and increasing renewable energy production, in line with the Trias Energetica. A critical note is made.

2.4.1 Zero energy building

Aside from the Dutch policies, an often heard term in sustainable building studies and policies is the Zero Energy Building (ZEB). Torcellini et al. (2006) show that a Zero Energy Building design can be approached by four different goals;

Site ZEB	energy production ≥ energy consumption per year, when accounted for at the site
Source ZEB	energy production ≥ energy consumption per year, when accounted for at the source (primary energy)
Net zero cost building	amount of money paid by utility to owner ≥ money paid by owner to utility in a year
Net zero emissions building	production of emission-free energy ≥ consumption of emissions-producing sources

All these zero-energy building definitions aim for a goal that is set over a year. In the case of energy-flatness, the site ZEB is regarded. In terms of all-electric buildings, source ZEB is equal to site ZEB (Torcellini et al., 2006, p. 6). Net zero cost and net zero emissions are goals that, at least in terms of a single household, suffice with an annual zero-energy balance.

So, the energy-flatness regards merely the actual, theoretically directly measurable, energy flows in a household. Aside from this definition being the most clear and insightful, it provides the most repeatable and consistent definition (Torcellini et al., 2006). This is favourable in terms communication and implementation for designers. Political, strategic and exergetic factors are not regarded in this first research of energy-flatness. When knowledge on the topic of energy-flatness expands, it might be useful to extend the principles to other energetic measures like exergy.

Time-dependent accounting

Time-dependent accounting relates to the change of weighting factors for energy over time. In the case of energy-flatness, the largest time scale is one year, assuming there are no big climate changes. Therefore, changes in weighting factors on the long run can be neglected.

Weighting factors could also be evaluated at an hourly base. This could result in having more energy production when the most energy is needed. In other words, stimulate peak production at times of (smaller) peak demand, to help the grid. The weighting factors on an hourly base could be seen as the theoretical representation of dynamic energy pricing. Though this might be interesting, this will not be accounted in this research because it is outside the scope.

2.4.2 Energielabel

The Energielabel is meant to stimulate the use of renewable energy and the reduction of energy consumption in buildings. In the Netherlands, the Energielabel is obligatory for buying or selling a household. It provides a clear and easy-to-understand insight in the energy performance of buildings for consumers and aims to improve consciousness of energy performance of buildings and stimulating the market of well-performing buildings. The Energielabel is determined by a set of static properties, namely the following:

- *Year of construction*
- *Residential type*
- *Type of glass*
- *Façade insulation*
- *Roof insulation*
- *Floor insulation*
- *Type of heating*
- *Type of hot tap water appliance*
- *Ventilation system*
- *Solar panels and solar heater*

The Energielabel can be improved by improving one of the properties of the list. Since these are all static building-bound properties, the actual performance of the building is not measured and does not influence the Energielabel. The Energielabel therefore receives criticism, because it often does not match the actual situation, let alone the actual use of energy.

2.4.3 Nul-op-de-meter and Energieprestatievergoeding

The commonly accepted term for an energy-neutral in the Netherlands is *Nul-op-de-meter* (NoM), literally translated to *zero-on-the-meter*. Thus, a NoM dwelling is a building that produces the same amount (or more) of energy as it consumes.

Landlords and tenants have the possibility to agree on an *Energieprestatievergoeding*. This is a compensation, in €/m^2-month, paid by the tenant to the landlord for a house that is energy neutral (i.e. *nul-op-de-meter*). The compensation was introduced to stimulate building owners to renovate their real estate to energy neutral buildings by supporting them financially. The benefit for the house owner is improved housing quality for the same price, since the energy bill is much lower. The *Energieprestatievergoeding* has some requirements:

- The household is well insulated; the heating demand is <50 kWh/m^2 per year.
- The household produces on average the same amount of (renewable) energy as it consumes per year. This translates to the following quantified demands:
    - At least the amount of energy that is needed to heat the building
    - All the energy required for fixed installations (e.g. ventilation)
    - 26 kWh/m^2 per year for electricity of housing appliances
    - 15 kWh/m^2 per year for hot tap water

For a better insulated house the compensation paid by the tenant should be higher. The energy bill of the tenant will reduce respectively. Furthermore, the energy generated is property of the tenant which results in receiving money for the energy surplus generated.

2.4.4 EPC & BENG

Since 1996 all new Dutch building will have to meet the energy standard, measured in an Energy Performance Coefficient (EPC). Over the years, the EPC has become more ambitious with regards to energy saving. In April 2008 the ‘Lente-akkoord’ was signed by Aedes, NEPROM, NVB, Bouwend Nederland and VROM. In this collective agreement, these parties state their incentive to contribute to energy-neutral buildings in the Netherlands. In 2015 the follow-up program *Zeer Energiezuinig Nieuwbouw (ZEN)* was set up, which emphasizes more on energy neutrality of buildings. In January 2021, the current EPC-regulations will be replaced by the BENG, Bijna Energie Neutrale Gebouwen. The current EPC-demand gives one, dimensionless value as requirement, thus a bad score on one aspect can be compensated by a higher score on another. BENG diminishes this problem by validating new buildings on three, dimensioned requirements :

1. **The energy demand of a building**; this includes the demand for heating, cooling and ventilation. By using prescribed standards for the energy use of inhabitants, the first indicator of BENG is mostly determined by the building envelope and ventilation system. It is required that the demand will be ≤ 25 kWh/m^2 per year for residential buildings.

2. **The primary energy use**; this will be the energy used by the building services for building related energy use, including hot tap water. Locally, self-produced energy can be subtracted from this primary energy demand. In other words, this primary energy demand is all the external energy that has to be added to the building. Also this demand is required to be at ≤ 25 kWh/m^2 per year for residential buildings.

3. **The share of renewable energy**; this is the percentage of renewable energy of the total energy use (i.e. renewable energy plus fossil primary energy use). Renewable energy can be provided by solar panels, heat pumps etcetera. The requirement will be a minimum share of 50% of renewable energy.

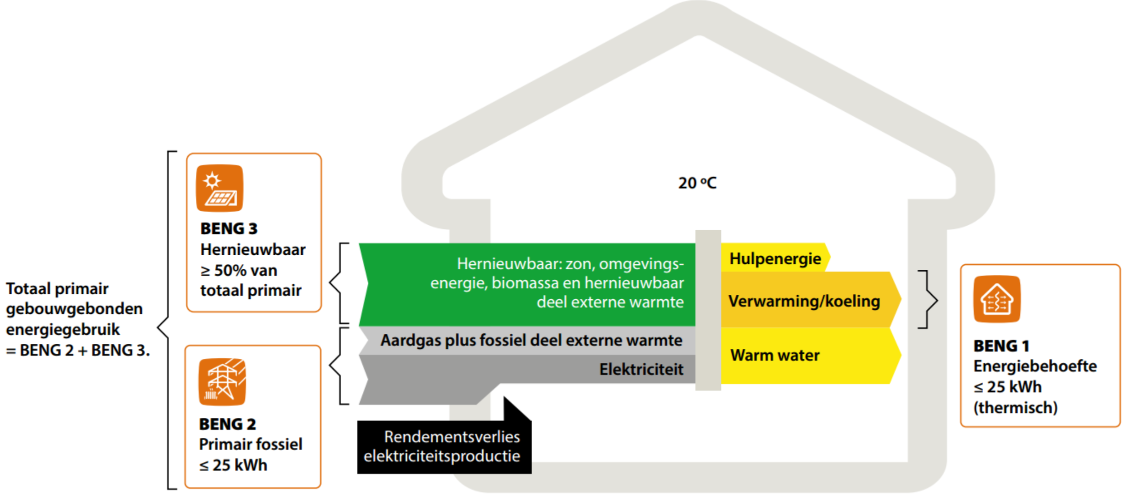


Figure 22: Schematic overview of BENG 1,2 and 3 (LenteAkkoord, 2017, p. 4)

BENG diminishes the effect of ‘fake sustainability’ - good sustainability scores by compensating one bad aspect by a high score on another - by having three, quantified demands. Nevertheless, the BENG once again only focusses on yearly totals in energy demands. Excessive solar electricity production in summer can compensate for the use of fossil fuels. Also, efficiencies of the renewable energy systems are not taken into account. For instance, very inefficient local renewable energy systems result in a higher share of renewable energy than efficient renewable energy systems, assuming the share of fossil fuels remains constant.

The energy policies in the Netherlands stimulate the reduction of energy consumption and the share of renewable energy. The regulations affect all the different actors and stages of the building process; landlords, tenants, designers and builders are forced to think about sustainable buildings from an energy point of view. In fact, all policies follow the rules of the Trias Energetica, introduced by Lysen et al. (1996) and developed as strategy at the TU Delft under the guidance of Cees Duijvestein (1979). This theory provides three basic steps that apply to the design of sustainable buildings.

1. Minimise the energy use
2. Use sustainable sources of energy
3. Produce and use fossil fuels as efficiently as possible

Van den Dobbelsteen (2008) rephrased and reordered the Trias Energetica in 2008 because by that time the steps did not fully prove their use anymore and needed an update. The New Stepped Strategy (NSS) was presented to serve as an updated version of the Trias Energetica that better suited the needs of contemporary sustainable buildings. The New Stepped Strategy is as follows:

1. Reduce the demand
2. Reuse and recycle
3a. Supply the resulting demand sustainably
3b. Let waste be food

The previous section of this research showed the resulting mismatch of reducing demand and increasing renewable supply. The order of the NSS is likely to result in an energy mismatch. In addition, the NSS is based on the idea that renewable energy production is less efficient than reducing the demand. As the production of renewable energy becomes cheaper due to the increasing industry, producing more renewable energy might become more efficient and/or cost-effective than reducing the demand, hence becoming possibly more environmentally friendly.

Energy-flatness could result in a slight demand increase (contradicting step 1) or slight decrease of sustainable supply (contradicting step 3a), but it would be paid back easily by the economic benefits and the eventual efficiency increase of the system a whole. Thus, regarding the future energy system, the chronological setup of the NSS is not correct anymore. By adding an iterative reflection on the system as a whole, the NSS could be updated. This could be done by implementing this iterative reflection as part of step 2, which in essence is also about exchanging surpluses and shortages.

In that sense, step 2 also serves as a fourth step which reflects on step 1 and 3 by mutually comparing them:

4. Analyse the energy-flat performance and, if necessary, mutually adapt step 1 and step 3a

This iterative fourth steps provokes a NSS loop, which could be iterated multiple times to optimize the system. By approaching the NSS this way, the overall sustainable effectiveness would be increased by diminishing negative environmental and economic effects caused by storage and energy balancing.

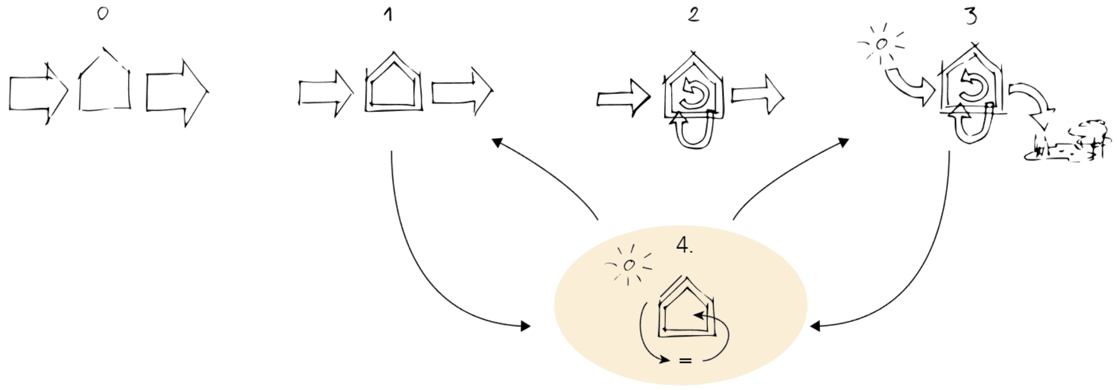


Figure 23: Implementing an iterative loop in the New Stepped Strategy to prevent the energy mismatch (adapted from "Towards Closed Cycles" by Van den Dobbelsteen, 2008)

2.4.5 Conclusion

The Netherlands has several political instruments with which they aim to stimulate the use and design of sustainable buildings. The *Energielabel* is a simplified measure that uses static building properties as input and is not influenced by the actual energy use. The *Energieprestatievergoeding* stimulates house owners to improve the energy performance of their real estate by letting tenants pay for their savings in energy use. It is focussed on a maximum amount of energy used per m^2. The *BENG* regulation replaces the *EPC*. The BENG performance can be achieved by meeting the maximum energy demand, the maximum primary energy demand and the share of renewable energy.

All regulations are based on the principles of the Trias Energetica, which first focuses on reducing demand and then on increasing sustainable supply. This principle is clear starting-point for sustainable designs. However, to prevent the stimulation of a mismatch, a fourth step could be added to the New Stepped Strategy, which focuses on adapting supply to demand and thereby optimising the use of renewable energy.

2.5 BUILDING PARAMETERS THAT INFLUENCE ENERGY-FLATNESS

This section describes the building parameters that might contribute to achieving energy-flatness in a building design. The main starting point of the research is the energy balance, which describes the sum of the energy flows of a building. All parts of the energy balance are shortly explained, and per part several energy profile adapting principles are described. Eventually, also storage and energy supply are described.

2.5.1 The energy balance

The energy demand of a building consists of conditioning spaces by heating and cooling, producing domestic hot water and use of user appliances. In the first stages of this research, demand is limited to the heating and cooling energy demand for buildings.

Domestic hot water (DHW) and user appliances are determined based on averages, because they completely depend on the user's demands. In other words, it will differ per household when and how much energy for DHW and user appliances will be used. The focus in the next section is thus based on energy demand for heating and cooling.

The energy demand needed for heating and cooling is determined with the energy heat balance. The heat balance is an overview of all energy flows of a zone, resulting in the heating or cooling energy required to maintain the intended temperature. Figure 24 shows a building and the energy flows of the heat balance. In the table below, the definitions of the energy flows are provided.

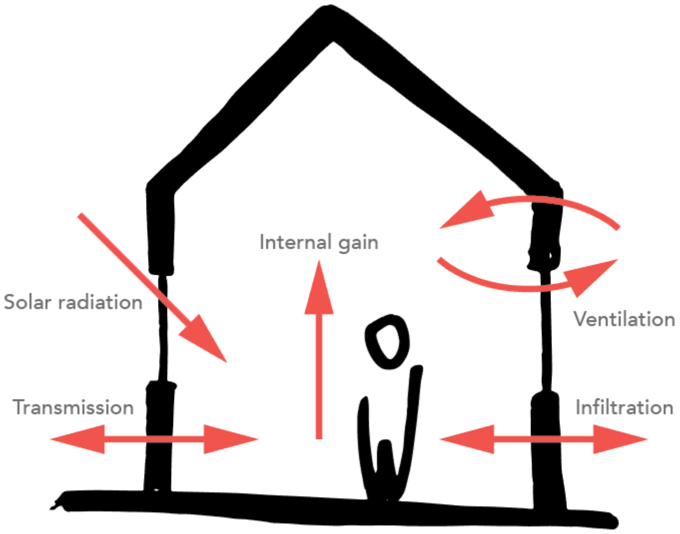


Figure 24: The energy flows of a building, together forming the energy heat balance

Q_{trans}	Heat transfer through transmission	$Q_{trans} = U * A * (T_e – T_i)$	[W]
Q_{vent}	Heat transfer through ventilation	$Q_{vent} = V_{vent} * ρ * c * (T_e – T_i)$	[W]
Q_{inf}	Heat transfer through infiltration	$Q_{inf} = V_{inf} * ρ * c * (T_e – T_i)$	[W]
Q_{sol}	Passive heat gains by solar radiation	$Q_{sol} = A_{glass} * q_{sun} * g$	[W]
Q_{int}	Internal heat gains by users, lighting and appliances	$Q_{int} = Q_{pers} + Q_{light} + Q_{appl}$	[W]

In which

U	*thermal transmittance of a surface*	$[W/m^2K]$
A	*area of surface*	$[m^2]$
T_e	*exterior air temperature*	[°C]
T_i	*interior air temperature*	[°C]
V_{vent}	*volume of ventilation flow*	$[m^3/s]$
V_{inf}	*volume of infiltration flow*	$[m^3/s]$
$ρ$	*density of air ≈ 1,2*	$[kg/m^3]$
c_p	*specific heat of air ≈ 1000*	[J/kgK]
g	*g-value of the glass surface*	[-]

From combining all these heat flows, the energy demand is determined by using the heat balance:

$$Q_{trans} + Q_{vent} + Q_{inf} + Q_{sol} + Q_{int} = Q_{demand}$$

Which, in favour of showing the balance characteristic, is also written as;

$$Q_{trans} + Q_{vent} + Q_{inf} + Q_{sol} + Q_{int} - Q_{demand} = 0$$

In which heat flows out of the zone are represented by negative values, which is implied by using the $\Delta T = T_e - T_i$, instead of taking the absolute value for ΔT. So, a positive value for Q_{demand} is a heating load and a negative value for Q_{demand} is a cooling load.

The formula describes the steady state heat balance. In a heat balance where time is accounted for, thermal storage could also be considered. Materials in a building store heat by increasing their temperature and provide heat by decreasing in temperature.

$$Q_{trans} + Q_{vent} + Q_{inf} + Q_{sol} + Q_{int} + Q_{demand} + Q_{storage} = 0$$

The heat balance is the starting point for the energy-flat simulations and evaluation, as will be discussed in chapter *3.2 Scope of the energy-flat building.* Moreover, the linearity of all the formulas of the energy flows of the heat balance make it an easy balance to calculate with. The elements of the formulas for the energy-flows, also provide insight in the relevant parameters that affect the mismatch. All heat balance elements are shortly described such that the influencing factors are related to a building.

Indoor temperature & adaptive thermal comfort

One aspect that is not directly in the heat balance, but influences four of the seven parts of the heat balance. The temperature difference between the indoor temperature and outdoor temperature proportionally affects the energy flows of transmission, ventilation, infiltration and storage.

To maintain the desired indoor comfort, certain heating and cooling setpoints are assumed by standards. These assumptions are based on conventional models like Fanger, including the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (Fanger, 1970). These methods are based on laboratory experiments done in the 60’s and are the base of most standards. However, the conditions in residential buildings are not comparable to those of the laboratory experiments, resulting in that the actual temperature range is much wider than what is generally assumed (Peeters et al., 2009, p. 774). The accepted indoor air temperature is largely dependent on the outdoor temperature, and the ‘running mean temperature’ (RMOT) in particular, which is because of its exponentially weighted nature a more appropriate input variable than the monthly temperature (De Dear et al., 1998). This theory results in the so-called adaptive temperature limits, as defined by Van der Linden et al. (2006). Figure 25 shows the adaptive thermal limits for buildings of type Alpha (i.e. buildings with a certain amount of indoor climate adaptive opportunity). Recent standards also consider these adaptive thermal comfort ranges (ISSO 73). Research is being done on further widening the bandwidth of thermal comfort (e.g. Schellen et al. (2010)).

Most energy flows are linearly dependent on the temperature difference between the outdoor temperature and the indoor temperature, ΔT. Adapting the thermal setpoints thus has a high energy saving potential.

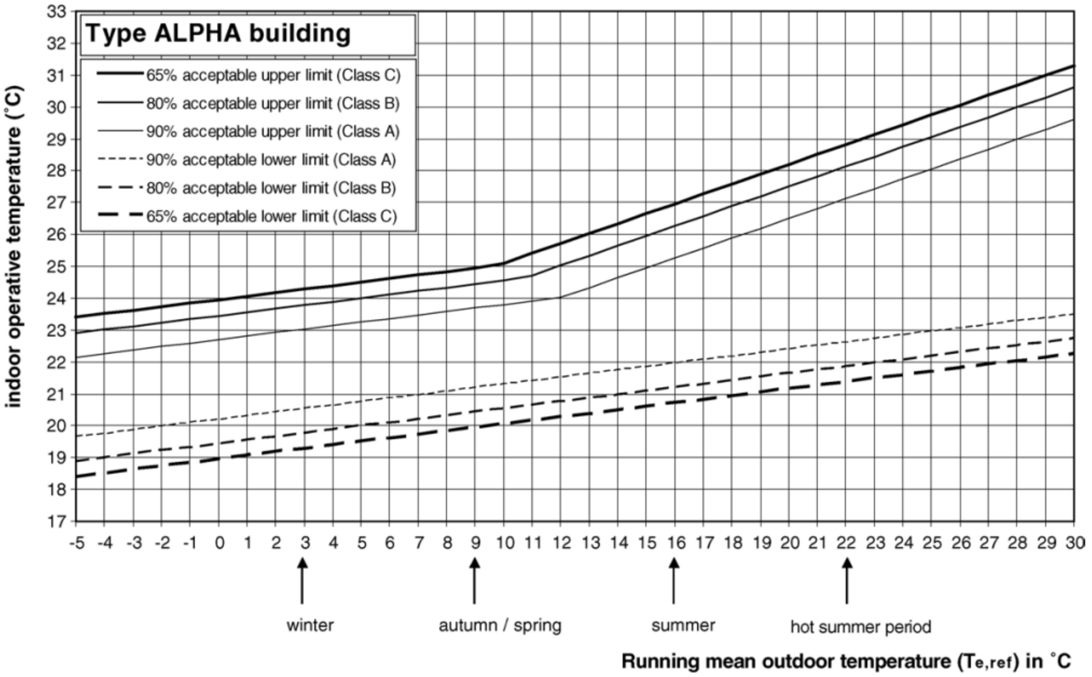


Figure 25: Maximally allowed operative indoor temperature for a specified acceptance level, as a function of the running mean (past four days) outdoor temperature Te,ref (Van der Linden et al., 2006).

2.5.2 Transmission

Transmission in a building is determined by the building skin. A buildings skin is the boundary between the indoor climate and the outdoor climate. In terms of energy, it aims to keep the indoor climate constant by mitigating the outdoor climate effects like wind and temperature. Usually, the building skin consists of floor -, wall - and roof surfaces. Each of these consists of its own specific materials, which influence the energy flow. The energy flow by transmission is calculated with

$$\mathbf{Q_{trans} = U * A * (T_e - T_i)}$$

The area **(A)** of a surface is determined by a buildings geometry. This is often the result of using certain typologies or architectural principles. The insulation value **(U)** of the materials of a surface is directly proportional to the energy flow through that material, and completely relies on the set-up of the building skin. The difference between the outdoor temperature and the indoor temperature **(Te-Ti)** differs depending on the time of the year. In the Netherlands, the outdoor temperature is almost always lower, resulting in an energy loss.

Windows

Windows are a part of the building skin that highly influence the energy lost by transmission. Windows are known to have relatively low insulation values. However, windows can also be a source of energy; the translucent property of windows allows for passive solar radiative heating. This is discussed in 2.5.4 Solar heat gain. Several recent technologies have highly improved the quality of glazing for energy performance, the technologies consider amongst others low emissivity coatings, evacuated glazing, aerogels and gas cavity fills, but also improved frame and spacer designs (Sadineni, Madala, & Boehm, 2011).

Building typologies

The shape of a building affects its energy demand and local supply potential. The shape of a building has evolved ever since humans started designing buildings. Buildings are adapted to provide the most comfortable indoor climate and to resist the challenges of the outdoor climate. Figure 26 shows four historical building forms in their corresponding climate. The Dutch climate is represented by 'B', the temperature climate. This climate is characterized by a special focus on heat transmission losses by having dense and well-insulated walls, designing a compact building form to prevent heat transmissions and having pitched roofs to reduce wind loads whilst allowing precipitation to drain (Hegger et al., 2008, p. 64).

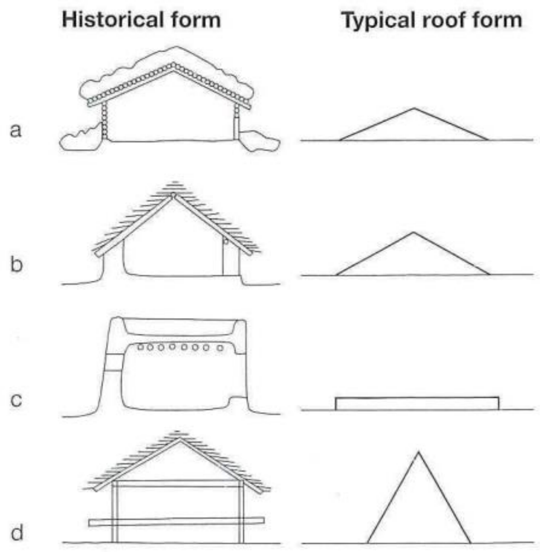


Figure 26: Traditional building typologies according to climate zones: a: Cold, b: Temperature, c: Dry/hot, d: Moist/warm (Hegger et al., 2008)

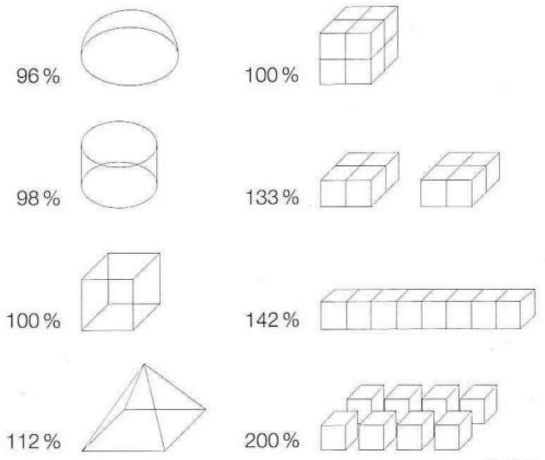


Figure 27: Transmission heat losses of various three-dimensional shapes with the same volume (Hegger et al., 2008)

The compactness of a building is determined by the A/V ratio, which shows the amount of facade surface compared to the internal volume. The buildings heat transmission losses are directly proportional to the surface area. Basic geometry shows the affects of changing a shape on the A/V ratio and the heat transmission losses, see Figure 27.

In cold climates especially, the role of energy-losses by transmission is high. Decreasing the relative amount of façade surface diminishes this effect. Nevertheless, a potential decrease in functional area because of non-typical façade shapes should be considered.

Building skin

The building skin influences the energy losses and gains by transmission and solar radiations gains. Moreover, the materials of the skin influence the amount of thermal mass (i.e. thermal storage) available. The insulation value of a material is directly proportional to the energy flow through that material. However, improving the insulation of one part of the surface, might cause energy flowing more easily to other parts of the surface. Moreover, some building surfaces are more subject to potential energy flow than others, like a roof which is subject to rising hot air. Most surfaces have one insulation layer, which considers a material that has a very low conductive value. The conductive values of modern insulation materials can be as low as 0.018 W/mK according to manufacturers (Kingspan Insulation Ltd, 2017). Windows, on the contrary, are parts of the building skin that have a significant share, and a relatively low insulation value. Most often, windows have a big impact on a buildings average insulation value. Some more complex building skin adaptations are discussed.

Green roof

A green roof reduces the surface temperature of a roof by several phenomena like shading and evaporation, which is beneficial for the energy demand and supply. By reducing the air temperature around the roof, HVAC systems can gain pre-cooled air and the heat transfer is reduced. Also, green roofs improve the efficiency of solar panels (Castleton et al., 2010). A study showed that a green roof can reduce the annual energy demand up to 6%, for a single family house in a temperature climate (Jaffal, Ouldboukhitine, & Belarbi, 2012, p. 162).

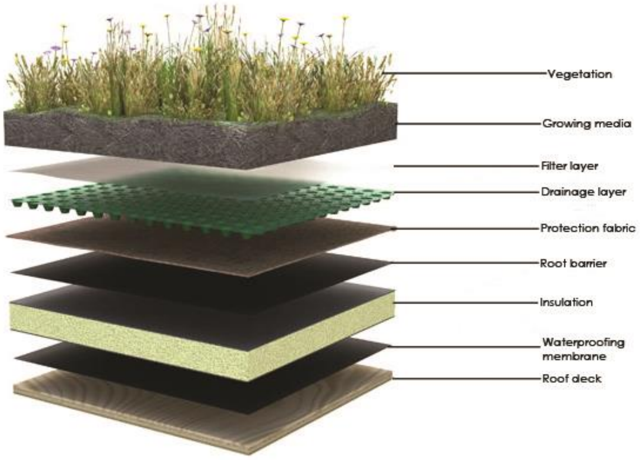


Figure 28: The layers of a green roof (Indovance, 2016)

A green roof is especially effective for reducing cooling loads in summer, although the effect strongly depends on the level of roof insulation; high insulation values reduce the relative cooling effect of a green roof (Jaffal et al., 2012). The additional thermal resistance that a green roof provides to the roof surface compared to that same roof surface without green, also decreases the heating demand. This effect, however, becomes negligible when the roof is insulated to modern Dutch standards (Jaffal et al., 2012, p. 163).

Double skin

A double skin basically consists of an extra layer of glass with an offset of 30cm to 3m from the ‘real’ (glazed) facade. A double skin façade is multi-functional in terms of energy adaptation. It is effective for influencing energy flows between indoors and outdoors, whilst providing architectural design flexibility. (Shameri et al., 2011). A double skin is proven to be an effective measure to save both heating and cooling energy in residential buildings (Xu & Ojima, 2007, p. 2014).

By including ventilation in- and outlets in the bottom and top of the double skin facade, different functional modes are possible, which allow for optimization in relation to the outdoor climate and the indoor comfort demands.

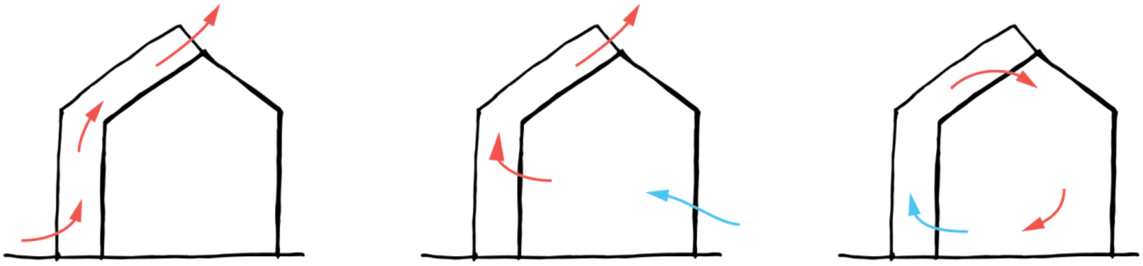


Figure 29: Possible ventilation functionalities of the double skin facade

Basically, the double skin can provide a stack effect in summer, a greenhouse effect in winter and an adaptive thermal barrier in the intermediate seasons. The stack effect, which only occurs if the cavity temperature is higher than the outdoor temperature, can be used to provide a natural ventilation draught through the building. In most cases, ‘cold’ fresh air is drawn into the house from the ‘cold’ north side. In winter, the greenhouse is closed resulting in a greenhouse effect and an intermediate temperature zone. The heat from this zone can be used in ventilation and diminishes heat losses through the facade.

2.5.3 Ventilation and infiltration

Ventilation and infiltration are separate energy flows but are considered equally because they both regard an energy loss or gain caused by the flow of air in and out of a building. The main goal of ventilation is to provide fresh air in a building to maintain a comfortable indoor air quality for the users. Ventilation may consume energy both by moving the air from outside to inside and around the house, and by climatizing the new, fresh air. In a study done for a Belgian dwelling was concluded that ventilation is responsible for up to half of the energy consumption in well insulated dwellings (Laverge et al., 2011, p. 1497). Though the demand for fresh air is fixed and should not be lowered, the way to provide fresh air and the timing can highly influence the energy use by ventilation.

Infiltration is the flow of air in or out of a building through gaps and seams. In conventional dwellings, this air flow was necessary because it was the only air inlet. In modern buildings, ventilation is more controlled and thus infiltration is unwanted.

Ventilation and infiltration are calculated as follows:

$$Q_{vent} = V_{vent} * \rho * c * (T_e - T_i)$$

$$Q_{inf} = V_{inf} * \rho * c * (T_e - T_i)$$

The density of air **(ρ)** and the specific heat of air **(c)** are physically determined and are constant when considering the same air temperature. These factors can thus not be influenced.

The difference between the outdoor temperature and indoor temperature **(Te-Ti)** results, like with transmission, in a positive or negative heat flow.

The volume of the airflow **(V)** can either be controlled and optimised for comfort demands (in case of ventilation) or can be minimized by making a building more airtight (in the case of infiltration). Being able to control the airflow results in being able to control the energy flow. Below, some ventilation principles are described.

Ventilation technologies and strategies

A minimum amount of fresh air is required to achieve a comfortable indoor climate. Achieving these comfort demands requires energy, thus strategically adapting these demands or the way they are achieved, may result in an energy demand adaptation. Moreover, the ventilation rate can be adapted based on outdoor conditions or energy of the outlet energy flow may be recovered. Technologies and strategies to save energy for ventilation are night ventilation, heat recovery, and demand controlled ventilation.

Natural ventilation and mechanical ventilation are distinguished. Mechanical ventilation drives the air flow by fans and is thus easy to control. Natural ventilation is an air flow based on pressure differences and is harder to control. In case of mechanical ventilation, decreasing the share of infiltration and increasing the share of ventilation thus results in an energy flow that is easier to control. To control the ventilation rate, mechanical ventilation is required. N.B., some techniques allow for controlled natural ventilation, but this considers the control of ventilation openings rather than controlling the exact ventilation rate.

Demand controlled ventilation

Demand controlled ventilation uses an analysis of the indoor air quality or the presence of users in a space to determine the need for ventilation. This way, the ventilation rate (and thus energy use) is lowered when less ventilation is required, while the indoor air quality always remains sufficient. A study showed that using different ventilation component parameters (i.e. vent hole, fan, CO_2, trickle) can effectively decrease energy consumption by ventilation (Laverge et al., 2011).

Night ventilation

The main concept of night ventilation is to improve ventilation rates during summer nights, to withdraw superfluous heat from a building. Inherently, a requirement for this ventilation strategy is a certain amount of thermal mass (Shaviv, Yezioro, & Capeluto, 2001, p. 445). Thermal mass is discussed more elaborately in *2.5.6 Storage.* The size of energy reduction by night ventilation depends on the temperature difference between day and night, the amount of thermal mass and the rate of ventilation (Shaviv et al., 2001, p. 451). However, it is found that the higher the cooling demand of a building is, the higher the potential energy saving by night ventilation becomes (M Santamouris, Sfakianaki, & Pavlou, 2010, p. 1309).

Heat recovery

Heat recovery is a technique that is used in ventilation system where both the inlet and outlet are mechanically driven, and thus their flow is controllable and positionable. By letting the inlet flow and outlet flow indirectly cross each other, heat (or 'coolth') from the outlet flow is transferred to the inlet flow, resulting in an inlet flow which has a temperature closer to the indoor climate. The need for heat recovery drops with the gradual rise of the outdoor temperature, resulting in a practical lower efficiency than technologically possible. This phenomenon is significantly large in well-insulated buildings, where ventilation heat losses are more dominant than transmission losses (Juodis, 2006).

2.5.4 Solar heat gain

Solar heat gain is the energy that enters a building as solar radiation and is then transformed into heat by absorption. This heat gain thus only regards translucent materials, which in the case of dwellings considers windows. Windows are key element in architectural design in terms of comfort and aesthetics, while being one of the most important elements for energy transfer in a building as well. With windows having relative low insulation values and the ability to transmit both visible and heat radiation, the total energy transfer of a window is high. Transmission is already discussed in *2.5.2* Transmission. This section describes the solar heat gain, which is calculated as follows:

$$\mathbf{Q_{sol} = A_{glass} * q_{sun} * g}$$

The area of glass **(A)** can be increased when more solar heat gain is desired. The window always is a certain share of the (opaque) surface that it is part of. In theory, 100% of a surface could be glazing. The low insulation value of glazing and the corresponding effect on transmission should be considered when increasing the surface area.

The solar power **(q_{sun})** depends on the season, the cloudiness and the orientation and considers both direct and diffuse radiation, as discussed in *2.1.4 The energy mismatch in residential buildings in the Netherlands*. The orientation relates to the area of the glass. For example, increasing the glazed area to increase total solar heat gain, is most effective on a southern orientation. When solar gain in the morning is desired, increasing the area on the eastern orientation would be more beneficial.

The g-value **(g)** represents the share of solar energy that is transmitted to the surface. A value of 1.0 means a transmittance of 100%. By using low-e coatings and specific types of glass, manufacturers influence the g-values of glass. Also, electrochromic windows are developed, which can adapt their g-value.

Windows & shading

So, windows affect the energy demand of a building by facilitating passive solar heat gain and by increasing transmission flows. Windows, however, can have a zero-energy effect on the building or even be net energy gainers. Key elements to do this, are relatively low U-values and adaptive transmittance (Arasteh et al., 2006). If passive solar heating is the aim, a balance must always be made between U-values and demanded solar heat gain, because a lower U-value most often results in a lower solar heat gain (Robinson & Hutchins, 1994). A translation to an optimal window-to-wall ratio is made accordingly, because a bigger window results in a higher average U-value and a higher passive solar gain. Assuming the Dutch climate, the latter may be beneficial in winter, but may cause overheating in summer. Shading might be a solution to adapt this.

Shading

By adding shading to windows, solar radiation may be blocked. The effect of shading and the most optimal type and shape of shading depends on the climate and the orientation. In southern facades, the shading may have a horizontal configuration (i.e. perpendicular to the facade) and makes use of the different solar altitude in summer and winter. On the other facades, vertical configuration of shading may be more beneficial. Figure 30 shows the difference between vertical and horizontal configuration of louvers, and indirectly shows the effect of a different solar altitude.

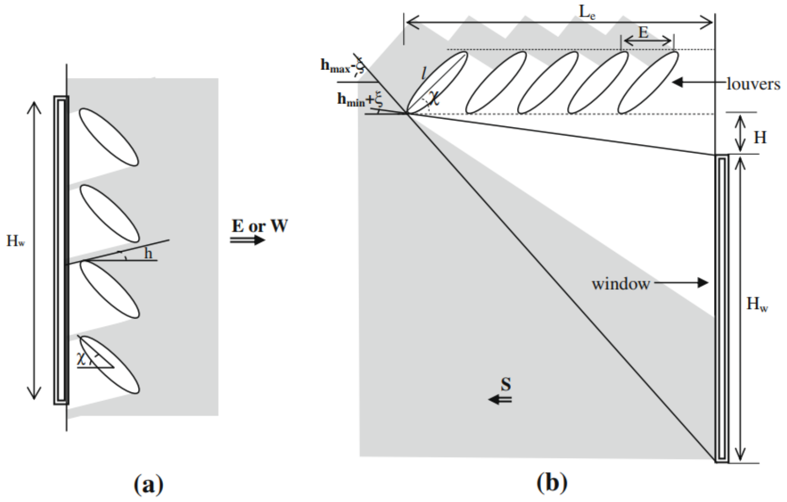


Figure 30: Configuration of the shading system in: (a) east or west facade and (b) south facade (Palmero-Marrero & Oliveira, 2010, p. 2042)

A study has shown that, for a Northern European climate, installing shading all year round may result in a yearly higher total energy demand as a result of the blocked solar radiation gain. In that case, it is advisable to implement (mechanically) adaptive shading to actively adapt to the building’s needs (Palmero-Marrero & Oliveira, 2010, p. 2049).

Shading thus mostly affects the undesired heat gain in summer. Shading might be effective in winter as well, if it would resolve the low insulation value of a window. Insulated shades are a topic that is elaborately explored, and it is a concept of which little commercial products are available. The assumption is made that this is a result of the increasing insulating values of windows and the potential high costs and building physics related challenges (e.g. thermal boundary, vapor-tight layers) of installing adaptive insulated elements.

Adaptive tinting of windows

Another recent development is the so-called adaptive tinting of windows. These windows electronically control the tint of the window, resulting in a higher or lower solar radiation transmittance. The response time of these windows is high and it does not require additional facade elements. The downside is the relatively high costs.

2.5.5 Internal gains

The internal gains is the sum of all heat-producing elements in the building. It is calculated as follows:

$$\mathbf{Q_{int} = Q_{pers} + Q_{light} + Q_{appl}}$$

Persons **(Q_{pers})** produce heat by their metabolism. Doing intensive activities result in a higher heat production by persons. Light **(Q_{light})** and appliances **(Q_{appl})** produce heat by the electricity that they use. Heat produced by lighting and appliances can be minimized by using higher efficiencies or by decreasing the total use. In times of heating demand, heat produced by internal gains is beneficial. The only downside; the heat produced by these elements is most often distributed worse than the heat produced by the heating system. In that sense, it is not desired to turn on all your appliances in times of heating demand. In times of cooling demand, these internal gains should be avoided. This can be done by using more efficient appliances and lighting or decreasing their on-time.

2.5.6 Storage

Energy storage in a dwelling means that energy is actively or passively taken from a space temporarily and given back to that space later. Because of its temporal nature, it is not part of the static energy heat balance.

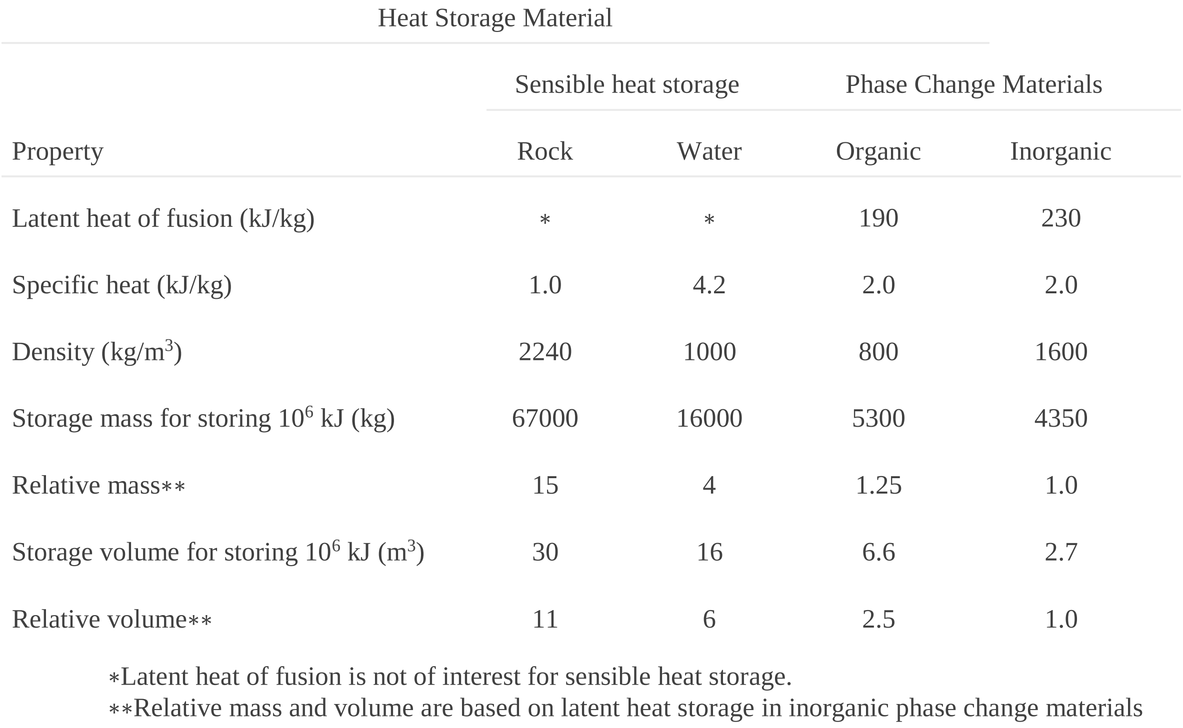
Thermal energy storage (TES) considers the storage of thermal energy. By storing thermal energy when its superfluous, it can be used in times of thermal energy need. The technologies of TES are used for different time periods, ranging from peak-shaving within minutes to bridging seasonal temperature differences (Matheos Santamouris & Asimakopoulos, 1996). The three main methods for TES are sensible, latent and thermochemical energy storage.

Sensible TES stores heat by using the specific heat of a liquid or a solid. The temperature of a material rises with the energy stored in it. In architecture, most often sensible TES takes the form of building materials as thermal mass. The mass of a building temporarily stores heat due to its conductivity, density and specific heat. Another form is sensible TES is storage of energy in a hot water tank, in which the water functions as thermal mass.

Latent TES makes use of the increased heat capacity of a material that is in the state of a phase change. Latent TES solutions often relate to Phase Change Materials (PCM) in the building industry. The PCM's are made in such a way that their melting point is at a favourable temperature at which they can store heat, and are thus often used for cooling as well. N.B., after the PCM has completely passed its phase change, it first has to cool down before it can be used again or vice versa in the case of heating.

The principle of a thermochemical TES is based on chemical reactions. The source heat (e.g. of a solar collector) is used to set up a reversible chemical reaction. When heat is demanded, the reversed chemical reaction is started, and the heat can be extracted.

From the three principles mentioned above, sensible TES in the form of thermal mass is always present in a building, simply by considering the heat capacity of building components like walls, floors etcetera. The effectivity of thermal mass is partly depending on the conductivity of a material and the so-called damping effect. This results in a reduced short-time effectiveness of thermal mass that is ‘deeper’ in a construction. Latent TES in the form of PCM’s has similar beneficial effects, aside some advantages due to smaller size, lower weight per unit of storage capacity and smaller temperature swing (Hasnain, 1998). Table 1 shows a comparison of four basic types of sensible and latent TES. It clearly shows the difference in relative volume and mass to store the same amount of energy.



	Heat Storage Material			
	Sensible heat storage		Phase Change Materials	
Property	Rock	Water	Organic	Inorganic
Latent heat of fusion (kJ/kg)	∗	∗	190	230
Specific heat (kJ/kg)	1.0	4.2	2.0	2.0
Density (kg/m^3)	2240	1000	800	1600
Storage mass for storing 10^6 kJ (kg)	67000	16000	5300	4350
Relative mass∗∗	15	4	1.25	1.0
Storage volume for storing 10^6 kJ (m^3)	30	16	6.6	2.7
Relative volume∗∗	11	6	2.5	1.0

∗Latent heat of fusion is not of interest for sensible heat storage.
∗∗Relative mass and volume are based on latent heat storage in inorganic phase change materials

Table 1: Comparison of various heat storage media (stored energy = 106 kJ = 300 kWh; ΔT) (Hasnain, 1998)

How and to what extent stored heat can be effectively used to produce tap water or space heating in times of demand, strongly depends on the efficiencies of building services. This is beyond the scope of this research and not furtherly discussed.

2.5.7 Energy supply

Energy supply logically is no input of the heat balance, because the heat balance only considers the energy that is needed, not the way it is provided. In this research, energy supply is considered to be a share of the solar supply potential. The solar supply potential is calculated using the following formula:

$Q_{supplypotential}$ Supply potential by solar radiation $Q_{supply} = A_{sup} * q_{sun} * \eta$ [W]

In which

A_{sup}	*potential supply area*	$[m^2]$
q_{sun}	*power of the sun*	$[W/m^2]$
η	*efficiency of converting solar power to supply*	[-]

The full supply potential considers an η of 1, which assumes no conversion losses and thereby shows the full potential. In practice, however, the solar power will be converted into usable energy somehow which will most probably imply energy losses.

Solar energy

Solar energy as renewable energy source is either transformed to electricity by using photovoltaics or to heat by using solar collectors. Orientation and angle of the collecting panels (either solar collectors or PV) determine how much energy a solar system will produce at what time of the day. Electricity peaks can be generated in the morning and evening when a PV system is oriented to east and west, with a high angle. A peak in the middle of the day is created when the solar panel is oriented south, and has a smaller angle. For solar collectors, the effect of orientation strongly depends on the type of solar panel that is used.

Modern residential photovoltaics have an efficiency up to 20%, meaning 20% of the solar radiation power is transformed into electricity. For residential purposes, in conventional cases this Direct Current electricity must be transformed to Alternating Current and is sometimes stored, resulting in a lower total system efficiency. In the Netherlands, the general assumed production of a PV system is 875 kWh/kW_p per year (van Sark et al., 2014, p. 3). An average (modern) solar panel has 170 W_p/m^2, meaning that a system of 20 m^2 produces approximately 3000 kWh electrical energy per year, being the average electricity use for a Dutch household where heating is not supplied by electricity.

Aspect	FPC	ETC	PVT
Efficiency [%]	20-50	30-80	20-40
Avg. annual thermal yield [GJ/m^2]	1.3	1.8	1.2
Avg. yield in winter [MJ/m^2]	90	180	60
Output temperatures [°C]	40-80	60-130	30-50
Price/m^2 [€]	200	300	900

Table 2: Performance and cost properties of three types of solar collectors (Goorden, 2016)

There is a wide variety of solar collector technologies. The basic principle is that a solar convector converts solar radiation to heat stored in a liquid. There are two types of solar collectors; concentrating solar collectors (CSP) and non-concentrating solar collectors (NCSP). For dwellings, NCSP's are standard, because CPS's are often big installations that are not suitable for the residential context. According to Goorden (2016), there are three types of solar collectors that are common in the residential context. The first one is the flat plate collector (FPC), which creates a small greenhouse effect through a black plate from which heat is extracted using water or glycol running through pipes. The second one is the evacuated tube collector (ETC), based on an array of double skinned tubes from which heat is extracted by the evaporating-condensing cycle of a liquid. The third one is the photovoltaic thermal collector (PVT), which is a combination of PV with the FPC. It is a new technology that is expensive, meaning that it is cheaper to have separate PV and solar collector system. However, as the product will become cheaper or when roof surface is limited, this is a useful solution. Table 2 shows an overview of the annual gain of the different types of solar collectors. The table shows that an array of 6 m^2 of ETC produces 3000 kWh of heat per year.

2.5.8 Conclusion

The heating or cooling energy demand of a building is determined by the heat balance. The heat balance takes into account all the energy flows of a building; transmission, ventilation, infiltration, solar heat gain and internal gains. Aside, thermal storage is considered which temporarily takes or gives heat to a building and thereby influences the heat balance. Passive solar energy gains through windows are included in the heat balance. The active solar energy supply potential is separate from the heat balance, because it considers supply rather than the demand.

For every element of the heat balance, several solutions are described that affect the energy demand and supply profiles and their effectiveness is substantiated with results found in literature. It is concluded that solutions are found in building typology, the skin of the building, windows, ventilation rates, temperature ranges and solar energy supply. The set of solutions described in this section is not exhaustive.

2.6 PRECEDENT STUDY

This section describes precedents that can be used as inspiration for energy-flat design. Whilst an analysis of three designs does not provide a complete overview of sustainable solutions, it is assumed that precedent study is a useful contribution to energy-flat design thinking. Almost all precedents are energy-neutral and have a high focus on sustainability. Per precedent, a description, an analysis of design principles and the expected energy-flat performance of these principles is given. The expected performance is visualised by the expected change in the load or production curve, using the load profiles as discussed in *2.3.1 Energy flexibility in the energy system*.

2.6.1 Contemporary Tiny House for Marjolein Jonker – Walden

Background

This dwelling is the first known house of the Tiny House-movement in the Netherlands that is legally permanently inhabited. It was designed for Marjolein Jonker, who is a blogger and pioneer in the Tiny House movement in the Netherlands (www.marjoleininhetklein.com, www.tinyhousenederland.nl). It was designed by Walden studio, a design studio for small, self-sufficient architecture that I co-founded myself in September 2015. The house is currently located in Alkmaar, though it can be moved relatively easy for it meets the requirements of a trailer that may be moved behind a car. Inspired by the Tiny House movement, the house has an extreme compact size, which led to a multi-functional design, of which both exterior, interior and furniture design were part. Being the inhabitant of this house requires for a minimalist lifestyle, corresponding to the Tiny House movement, which is characterized by having little stuff, being self-sufficient and aiming to live a simple life.

Figure 31: Tiny House for Marjolein Jonker, interior (left) and exterior (right). (Walden studio, 2016)

Description

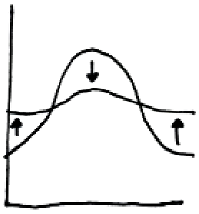
The house has a floor area of 17m^2 and a volume of approximately 60 m^3, in which all the basic residential functions are integrated; living/dining space, kitchen, desk, bathroom including a small bath tub, sleeping loft and even outdoor storage. The interior is characterized by minimal design and uses bright materials. Roof windows provide a lot of light in the home, which reduces lighting energy usage and makes the room look bigger. Reducing ecological impact was a cornerstone in both the construction- and user-phase of the house. Where possible, bio-based materials are used. The façade is made from thermally modified Scandinavian pine, the construction consists of spruce wood and Ecoboard® and the interior is painted with ecological paint. The floor is made of cork and the construction is insulated with sheep wool.

Figure 32: The tiny house has a hard time to provide sufficient energy in winter (Jonker, 2017)

The house is heated by a small wood stove, which combines radiative heat and convective heat to comfort the house. The insulation value of 2,5 m^{2}K/W is low compared to modern housing standards, this has to do with the high ventilation replacement factor: the house is so small that the amount of energy lost by ventilation is relatively high. Increasing the insulation value of the house would not result in significant energy savings because the ventilation losses are determinative. Furthermore, one electric radiative heat panel is installed in the lounge space. This can provide local radiative heat. Radiative heat is an efficient way of heating, because it is small and radiates locally. This is ideal for autumn and spring evenings, when heating the complete house, which would require much more energy, would be unnecessary.

The house contains three solar panels of 300 Wp and a battery pack of 2x 2kWh to fulfil the electrical energy demand. It should be noted though, that the PV-system is not big enough due to financial limits and during winter there is not always enough electricity. In disappointment of the designers, the remaining necessary electricity demand is then provided by a small diesel driven generator. Domestic Hot Water is provided by an LPG boiler and the oven uses gas as its heat source.

Potential energy-flat design principles

Principle	Explanation	Result
Small building means small volume and small surface area	The compact size of the house is probably the biggest advantage in terms of energy. The volume of air that is heated is much smaller. Moreover, the surface area through which energy is lost by transmission is much smaller as well. N.B. the smaller volume results in a higher air change rate. This results in a smaller effect of eventual increase of insulation, because the energy losses balance is more shifted towards ventilation. This could be compensated by integrating a ventilation heat exchanger.	 Strategic conservation
Lightweight	The house is very lightweight, due to trailer-restrictions, which result in a lower thermal mass. The house thus requires little energy to heat, because the materials do not ‘store’ much heat. This also results in the indoor temperature being very responsive, the house heats up fast, but cools down fast as well.	 Strategic conservation
Inhabitants consciousness and flexibility	The inhabitant, Marjolein Jonker, is blogging about her experiences. She explains how she adjusts her energy consumption to the availability of energy. For example, being very efficient with water consumption in times of little rain, and going to public spaces to work with her laptop. Though this might not be a solution for everybody, it shows the high potential of the flexibility of a user.	 Flexible load shape
Multiple energy sources	The combination of a wood stove and an electric radiative panel, provides the possibility to choose one out of two different energy carriers. This corresponds with the availability of substitutes as mentioned in 2.3.5 Smart grids Though the actual demand does not change, one is able to use an energy carrier to reduce the load on another.	 Load shifting

2.6.2 ReVolt - TU Delft Solar Decathlon entry 2012

Background

The ReVolt house is the entry by the TU Delft for the Solar Decathlon 2012, which has unfortunately not been realized due to financial limits. The Solar Decathlon competition is a bi-annual competition in which team are requested to design a completely solar powered house. The design location for the competition was Spain, so some considerations concerning the different climate should be considered when using this precedent as inspiration. ReVolt House is a floating and rotating house, which combines the warmth of solar heat and the coolness of water. The origin of the floating concept derives from the vast amount of water surface available and the increasing risk of floods in the Netherlands. The rotation concept is based purely on energetic considerations, as explained in the next section.

Description

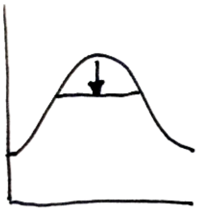
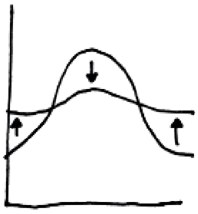
ReVolt House is a household for two persons, it consists of one level with a circular floor plan. The interior consists of three living zones for the main functions; a kitchen, a living and a sleeping area. The bathroom is in the centre of these areas whereas all other functions (i.e. toilet, technical room) are located at the façade. The sleeping area can be transformed into a working space. Outside is a circular terrace surrounding the house. Interesting is that the sun shading is provided by the rotation of the house and thus has a 100% block of direct sunlight without creating any obstruction to the view. The walls of the house are made from a 270mm PET foam core covered in glass fibre reinforced plastic and extra measures are taken to increase air tightness.

The house rotates with the sun. The 'open' glazed façade is aimed to the sun in winter, to gain all the possible passive solar heat. The reflective water surface increases the potential radiative heat. During summer, the closed side of the façade turns to the sun path and blocks 100% of the direct light (i.e. heat), resulting in a potential cooling decrease of 9 kWh per day (ReVolt House, 2011). A heat pump is installed under the house which takes advantage of the temperature of the lake and provides both cooling and heating in the house through the ceiling and floor respectively. The house is passively ventilated with the possibility to heat or cool the incoming house by heat exchanging and indirect adiabatic cooling respectively. Furthermore, Phase Change Materials are integrated in the floor and ceiling to increase the thermal mass.

Figure 33: The floating ReVolt House (ReVolt House, 2012, p. 8)

The roof of the house is filled with solar panels, which also benefit from the rotation of the house. The vast number of windows provide enough daylight for the living spaces whereas the bathroom is provided with a daylight illuminator. It is unclear whether the house has a grid connection or functions purely on batteries. It is expected that a grid-connection is present, because off-grid functionality would require a high volume of batteries which cannot be found in the description of the house.

Potential energy-flat design principles

Principle	***Explanation***	***Result***
Maximum use of passive and solar gains	The rotation of the house is the most unique and exceptional property of the house. In the first place, because it fully adapts to the sun. Decreasing the cooling load drastically in summer by blocking all direct light and decreasing heating load by gaining all passive heat.	 Strategic conservation
Rotate; energy production	The rotation also provides increase solar energy production. It is not clear why all the panels are lying flat on the roof, but the rotation of the house allows the solar panels for movement with the azimuth. An extra hinge could allow the panels to move with the altitude as well. Optimal solar gain would be the result.	 Strategic growth
Connection with water	The location of the house on the water allows for the high thermal mass of the water. The heat pump makes optimal use of this. The water provides a more balanced out source temperature, which allows the pump to function at a higher efficiency over the whole season, compared to a relatively low efficiency in times of high need with a conventional air source heat pump. The winter peak loads for heating are flattened out.	 Peak Clipping
Phase Change Material	The phase change material (PCM)l in the floor and ceiling highly improve the thermal mass. It slows down the temperature changes of the building and thereby flattens out peaks in the energy consumption for heating and cooling. Because of the active heating and cooling systems in the floor and ceiling, the use of the PCM buffer can be timed; it energy may be put in or pulled out in times of energy surplus.	 Load shifting

2.6.3 Prêt-à-loger - TU Delft Solar Decathlon entry 2014

Background

Prêt-à-loger is a zero-energy refurbishment concept, designed by a team of the Delft University of Technology as an entry for the Solar Decathlon 2014 competition. Opposite to the ReVolt House, Prêt-à-loger was constructed and was, after the competition in Versailles, moved to the campus of the University. Prêt-à-loger won the overall third price in the Solar Decathlon competition. Prêt-à-loger stood out in the competition, because it was the only refurbishment design. The aim of the team was to provide a zero-energy-refurbishment solution for the typical Dutch row houses, of which we have 4 million in the Netherlands. A second skin is added to the house which solves four ‘problems’; insulation, airtightness, humidity and space. The skins most iconic part is the green house on the south facade of the house, which allows for optimal use of the characteristics of different seasons by either being open for ventilation, completely open or completely.

Description

The house is a replica of a row-house in Honselersdijk, The Netherlands, constructed around 1960. The second skin that covers the house consists of three parts. The North-side is covered with an extra layer of insulation, replacing the formal outer brick layer of the cavity wall. The windows are replaced taking into account both insulation and improved airtightness. The northern roof is transformed into a green roof that diminishes rain-water problems in The Netherlands, improves air quality and saves cooling energy in summer by evaporative cooling. On the Southern side of the building, the greenhouse is added which can be seen as the heart of the building, for it contains the most critical functions.

Figure 34: Prêt-à-loger and its remarkable green house (Prêt-à-loger, 2014)

The glass-house is covered with PV-cells that provide 3900 kWh of electrical energy per year, whilst the energy consumption is approximately 3200 kWh. The glass-house captures the radiative heat of the sun and uses it to heat the house, both by being the source of ventilation and the heat pump. Moreover, it provides extra space which can be used often because of its comfortable indoor climate. Last of all, the greenhouse is used to capture rainwater used for toilets and to provide space for growing food.

Building installations

The conventional gas-powered boiler is replaced by a heat-pump with a hot-water-storage tank of 300L. The heat-distribution system is unchanged, but because of the highly increased insulation level a slightly lower heating temperature suffices; 57°C instead of approximately 70°C. The heat-pump is a water-water heat pump that uses the passively heated liquid from thermodynamic panels in the greenhouse, simultaneously cooling the green house (including the PV-panels) and heating the house. One downside is that the panels also cool the greenhouse in winter, which counterworks the heating concept of this space. The ventilation has both a mechanical inlet and outlet which allows for a heat-exchanger, which keeps around 95% of the heat whilst refreshing the air. The ventilation system has four different power-levels that are turned on based on CO2, VOC or humidity levels. Moreover, the ventilation has three different inlets that are used depending on the outside temperature compared to the inside temperature; a PCM inlet with cooled air, a ground inlet with naturally precooled air and the green-house inlet with preheated air.

The house has a domotica system that controls ventilation, opening of windows, heating, lighting and sun shading. Moreover, it provides insight in the residential energy supply and demand. Controlling lighting saves energy when people are not at home or accidentally leave the light on, controlling the opening of the windows assures the right climate within the green house. The insight in energy supply and demand has proven to save energy in several cases, e.g. the CloudPower in Texel in which electricity reduced by 5% and gas consumption by 10% (RVO, 2015).

Potential energy-flat design principles

Principle	***Explanation***	***Result***
Green house: heat demand	The passive solar heat collection of the house is used in many ways; a thermal buffer, as ventilation heat source and as heat-pump heat source. Although these three ways of heat collection might counterwork each other partially, they result in a reduction of the total heating load.	 Strategic conservation
Green house: supply perspective	Apart from reducing the heating demand, the green house is beneficial for the energy supply. The green house adds extra roof surface which is used for PV-panels. Moreover, the openable windows of the greenhouse with integrated PV aim to the sun in summer, whilst being more vertical in winter.	 Strategic growth
Ventilation; different inlets & heat exchanging	The use of different ventilation inlets saves heating and cooling loads, because the inlet with the most ideal temperature is chosen. The mechanical ventilation allows for heat exchanging, which results in less ventilation losses. The ventilation system saves energy.	 Strategic conservation
Green roof; reduce cooling energy	The green roof on the house provides evaporative cooling, which reduces the heating load. The effectiveness of this cooling may reduce with higher insulation values of the roof. The passive cooling reduces the (active) cooling load.	 Strategic conservation
Heat pump with thermal buffer for DHW and heating	The heat pump combined with the thermal buffer allows for a flexible load shape. The heat pump can be turned on when it is the most efficient (i.e. when the source temperature is the highest). The hot water of the buffer is used when there is a need for heat. Supply and demand are thus independent.	 Flexible load shape

2.6.4 Conclusion

Three designs are briefly reviewed and their sustainable properties summarized and categorized. The principles used in the designs influence the demand and supply profiles in different ways. Whilst an analysis of three designs does not provide a complete overview of sustainable solutions, the aim to provide inspiration for the energy-flat design is achieved. More solutions might be present, and some solutions might interfere with each other. Further study will show what the affect is of these building parameters on minimizing the mismatch of supply and demand.

3 WHAT IS ENERGY-FLATNESS?

This section answers the first sub-question: *"What is energy-flatness and what are its key performance indicators?"*. The definitions of energy in the context of this research are given and the system boundary for energy-flat building analysis is provided. Moreover, the key performance indicators (KPI's) are explained. These KPI's serve to evaluate energy-flatness in this research.

3.1 ENERGY DEFINITIONS

A large amount of definitions and interpretations on energy exist and to provide a quantitative analysis of the energy consumption of a building, definitions should be made clear. Konstantinou (2014, p. 91) summarises the following definitions on energy. N.B. definitions are cited from this source unless stated differently:

Non-renewable energy	Energy taken from a source which is depleted by extraction (e.g. fossil fuels)
Renewable energy	Energy from sources that are not depleted by extraction (e.g. solar or wind energy)
Primary energy	Energy that has not been subjected to any conversion or transformation process. It is the "raw" energy contained in the fuels, such as coal, oil and natural gas. Primary energy includes non-renewable energy and renewable energy. If both are considered it can be called total primary energy. For a building, it is the energy used to produce the energy delivered to the building. It is calculated from the delivered and exported amounts of energy carriers, using conversion factors. N.B. often, only the fossil or non-renewable part is meant when people talk about primary energy.
Secondary energy	Energy obtained from primary energy through the transformation process. The percentage varies according to source and process type. In electricity production, for example, it is only 30 to 40% of the primary energy contained in the fuels
Delivered or final energy	Energy supplied to the consumers, to be converted into useful energy (e.g. electricity at the wall outlet). It is a proportion of secondary energy, after subtracting transportation losses.
Exported energy	Energy, expressed per energy carrier, delivered by the technical building systems through the system boundary and used outside the system boundary. It can be specified by generation types (e.g. CHP, photovoltaic, etc.) in order to apply different weighting factors.

Energy demand [edited by author]	The quantity of energy needed by a space to for heating and cooling or by user devices to function. For example, heat to be delivered to or extracted from a conditioned space to maintain the intended temperature conditions during a given period. The energy need is calculated and cannot easily be measured (EN15603, 2008). It is derived from the delivered energy, taken into account the system efficiency.
Local energy supply [added by author]	Energy produced within the system boundary of the building. In this case it relates to energy that is sustainably produced by for example solar or wind. It regards energy that can be spread through the building to serve different needs. (i.e. solar collector energy is energy production, but passive solar heating energy is not energy production).

These different energy definitions are the result of different losses in the different steps of the energy supply chain, which depend on the system efficiencies of transportation, transformation and installations. Figure 35 provides a visualisation of the relation of the different energy definitions. It shows that only a share of the primary energy becomes supply and demand. It also shows the relation between the share of local supply and external supply. Please note that the energy supply is equal to the energy demand in the conventional situation.

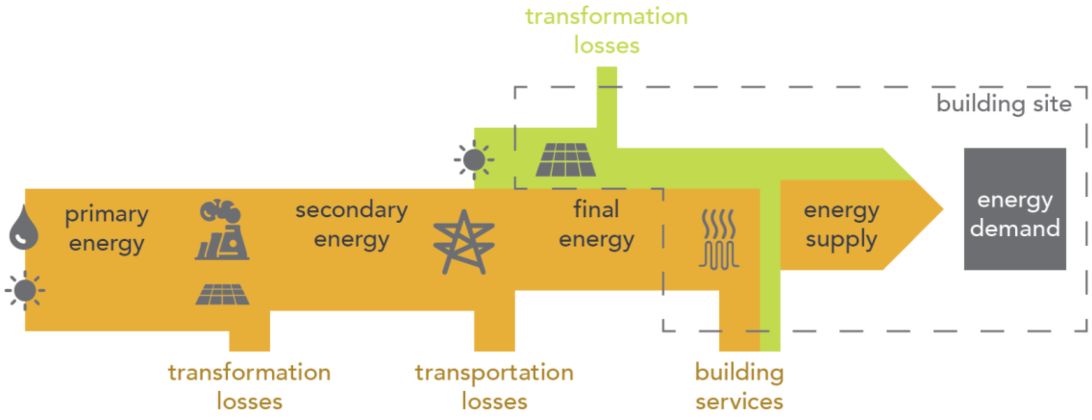


Figure 35: Visualisation of the energy definitions in the conventional energy situation

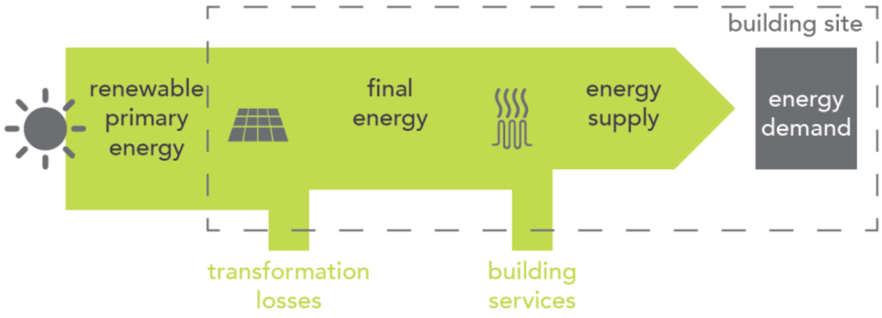


Figure 36: Visualisation of the energy definitions in the case of local, renewable energy supply

In the case of energy-flatness, the supply is completely local and renewable. This does not affect the definitions, although the transportation losses are minimized, and the system boundary affects more steps of the process. See Figure 36 for the energy-flow with local, renewable energy supply.

In this research, the mismatch of a residential building is considered. The mismatch is determined by the difference between energy demand and energy supply, not on an annual basis but as the sum of all timesteps in the total year. Energy demand and energy supply are discussed in the next section.

3.2 SCOPE OF THE ENERGY-FLAT BUILDING

A lot of different approaches exist for analysing a buildings energy system. Therefore, it is very important to define a clear scope and system boundary of the energy system to be studied. In this section, the scope of the energy-flat research is clarified.

Sartori et al. (2012) set up a framework to describe the relevant characteristics of assessing zero-energy buildings. Energy-flatness is different from zero-energy buildings, because of the smaller time interval. The following aspects of the framework are discussed in this section:

Physical system boundary

Balance boundary

Balancing period

3.2.1 Physical system boundary

The physical boundary is used to identify the difference between on-site and off-site supply and demand. In this study only one single household is regarded, and all the renewable energy production resources that are directly attached to the household. All on-site energy production is within the boundary, though the requirement is that the energy production is merely meant for this single household (e.g. collective solar production on a communal parking lot may not be accounted as local energy production). Furthermore, it is assumed that in terms of energy only a two-way electricity connection goes into the house, there is no external thermal-network or gas-grid connection. The two-way electricity grid can deliver and import energy, though the ideal goal with energy-flatness is that these two values are always zero.

3.2.2 Balance boundary

The balance boundary determines which energy flows are accounted and which are not. The Dutch NOM dwelling (see *2.4.3*) provides a so-called ‘maatlat’, which is an overview of the demands for Zero-Energy-Design (S. Klijn Velderman et al., 2016, pp. 29-33). In terms of energy, the overview demands the following:

- 1.A Total annual production of electrical energy
- 1.B Heating demand
- 1.C Domestic Hot Water (DHW) demand

- 1.H Total annual electrical energy consumption
    - 1.D Electricity use heating producer (for heating demand and DHW)
    - 1.E Electricity use ventilation system
    - 1.F Electricity use additional systems (monitoring systems, additional pumps)
    - 1.G Electricity use plug-loads (including lighting)

The energetic demand of the NOM dwelling is that the total annual production of electric energy (1.A) is equal to the total annual electrical energy consumption (1.H). The demand for all other flows is to be ‘’produced in a sustainable way”, in accordance with the EPV regulation (*see 2.4.3 Nul-op-de-meter and Energieprestatievergoeding)*.

Energy-flatness regards the same balance, but then with the requirement that the electrical energy consumption and electrical energy production are equal **at every moment in time**, instead of at the end of the year. This also means that thermal energy flows do not have to be equal at any time, for the inequality of heating flows might be compensated by electrical energy, which can then result in electrical energy-flatness.

However, the thermal energy balance is the origin of the electricity balance. In this research, only the energy needed for heating and cooling the indoor environment of a dwelling is considered. So the final demand that has to be fulfilled with supply, is the heating and cooling demand. As can be seen from Figure 37, it is impossible to determine the electricity need to fulfil the heat and cool demand, without knowing the efficiencies of the building services. Because this research is the first research that explores energy-flatness and is future-oriented, it is not desired to scope it with state-of-the-art building services.

To achieve electrical electricity energy-flatness, one should start with focussing on the heat balance energy-flatness. This research focuses on that balance. Eventually, in the final example energy-flat design, a translation to electricity energy-flatness is made.

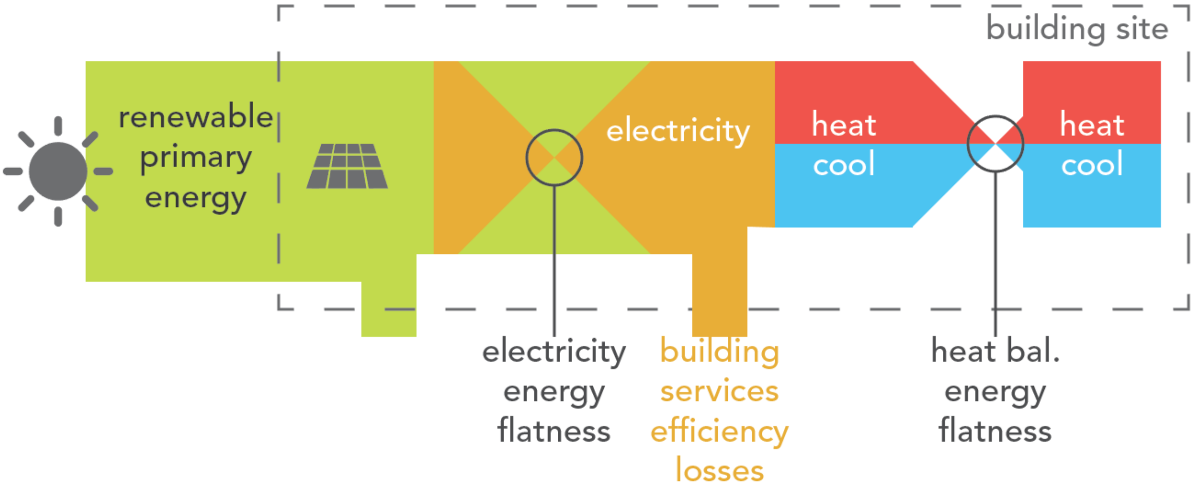


Figure 37: The relation of the electricity balance and the heat balance, in addition to the visual of the energy definitions (see Figure 36)

An energy flow that is in the NEN-5128 but not considered separately in this research, is the energy used for humidification, for this is considered not to be present in dwellings. The loads for DHW and plug-loads are based on a pre-set and fixed profile, because it is not in the scope of this research to change these loads. For lighting, a certain comfort standard will be set that has to be achieved, either by artificial lighting or natural lighting.

It is made clear that only operational building related energy is considered in this research. Embodied energy, energy use to construct and demolish the building et cetera is not taken into account, for it is not the focus of the study.

3.2.3 Balancing period

As already became clear, the major property of energy-flatness is that it aims to match energy demand and supply at any time of the year. Since 'time' can be endlessly small, some specifications are made.

It is important to consider that the balancing period has a big influence on the value for load matching (Sartori et al., 2012). The shorter the time interval, the harder it is to reach perfect balance. This ranges from continuous energy-flatness to yearly energy neutrality. The reason that smaller timesteps increase the challenge, is that time plays a major role in mitigating peaks. For instance, when looking at annual totals of photovoltaic supply, the peak in summer and valley in winter stay unnoticed. But when looking at the monthly totals in that same year, the differences become clear. On the other hand, a smaller timestep is not always logical. The energy needed to heat a regular sized space, for instance, is not relevant at a timesteps smaller than 15 minutes.

In this research, the smallest timestep that is considered is one hour. So, perfect energy-flatness in this research means equal supply and demand at every hour of the year. Apart from the hourly values, also the daily totals and monthly totals are considered. These totals are always a sum of the hourly values within that particular timespan. The following intervals will be analysed:

Analysis intervals	Size of timestep	Amount of summed values per timestep
1 week	1 hour	1
1 month	1 day	24
1 year	1 month (28, 30 or 31 days)	672, 720, 744

Table 3: Different analysis intervals and corresponding timesteps

It is to be expected that the hourly values in the weekly analysis provide information on the responsiveness of a building and bridging day/night differences. The daily totals in the monthly analysis will show the typical energy demand and supply in the different weather conditions. The monthly totals in the annual analysis will show how to bridge the differences between the seasons.

3.3 KEY PERFORMANCE INDICATORS

Energy-flatness aims to reduce the mismatch of electrical or heat supply and demand at any given hour of the year. Three key performance indicators (KPI's) are defined to quantify the energy-flatness. The first performance indicator describes the actual energy-flatness, the second and third performance indicator provide characteristics of the non-flatness.

The goal of the KPI’s is to indicate to what extent a design is energy-flat and thereby being able to compare the energy-flatness of different designs easily, consequently and quickly. It is assumed that the three KPI’s as described below provide a succinct and complete evaluation of energy-flatness in three values. It should be noted, that each of the KPI’s can also be calculated separately for every energy flow in the heat balance; heat, cool, supply. The KPI can also be calculated for the electricity balance. The relation between these sub-KPI’s may provide new insights.

3.3.1 KPI1: Absolute energy-flatness

The first performance indicator describes the state of absolute energy-flatness. It is defined as the combined total difference between supply and demand over a set time interval. In the graph of the supply and demand profiles (Figure 38), it is represented by the total area between the two lines.

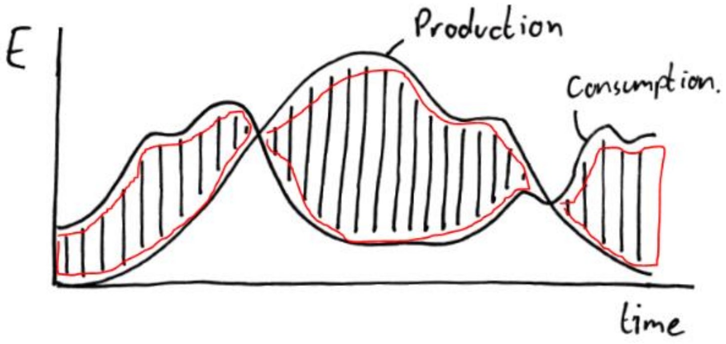


Figure 38: KPI 1; the total mismatch between supply and demand

The corresponding mathematical definition is as follows:

$$\int_0^{8760} |E_{prod}(t) - E_{cons}(t)| \, dt$$

Where $E_{prod}(t)$ is the electrical energy production at time t and $E_{cons}(t)$ is the electrical energy consumption at time t. Energy surplus and energy shortage mismatches are combined in this KPI. For analysis goals, they could be separated, though the result is a decrease in functionality of defining the flatness.

This performance indicator always results in a positive, absolute value, or zero. The closer it is to zero, the closer it is to optimal energy-flatness. It is assumed that optimal energy-flatness (i.e. KPI1 = 0) is not reached and a small mismatch will always be present. KPI2 and KPI3 are used to determine the characteristic of that mismatch.

3.3.2 KPI2: Maximum mismatch peak

The second performance indicator shows the biggest difference in any moment of time between supply and demand that can be found within the total time interval investigated. Opposite to KPI1, KPI2 is time-dependent and relates to power (W) instead of an amount of energy (J or kWh). In the graphical representation (Figure 39) it is the largest vertical distance between the demand and supply profiles.

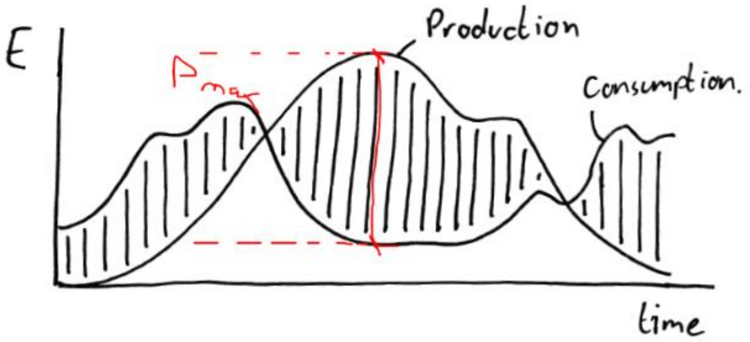


Figure 39: KPI 2; the maximum peak between supply and demand in time

The mathematical definition is as follows:

$$\underset{0\leq t\leq 8760}{max}\left(\left|E_{prod}(t)-E_{cons}(t)\right|\right)$$

Where $E_{prod}(t)$ is the electrical energy production at time t and $E_{cons}(t)$ is the electrical energy consumption at time t.

3.3.3 KPI3: Maximum cumulative mismatch

The third performance indicator describes the biggest cumulative mismatch of supply and demand. It gives the biggest difference between cumulative overproduction and overconsumption. This is the theoretical size a battery or storage would need in order to make an autarkic energy system. The graphical definition shows the integral of the difference between supply and demand over a year, or in other words the change in area between the supply and demand profiles.

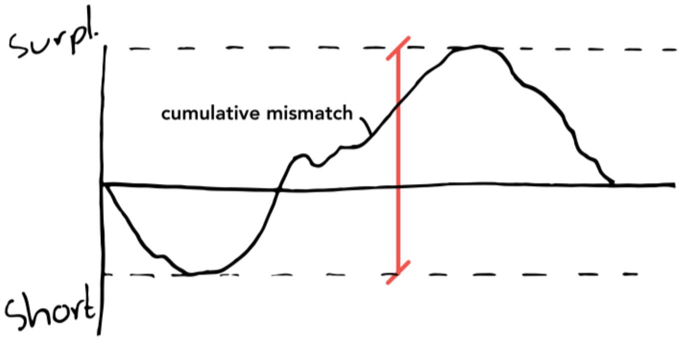


Figure 40: KPI 3; the maximum cumulative mismatch of supply and demand

The mathematical definition is the global maximum minus the global minimum of the cumulative mismatch. Boundary condition is an energy-neutral situation. The definition is as follows:

$$\left(\max_{0\leq a\leq b\leq 8760} - \min_{0\leq a\leq b\leq 8760}\right)\int_a^b E_{cons}(t) - E_{prod}(t)dt$$

Where $E_{prod}(t)$ is the electrical energy production at time t and $E_{cons}(t)$ is the electrical energy consumption at time t. The KPI is the maximum value of the two formulas.

3.3.4 Meaning of the KPI’s in the heat and electricity balance

The KPI’s can be applied on both the heat balance and the electricity balance (see *3.2.2 Balance boundary*). In both balances, the meaning and purpose of the KPI’s is different. Moreover, the energy flows on which they can be applied differ.

KPI’s in the heat balance

The main goal of the KPI’s in the heat balance is architectural optimisation. This means that the absolute values of the KPI’s can be used to compare different designs to each other, but they do not state anything about the final energy demand or supply. In other words, it serves as a useful means for profile matching, but it cannot be used to select building installations nor say something about the final energy required to achieve energy-flatness. This difference is very important when analysing the results of the optimisation studies.

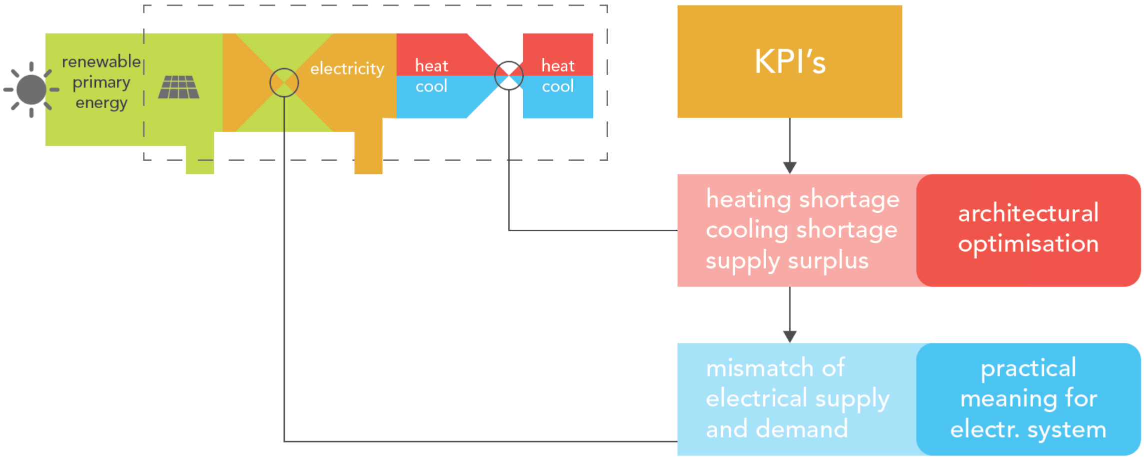


Figure 41: Different meaning, applicability and purpose of the KPI's in the heat balance and electricity balance

In the optimisation of the heat balance, the KPI’s can be applied on three different mismatches:

Heating shortage	*when there is a heating load that is not fulfilled by supply*
Cooling shortage	*when there is a cooling load that is not fulfilled by supply*
Supply surplus	*when there is a supply potential that is not used by a heating or cooling load*

KPI1 and KPI2 can be applied on all these three mismatches individually or on the sum of the mismatches. KPI3 can only be applied by combining the heating and cooling shortage in one value (i.e. ‘demand shortage’).

KPI’s in the electricity balance

In the electricity balance, the KPI’s are much less abstract and the results give actual, applicable numbers for the energy system. In this electricity balance, the original problem statement of the energy mismatch is quantified with the KPI’s. When considering the electricity balance, the mismatch consists of two sub-mismatches:

Electricity shortage	*when there is an electrical energy demand, but no electrical supply*
Electricity surplus	*when there is an electrical supply, but no electrical demand*

Together, these result in the total mismatch. In this electrical context, the meaning of the KPI’s can be explained by two different system; one system in which the mismatch is compensated by a local electrical energy storage system within the system boundary (e.g. a battery), and one system in which the mismatch is solved by an electricity connection to the utility grid. For every KPI, a short description is given on how it relates to both a grid connection and a battery storage connection. This will improve the clearness of the KPI and will show its relevance in these contexts.

In the situation where local energy storage compensates the mismatch (Figure 42), the first KPI shows the total annual battery energy flow. It might be useful when considering the deterioration or lifetime of the battery. The second KPI states the required power of the battery; the value of KPI 2 represents the maximum peak power that will occur in a year which will have to be provided by the local energy storage. The third KPI literally shows the theoretical size of the battery. This, however, considers a battery without any self-discharge and a cycle efficiency. So, KPI3 should be increased with the cycle efficiency and self-discharge losses to get the actual required size of the battery.

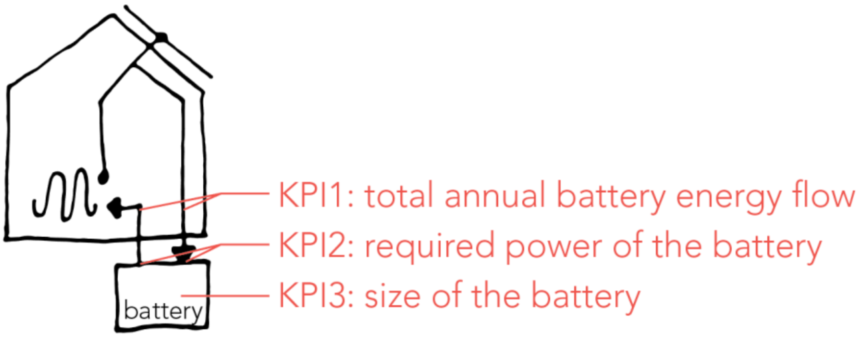


Figure 42: The meaning of the KPI's considering a situation with local energy storage

In a situation of a grid connection, the first KPI represents the total amount of energy that is delivered from and exported to the energy grid (Figure 43). From this point, the difference between energy-neutral and energy-flat becomes clear; an energy-neutral building can still have a high KPI 1. The meaning of this KPI can be found in terms of costs or restrictions of the energy grid; maybe a maximum flow is set or the price is determined based on the total flow. The second KPI represents the maximum power required from the grid. In a future situation, utility grid might put restrictions on the maximum power a dwelling can get delivered from or export to the grid. After all, a higher power capacity connection means a potential higher contribution to a surplus or shortage on the grid. The third KPI represents the annual reliance on the grid. In the situation of a grid connection, this KPI is less relevant, because how or when energy is stored in the grid is also determined by other connections.

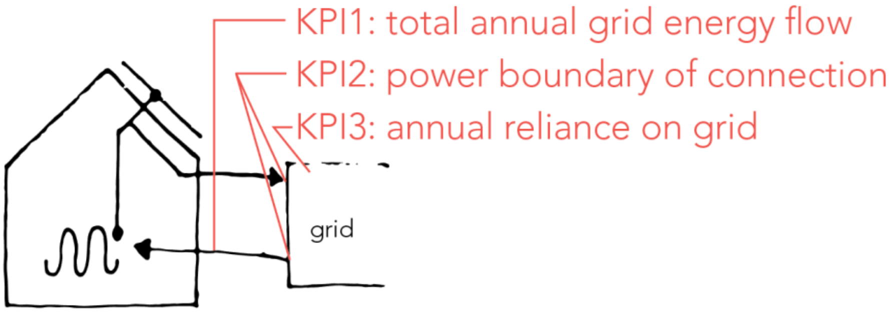


Figure 43: The meaning of the KPI's considering a situation with a grid connection

The explanations of the battery and energy-grid perspective are merely for clarification. In a more realistic situation, a combination of a grid connection and local energy storage is probably more effective.

3.3.5 Relation between KPI2 and KPI3

Whereas KPI1 describes the absolute energy-flatness, KPI2 and KPI3 describe the characteristics of the mismatch. The maximum peak-power and the maximum cumulative mismatch relate to each other, because both influence the required back-up installations that compensate for the mismatch (i.e. battery or grid). All designs will be a combination of a value for KPI2 and KPI3, which can be plotted in a graph, see Figure 44.

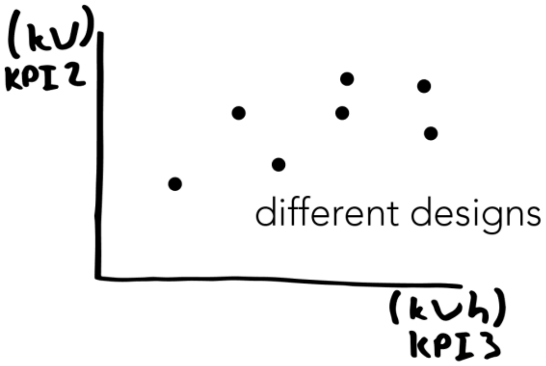


Figure 44: The relation between KPI2 and KPI3 will differ per design. Depending on the technology, one relation is optimal.

Depending on the technology that has to compensate for the mismatch, a different relation between KPI2 and KPI3 might be ideal; some storage technologies, for example, will be easily scalable in terms of total storage capacity, but might be hard to scale in terms of power output. Finally, the spread of dots of different designs can be used to analyse common mismatches.

3.4 CONCLUSIONS

This chapter answers the sub-question *‘’what is energy-flatness and what are its key performance indicators?”* by describing relevant energy definitions, setting the scope in terms of physical, balancing and time-related boundaries and defining the key performance indicators both mathematically and graphically.

Energy-flatness is the state of a buildings energy performance in which the difference between supply and demand is zero at any time. An energy-flat building handles the fluctuations in energy supply and demand profiles caused by users, climate and intermittency of renewable energy supply and thereby strongly decreases the need for grid- or battery storage.

The energy-flatness relates to a single household, and only to the energy that is consumed and produced directly in the house or by systems attached to the house. Electricity energy-flatness and heat energy-flatness should be distinguished. The heating and cooling demands are the origin of the final energy demand. They are determined by the architecture and building physical properties, hence balancing these flows is the starting point for energy-flatness. The final, electricity energy-flatness is determined by the (efficiencies) of the building services which provide heat, coolth and supply.

Energy-flatness is quantified by three performance indicators. KPI1, the total mismatch, describes the actual energy-flatness by calculating the annual sum of the mismatches. KPI2 and KPI3 are used to described the characteristics in the case when energy-flatness is not reached. KPI2 describes the maximum mismatch peak and KPI3 describes the maximum cumulative mismatch. KPI2 and KPI3 are related to each other and can be valued according to the context.

4 SIMULATION OF ENERGY-FLATNESS; THE ENERGY MODEL

This chapter describes the research methodology related to the energy calculations and describes how the energy-flatness simulation model is set up. It covers the software that is used, the static and variable inputs and the outputs. In other words, it describes how the designs will be analysed.

4.1 APPROACH TO DEVELOP AN ENERGY-FLAT DESIGN

Energy-flatness is defined in *3 What is energy-flatness*? as the situation where the energy demand is continuously equal to the energy supply. From the problem statement, it is derived that energy-flatness considers a balance for electrical energy consumption and local, renewable electrical energy production. In contrast to concepts like the NoM and NZEB buildings, this balance should occur at every moment in time.

The energy demand of a building, however, starts with a heating and cooling demand, which is the direct result of the heat balance and thus of the architecture of the building and the building physics properties. So, energy-flatness should be achieved in the heat-balance in the first place

The final electricity balance depends not only on the building physics properties and the architecture itself, but also on the properties of the energy system. These properties regard efficiencies and losses by the building services, and are strongly dependent on the state-of-the-art performance of building services.

Hence, to study the energy-flatness of a building, first the heating and cooling demands and the effects of the architecture and building physics properties on these demands are studied. The supply is, in this heat balance, represented by the solar potential. This study is done using a reference design. Several studies are done to research the effects on the match by changing individual parameter in this reference design. The match is sought between the heating and cooling profiles and the supply profiles.

As a next step, adaptations in architecture and building physics properties are combined in new designs in order to optimize the heating, cooling and supply profiles. This is done in three successive steps:

- First, the design is optimized to match the demand to the original supply
- Second, the design is optimized to match the supply to the original demand
- Last, the optimal mix of solutions in both supply and demand is sought in one design.

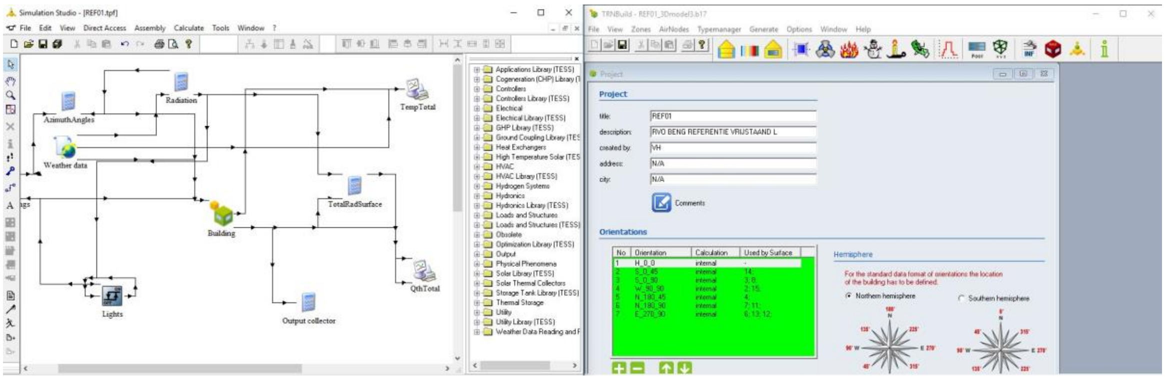
As a final step, the electricity match is approached by designing an energy system in which efficiencies and functionalities of building services are considered. This system might include some storage, to compensate for the ‘unsolvable’ mismatch.

The simulation software and its outputs are described in chapter 4. The reference design and its properties are described in chapter 5. The parameter studies are described in chapter 6 and the final designs are described in chapter 7.

4.2 SIMULATION SOFTWARE SELECTION

Two software packages are considered for the dynamic energy modelling of the designs. The core principle of dynamic energy modelling is that it performs iterative calculations with changing variables rather than a calculation with static variables. The goal of the software is to achieve the desired quality of results whilst being as fast and simple as possible. This saves calculation and set-up time and improves workability. For this research, the software packages TRNSYS and Honeybee are considered.

TRNSYS is a software environment that can be used to simulate transient systems, including the dynamic energy modelling of a building (TRNSYS, 2017). The software has been commercially available for over 35 years and is commonly used in professional practice. The software package consists of a kernel which translates the input to the output and a library of components that can be used to be part of the simulation. The model is set-up using partly a graphic interface and partly a textual interface (FIGUUR). A key characteristic of TRNSYS is the possibility for highly customizable input and output, which also is the reason that it is used for a variety of energy simulation subjects, ranging from wind turbines to detailed HVAC systems to multizone buildings. TRNSYS has a very extensive, structured documentation in which both the mathematical definition as tutorials are described.



title: REF01
description: RVO BENG REFERENTIE VRIJSTAAND L
created by: VH
address: N/A
city: N/A

No	Orientation	Calculation	Used by Surface
1	H_0_0	internal	-
2	S_0_45	internal	14;
3	S_0_90	internal	3; 8;
4	W_90_90	internal	2; 15;
5	N_180_45	internal	4;
6	N_180_90	internal	7; 11;
7	E_270_90	internal	6; 13; 12;

For the standard data format of orientations the location of the building has to be defined.

Figure 45: Interface of TRNSYS simulation software with the graphical interface (left) and building parameter interface (right)

Honeybee, as part of Ladybug Tools (Ladybug Tools, 2017), is an opensource plug-in for Grasshopper, which is in turn a plug-in for Rhinoceros. Grasshopper can be described as a visual programming interface which allows for parametric design solutions. Honeybee smartly makes use of this visual programming interface by linking it to EnergyPlus, a renowned building energy simulation program (EnergyPlus, 2017). In that sense, Honeybee can be described as a tool to visually and parametrically set-up the input for an EnergyPlus calculation, allowing for a highly flexible and insightful set-up of inputs. Since Honeybee and Grasshopper are open-source software, they have large online community in which new ideas, questions and bugs are shared and solved.

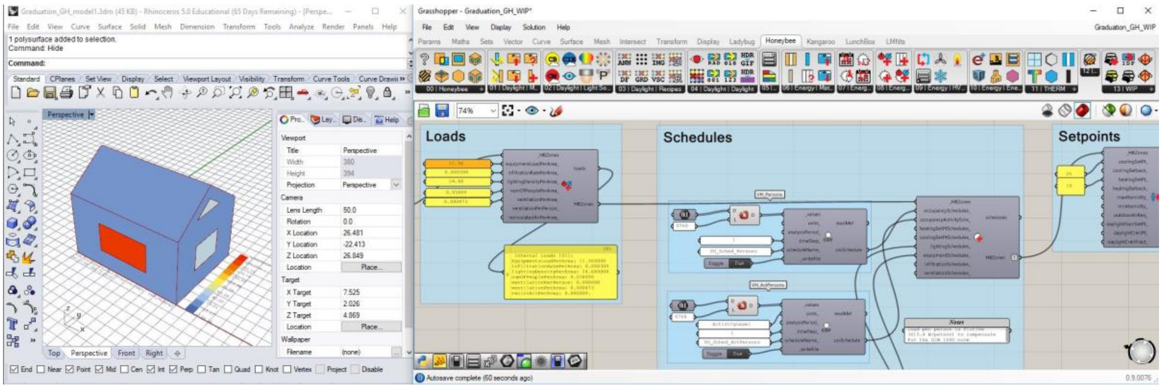


Figure 46: Honeybee interface with 3D viewport of Rhino (left) and visual programming interface in Grasshopper (right)

In short, TRNSYS allows for more complex design solutions and provides more detailed results, but the information on troubleshooting is limited and it is more complex to learn. Honeybee is insightful, allows for a quick set-up of the model and has the possibility for online troubleshooting, but the design possibilities are limited.

In favor of keeping all design and output possibilities open, the initial choice was TRNSYS. But as soon as the model became more complex, it was concluded that defining calculations and setting output parameters strongly relies on manual input surface identities. Because of this, changing geometry and its properties later would require loads of adaptation in the model for every new design. Since part of the research is doing a lot of different design studies, this was not a good prospect.

It was concluded that the slight reduction of design possibilities when using Honeybee would strongly be compensated by time saved using the parametric set-up of Honeybee. Moreover, the desired level of detail for the outputs can be provided by Honeybee as well, thus the more complex outputs of TRNSYS were unnecessary. Concluding, the final energy model is built in Honeybee and all results in this research are made using that software.

4.3 FUNCTIONALITY OF SINGLE ZONE-MODELLING

Energyplus calculates the energy balance according to the so-called zone-model. A single-zone model is used to simplify the complexity of the model and shorten calculation time. The results of a single-zone model suffice for energy-flat analysis.

The single-zone model consists of one node. For this node, all the energy flows are calculated. The boundary of the zone are the inside surfaces of the construction. This means that an energy flow always regards the flow from just inside the inside surface to the inside surface. Figure 47 clarifies this principle.

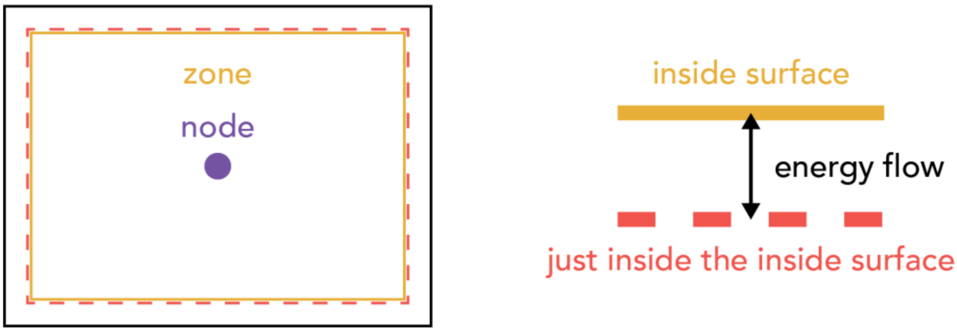


Figure 47: The energy flows in the single-zone model

An energy flow from the inside surface to just inside the inside surface is different than the energy flow from the inside surface to the outside surface. In static calculations, energy flows are commonly considered as the flow from inside to outside. The functionality of this model thus should be critically considered when analysing the results.

4.4 MODEL SET-UP & INPUT

An energy model requires an extensive amount of input parameters, ranging from design properties to analysis periods. Honeybee makes use a successive set-up flow, in which data is added to the energy simulation input file at every new module.

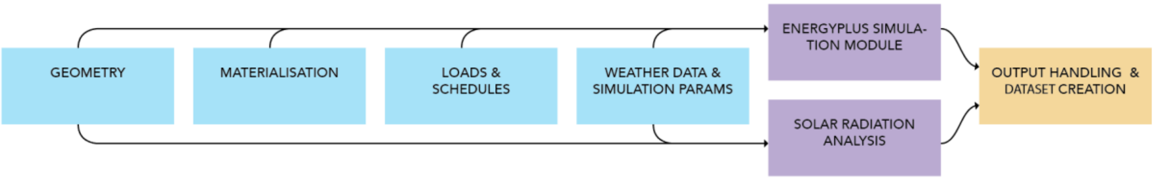


Figure 48: Honeybee model set-up: data-flow with successive modules resulting in output file

Figure 48 shows the schematic set-up of the energy model. How the simulation tool works, is extensively described in Appendix 1. The initial input of the simulation tool, which is determined by the reference design, is described in the next chapter (see *5.1.2 Properties and simulation input of the reference design*)

4.5 OUTPUT

The output of the Grasshopper Honeybee simulation is partly processed in the Grasshopper interface and partly processed in excel. In the outputs, abbreviations are used to shorten references. The results are processed in two ways. The first way is a visualization of the results in Rhino, using the native visualization tools of Grasshopper. These visuals are not clear and nice enough for final energy analysis and this report, but they are a useful means to gain quick insight in the results. The second way provides more elaborate result analysis. For this method, the results are translated into a -.csv, which is loaded into Excel and then used to analyse the results by plotting graphs and running calculations on the values. This second way is explained in Appendix 1.

4.6 CONCLUSION

In this chapter the question *"How should energy-flatness be simulated?"* is answered by choosing simulation software, describing the model set-up and the processing of the output.

The software package Grasshopper Honeybee is chosen over TRNSYS to provide the dynamic energy calculations, because it allows for quicker analysis of multiple design possibilities due to its parametric set-up. The model is set-up by a flow of information addition. Geometry is the starting point, and in the model the aspects of materialization, loads, schedules, weather and solar radiation are added. The simulation tool produces a result file that can only be handled by Grasshopper or EnergyPlus. Thus, this file is translated to a -.csv file that is read by Excel. In Excel, the final results are processed and analyzed using summarized values, graphs and key-performance indicator calculations.

The complete simulation tool is set-up in such a way, that it can be used in the future to analyse new designs and their results.

5 ENERGY MISMATCH IN THE EXISTING SITUATION

This chapter considers the current residential energy mismatch by providing the energy performance of a reference design. This design is modelled with the simulation tool as explained in *4 Simulation of energy-flatness; the energy model*.

The design and its energy performance results are used as a reference to compare the parameter studies, the early designs and the final energy-flat design to. This way, all designs are compared to the same reference and all results are created with the same tools. The first section describes how the reference design is translated to the simulation-input and the second section analyses the results of the reference.

5.1 THE REFERENCE DESIGN

A reference design is used to be able to compare the energy performance of design variants with each other and with a reference. The DGMR (2016) documented, on behalf of the *Rijksdienst voor Ondernemend Nederland*, a collection of *BENG referentiegebouwen*. It is a collection of 33 building types that are assumed to be representative for the Dutch building stock, designed to fit the new BENG regulations (see 2.4.4 EPC & BENG). All references consist of a short building description, some building construction and installation properties, and the energy performance. Per reference, three energy performance concepts are distinguished; gas, all-electric or external heat delivery. In this research, the all-electric concept is considered as is required by the scope of the research.

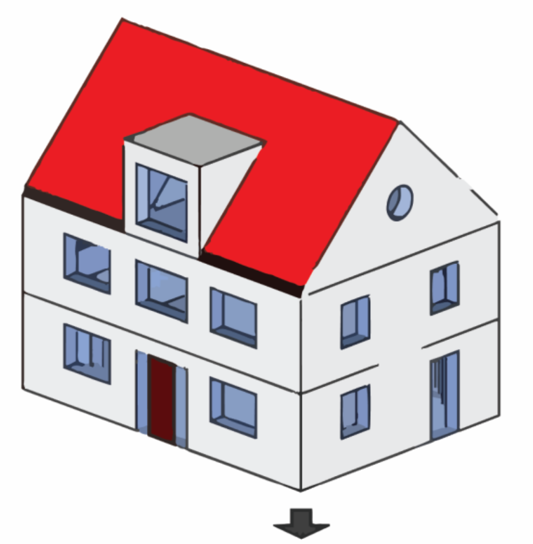


Figure 49: BENG referentiewoning Woning L vrij as previewed by (DGMR, 2016)

There are three reasons that the BENG reference case is used. First, these references are provided by the government and modelled by DGMR, which increases the validity of the energy performance. Secondly, one of the requirements of an energy-flat building is that it is energy-neutral. After all, if supply and demand are not equal in a yearly total, neither are they on every moment in the meantime. BENG buildings approach energy neutrality and thus provide a good reference. Lastly, the design should be compared to the status quo in buildings for optimal relevance. It is most probable that BENG buildings represent the modern status quo of buildings.

For this research, the *Woning L vrij* is chosen (Figure 49), which is a large, detached house. The choice for this reference is that the research aims to explore possibilities for energy-flatness design by testing out the extreme situations. The far-most opposites of the detached house in terms of autonomy are the apartment and the row-house. Both of these designs will benefit from their neighbours in terms of energy-flatness; peaks will partly be balanced out by the big number of dwellings connected to one system. The detached house purely has its own demand and its own supply, which will not be flattened out by neighbours. In that sense, making this to an energy-flat design will be the hardest and thus the most useful for this research.

5.1.1 Scope of the Referentiewoning

The *BENG referentiegebouwen do*cumentation (DGMR, 2016) does not consider all information required for an energy simulation. In other words, some aspects of the energy simulation are not within the scope of the *BENG referentiegebouwen* documentation. The following aspects are within the scope of the documentation:

- Geometry and skin
    - orientation
    - shape
    - floor, facade and roof areas
    - window ratio
    - Insulation values for all surfaces
    - g-values and sun-shading for all windows
- Linear cold-bridges
- Building installation details
    - Heating (including heat exchange)
    - Cooling
    - Domestic Hot Water
    - Ventilation
    - Lighting
    - Size and capacity of energy production installations (PV, solar collector)

This means the documentation includes no information about the energy consumption by the user nor about the amount of ventilation and lighting required. This is added separately in the energy model. All properties of the reference design are translated into input for the simulation. The input is described in the next section.

5.1.2 Properties and simulation input of the reference design

This section describes all the input for the simulation to calculate the energy-performance of the reference design. This input is the starting point for all designs in the research. All design- and parameter variant studies in this research will substantiate their deviation of parameters in relation to the reference design. In other words, all designs use the input of the reference design as described below, unless indicated otherwise.

Geometry

The building is simplified to one zone, because a multizone analysis does not match the needs of this research and would make comparison of design variants needlessly complex. The measures of the volume are according to the reference design. The usable floor area is 181 m^2 according to the documentation (DGMR, 2016).

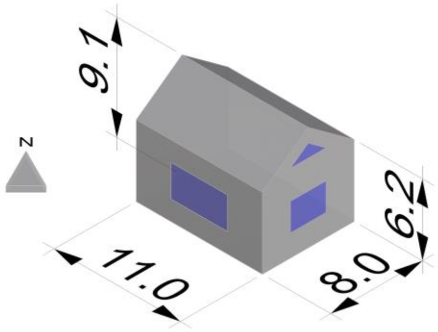


Figure 50: Measures and window configuration of the reference design as input for the energy simulation

The windows in the facade are simplified to one or two windows per facade in favour of calculation speed (see Figure 50). Since the radiation calculation is based on orientation and area, the effect of the simplification of windows on the results is negligible. The percentages of window surface are 15%, 20%, 15% and 20% for respectively the SE, SW, NW and NE facade.

Materialization

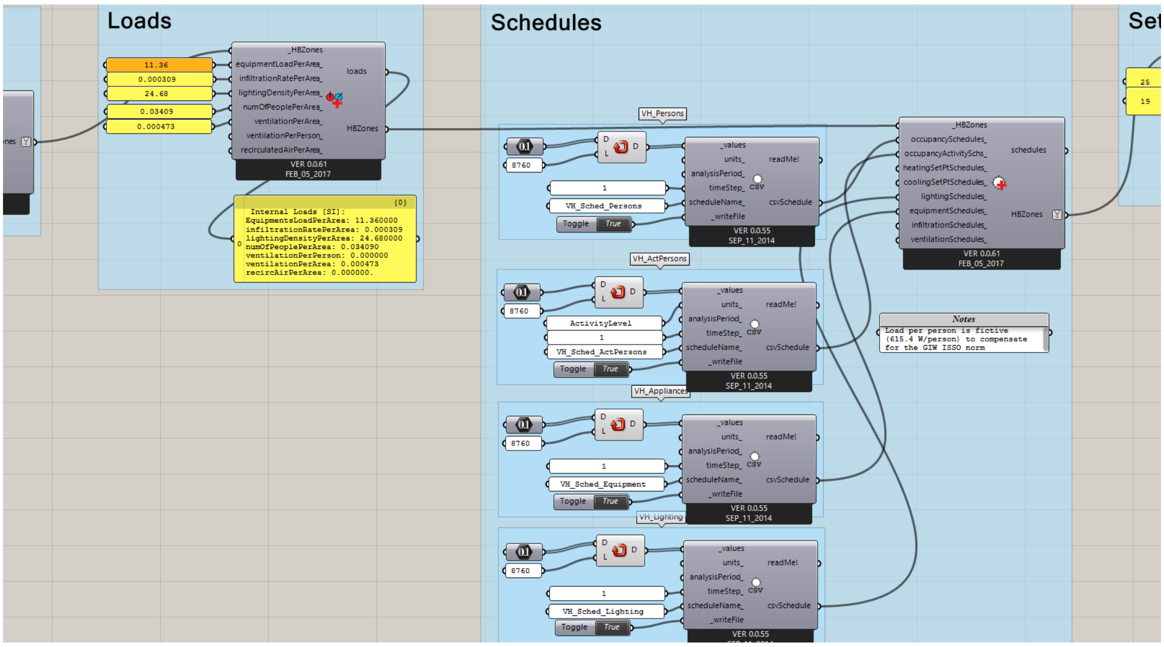
The reference design by SenterNovem only prescribes the insulation values for opaque surfaces and the U-and g-value for glass surfaces, hence neglecting the precise layers. In the simulation, all constructions are simplified to a structural layer and an insulation layer. The thicknesses of these layers are input such that the insulation values perfectly match the prescription. In Table 4, the insulation values are summed up for all building surfaces. A detailed description of construction layers and properties can be found in *12.3 Appendix 3: Properties construction elements of the reference design.*

Element	**R-value [m^2K/W]**	**g-value [-]**
Wall	7.0	-
Roof	9.0	-
Window	0.8 (U = 1.3 W/m^2K)	0.6
Floor	6.0	-

Table 4: Summarized insulation properties of the construction layers

Loads & schedules

The SenterNovem reference design prescribes the **infiltration rate**, which is 15 dm^3/sm^2. The Ag (user surface) of the reference design is 181 m^2. The Honeybee geometry is simplified to one zone, resulting in a (fictive) floor area of 88 m^2. The input for infiltration is requested in m^3/s m^2, resulting in an input value of (15*181)/(88*1000) = 0.000309 m^3/s m^2. The infiltration rate is constant, for the entire duration of the simulation



```
{0}
 Internal Loads [SI]:
EquipmentsLoadPerArea: 11.360000
infiltrationRatePerArea: 0.000309
lightingDensityPerArea: 24.680000
numOfPeoplePerArea: 0.034090
ventilationPerPerson: 0.000000
ventilationPerArea: 0.000473
recircAirPerArea: 0.000000.
```

Notes

Load per person is fictive (615.4 W/person) to compensate for the GIW ISSO norm

The **ventilation rate** is simplified to be 150 m^3/h at all times. This is based on a count of three inhabitants with a rule-of-thumb-based ventilation demand of approximately 50 m^3/h*person. Bouwbesluit 2012, article 3.29, demands a ventilation rate of 0.9 m^3/m^2 of residential area, resulting in 146 m^3/h in the reference design if one assumes that 10% of the building is non-residential area (e.g. stairs, closet). The input for ventilation is requested in m3/sm^2, resulting in an input value of 150 / (88 * 3600) = 0.00047 m^3/sm^2. The ventilation rate is constant, for the entire duration of the simulation.

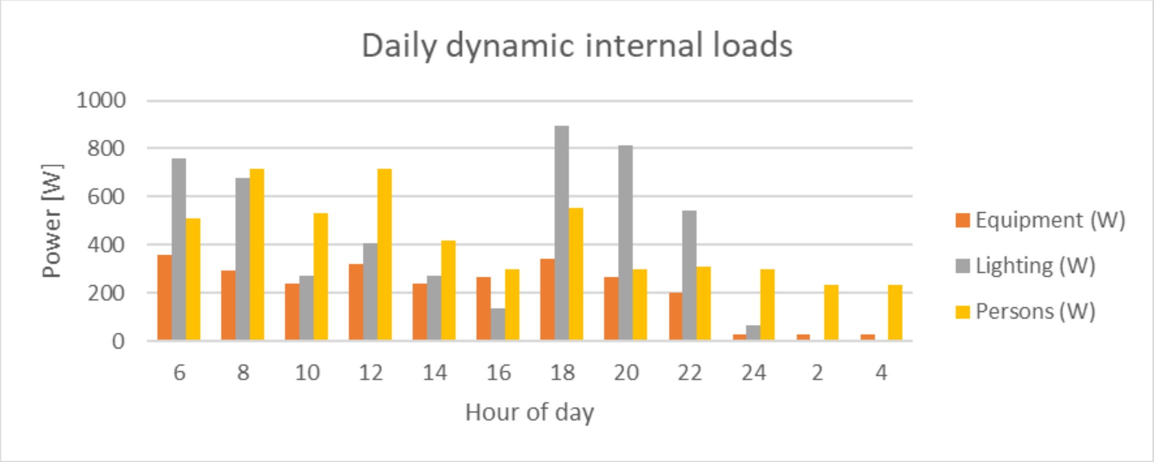


Figure 51: Daily dynamic internal loads for equipment, lighting and persons based on GIW/ISSO 2008

The internal heat gains are calculated according to the GIW/ISSO-publication 2008 (GIW, 2008, p. 62). This publication provides the loads and fractional schedules for **persons,**

equipment, and **lighting** for four main functions of a dwelling. Since the model contains just one zone, all the loads are summed up. This results in a dynamic load per internal load source for every day, as shown in Figure 51. The precise calculation and schedules can be found in Appendix 2.

N.B. the inputs in the Honeybee images in this section show different numbers because of conversion calculations.

Setpoints and weather data

The heating and cooling *setpoints* determine the boundaries of accepted indoor air temperature. In other words, a cooling setpoint of 24°C turns on the cooling demand when the temperature is about to exceed this temperature. The setpoints for heating and cooling are respectively set to 19°C and 24°C. The setpoints are constant values, for the entire duration of the simulation.

The documentation of the reference design does not state any properties concerning climate. Nevertheless, the reference design is designed as a reference for buildings in the Netherlands. Moreover, the energy-flatness is For this research weather file of Amsterdam, The Netherlands, is used. It can be openly downloaded from http://www.ladybug.tools/epwmap/ .

Solar radiation

Since the solar potential is calculated per surface, considering the orientation and angle to the ground surface, the solar potential is calculated using the geometry of the building as described in the first section.

The total solar supply potential is the sum of the solar power per surface multiplied by the share of potential per surface. For instance, if the solar power on the south surface is 500 kWh in one hour, and the potential share is 0.01, the supply is assumed to be 5 kWh in that hour. In the reference design, all surfaces have the same share. These shares are set such, that the annual total supply is equal to the annual total demand (i.e. energy-neutral).

5.2 ANALYSIS OF THE CURRENT RESIDENTIAL MISMATCH

The reference design is modelled using the simulation set-up as described in chapter 4.3. The results of the simulation are analysed in this section and will provide insights in the characteristics of the initial mismatch. The demand and supply of heating energy are analysed separately. First the demand is analysed, in which all the heat flows of the energy balance are considered in balance periods of a year, a month and a week to respectively analyse the monthly, daily and hourly energy data.

Second, the supply is analysed. This is done by first considering the total radiation potential of all surfaces separately and then translating these values to the PV-potential, the solar collector potential and the window radiation gain.

Lastly, the supply potentials are compared to the demand values. This comparison serves as the base for the energy-flat design.

5.2.1 Energy demand

Below, the results of the reference design energy simulation **REF05d** are shown. The complete energy results can be found in Appendix 4.

Totals

The total energy demand for heating is 3732 kWh, the total demand for cooling is 3675 kWh. This results in an energy demand of respectively 20,6 kWh/m^2 and 20,3 kWh/m^2 of floor area. The cooling load is relatively high, which is the result of ventilation settings as is explained in *12.1.7 Other settings.*

REF05d	**Energy gain/loss**	**Normalized**
Yearly totals	[kWh]	[kWh/m2]
Qheat	3732	20,6
Qcool	-3675	-20,3

Table 5: Overview of the annual heat and cool demand for the reference design

The energy balance contains active energy flows and passive energy flows. Active energy flows consider the heating and cooling energy that is needed to maintain the desired indoor temperature. It is energy that should be added by heating or cooling systems. Passive energy flows regard all other energy flows of the energy balance. Figure 52 shows the yearly totals of all elements of the energy balance. From the figure can be seen that the share of heating compared to passive gains is relatively low, namely 8%. The cooling has approximately the same share. Conduction through both glazing and opaque surfaces is the biggest cause of heat losses, followed by ventilation.

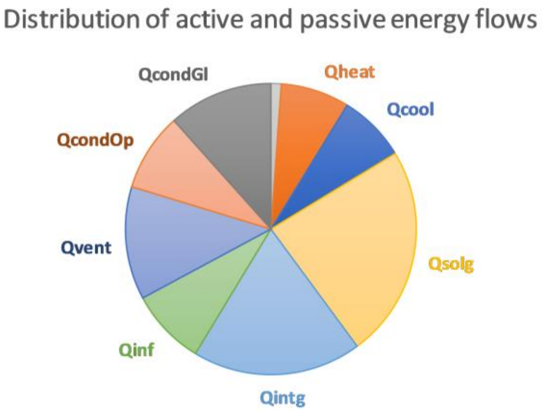


Figure 52: Distribution of active and passive energy flows of the reference design; the share of heating (Qheat) and cooling (Qcool) is low compared to the passive flows

Yearly demand analysis

The impact of the seasons can be seen on a monthly chart (Figure 53). This chart shows all the elements of the energy balance as clustered columns, the total heating and cooling required as areas and the outdoor and indoor temperatures as red lines.

Heating and cooling

The heating values (*Qheat*) have high peaks in winter and become nearly zero from April to September. The cooling loads (*Qcool*) are approximately equal and have a peak in July.

Temperatures

The indoor temperature (*Tair*) ranges from 19°C to 25°C, in line with the temperature setpoints, and follows a curvature similar to the outdoor temperature (*TdryBulb*), but mitigated. The *TdryBulb* monthly averages range from 3.9° in February to 17°C in August. The relation of these curves obviously shows the effectiveness of higher cooling setpoints and lower heating setpoints.

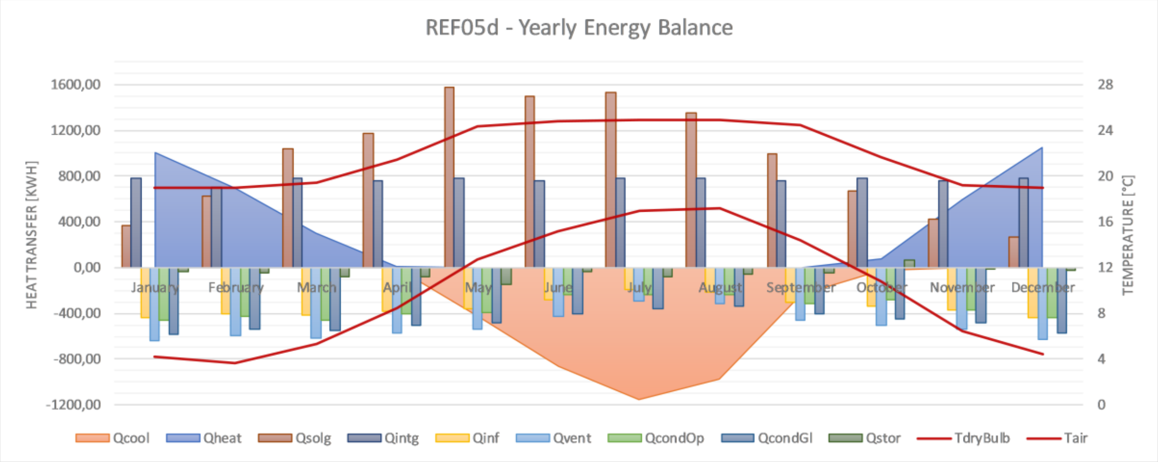


Figure 53: Yearly Energy Balance of the reference design, with monthly averages

Heat gains

The solar gain (*Qsolg*) shows a clean curvature with a peak in the beginning of summer and a valley in December. The difference between the lowest value and highest value is big; the monthly solar gain in May (1572 kWh) is almost six times as much as the solar gain in December (268 kWh).

The sum of internal gains by persons, equipment and lighting (*Qintg*) is constant, only varying based on the length of the month. This is in line with the set input for internal gains according to the GIW/ISSO documentation which provides an all-year repeating daily schedule.

Heat losses

All heat losses show their highest peaks in winter (i.e. January, December) and gradually decrease towards mid-summer, with the lowest values in July and August. The heat losses by ventilation (Qvent) are highest, followed by the heat losses by transmission through glazing (QcondGl). In summer, the losses through glazing in some cases is equal or higher than the losses by ventilation. Infiltration losses (Qinf) and losses through opaque surfaces (QcondOp) are similar.

Monthly demand analysis

February

Zooming in to daily values by evaluating a single month, gives insight in the relation of energy demand and climate. The chart (Figure 54) shows all the components of the energy balance as stacked columns in the month of February, giving more insight in the total heating gains and losses.

The indoor temperature is almost constantly 19°C, meaning there never is a surplus of heat gains. This can also be seen from the fact that there is always a positive value for active heating.

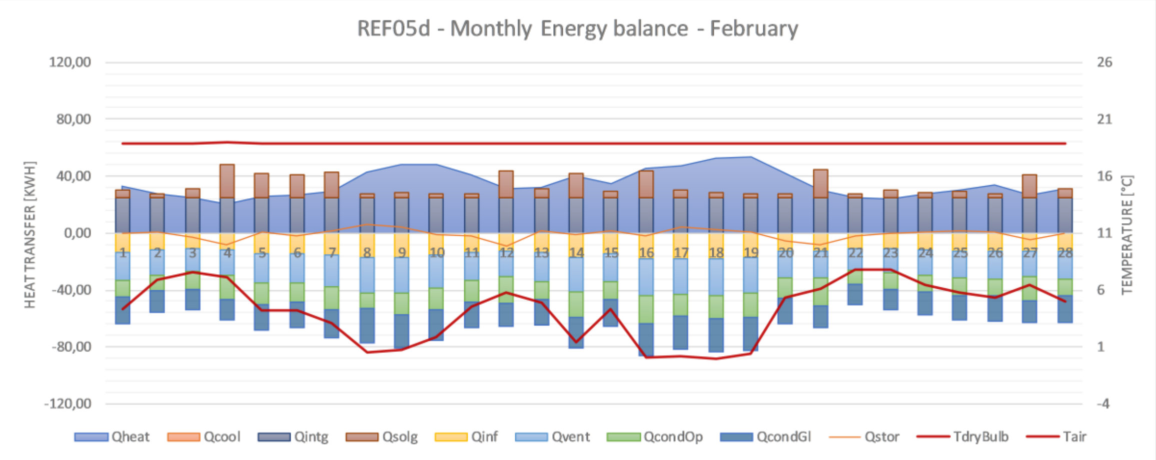


Figure 54: Monthly Energy Balance of the month of February, showing daily values as stacked columns

The total of heat losses follows the line of the outside temperature approximately. There is no particular component in the balance reacting the heaviest on changes in the outside temperature, although the ventilation losses and losses through glazing become significantly higher at a lower outdoor temperature. The transmission through walls is higher at days of high solar gain, meaning that a part of the solar gain is directly flowing out of the zone, which is a logical result of the zone-type modelling; the solar radiation energy is directly absorbed by the walls, hence flowing from the surface out of the zone (see also *4.3 Functionality of single zone-modelling*)

Lastly, the heating is mostly determined by the outside temperature and the solar gain. A lower outside temperature means a higher heating value, unless there is a high solar gain.

August

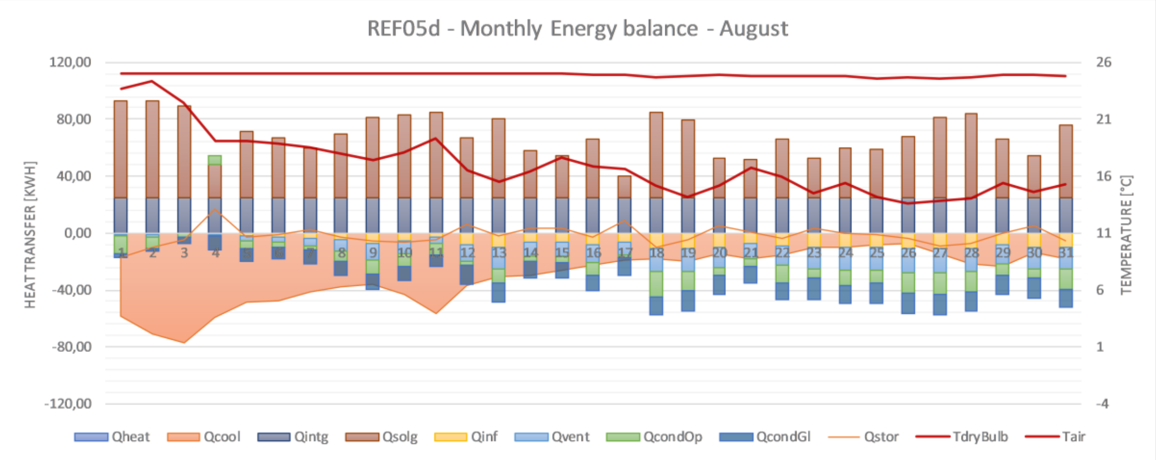


Figure 55: Monthly Energy Balance of the month of August, showing daily values as stacked columns

Figure 55 shows the monthly energy balance for August. The indoor temperature now stays around 25°C. Active cooling is constantly required, though there is a peak at the beginning of the month with outdoor temperatures >22°C and high solar gain. The graph shows that cooling gets lower as passive heat losses increase. In other words, the building needs to dispose its heat. Like the month of February, the losses show a relation with the outside temperature, meaning a higher outside temperature is a lower passive heat loss. This relation is also influenced by the solar gain.

Daily demand analysis

Hourly values provide information on the direct relation between all the components of the energy balance, for they are only averaged on the time-step of one hour which induces little changes in climatic context. Figure 56 shows the hourly values of one week starting on the 21st of February.

A recurring daily pattern is shown, with solar gains during the middle of the day and outdoor temperature drops during the night. During the night, the heating demand is highest.

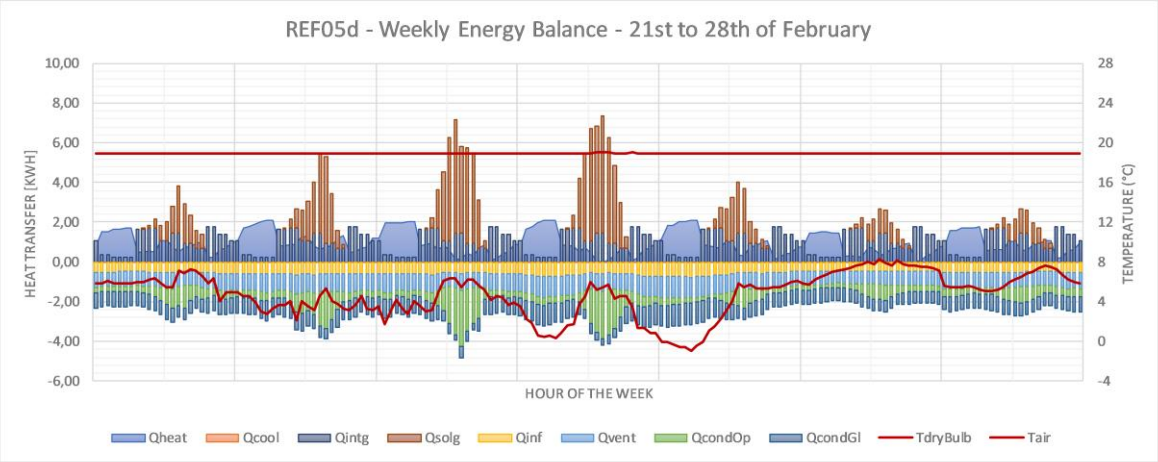


Figure 56: Weekly Energy Balance of February 21st-28th showing hourly values as stacked columns

The transmission through opaque surfaces (QcondOP) is higher during day time when the ΔT is lower and solar radiation is higher, which is the logical result of the type of zone modelling; energy leaving the zone by being ‘absorbed’ by the thermal mass is considered conduction through opaque surfaces. The solar radiation heats up the indoor surface of the construction, resulting in a higher surface temperature and thus a higher heat flow.

Conclusion

The demand side of the reference design is analysed. The total heating and total cooling load are almost equal, and their share compared to the passive energy flows is low. On a yearly scale, the demand is characterized by high heating loads in winter when outdoor temperature is low and solar radiation is little. In summer, high cooling loads occur as a result of high solar radiation and the decreased ability of the building to dispose its superfluous heat.

On the monthly chart, the effect of the outdoor temperature on all ΔT dependent energy flows becomes clear. The share of energy losses by ventilation and transmission is the biggest. Opaque surfaces absorb solar radiation by using their thermal mass, as a result this value increases as solar radiation increases. In hot months, the building has the need to dispose superfluous heat at nights. When the night temperature stays high, this results in a cooling load during daytime. The weekly chart shows that peak heating loads occur at night.

5.2.2 Energy supply

Below, the results of the reference design energy simulation **REF05d** are shown. The total energy results can be found in Appendix 4.

Total solar radiation potential

The table below shows the solar potential per surface of the reference design. The surfaces are named by their orientation (e.g. **NE**90) and their vertical angle to the ground surface (e.g. NE**90**). The values are the sum of the solar power (kWh/m^2), corrected by the incident angle and multiplied by the area of each surface, resulting in the total solar radiation potential of the building per year.

Surface	Surface	Solar potential [kWh]
Rad_SE90	Vertical south-east surface	44030
Rad_NW90	Vertical north-west surface	24682
Rad_NE45	Slanted north-east surface	37393
Rad_SW45	Slanted south-west surface	58373
Rad_SW90	Vertical south-west surface	50899
Rad_NE90	Vertical north-east surface	26656
RadTot		**259786 kWh**

The total radiation potential is 259786 kWh/year for the total of all external building surfaces. The lowest solar potential is on the north-east facade (26656 kWh) and the highest potential is on the south-west roof surface (58373 kWh).

Yearly solar supply potential analysis

The monthly values show the differences in solar potential over the seasons. Figure 57 shows how the potential is build up over the year, looking at the total values per month per surface.

All surfaces have higher solar radiation potential in summer than in winter. More specifically, the roof surfaces show the biggest differences between summer and winter. All surfaces show a similar pattern, characterized by a gradual increase from winter to summer and a similar gradual decrease from summer to winter.

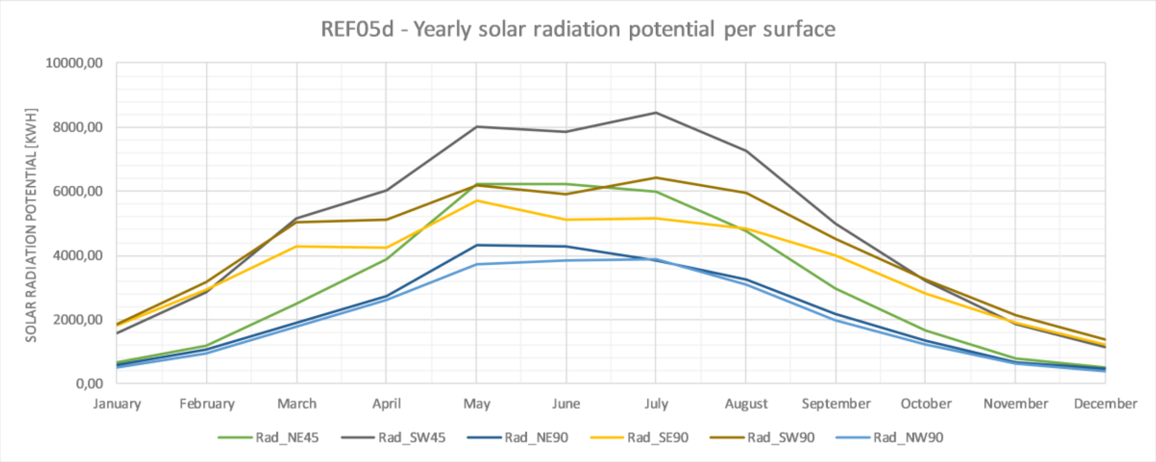


Figure 57: Yearly solar radiation potential per surface of the reference design in kWh

The total radiation potential is the highest in the months of May (36801 kWh), June (35806 kWh) and July (36489 kWh) and the lowest in December (5427 kWh). The total potential in summer is approximately 6.5 times higher than in winter. From March till September, the south-west roof has the highest potential. From October till February, the south-west facade has a slightly higher potential than the SW-roof. Moreover, the north-west facade, north-east facade and north-east roof surface have a significantly lower potential in winter than the south-east facade, south-west facade and south-west roof.

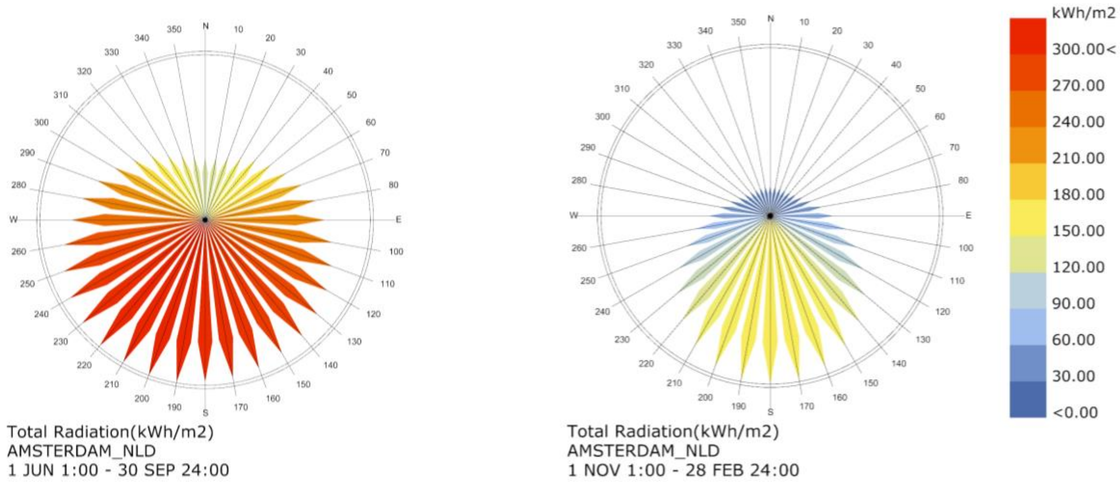


Figure 58: Radiation roses for summer (left) and winter (right) for the Amsterdam latitude

The low energy supply potentials in winter and the increasing importance of northern values in the summer are the result of increased solar radiation power and the extended solar path during summer. Figure 58 shows the radiation roses for Amsterdam, in which the difference between winter and summer becomes clear.

Monthly solar supply potential analysis

The monthly values show the change in solar radiation per day. Both the month of February and of August are considered in respectively Figure 59 and Figure 60.

The graph shows a 'base solar potential' that is present on any day, created by the diffuse light, which is 20 to 40 kWh per day per surface, resulting in a total of approximately 200 kWh per day.

A difference can be seen between sunny days and cloudy days, characterized by high solar potential values on some surfaces. On sunny days, the highest peaks of solar potential range from 220 to 270 kWh for the south-west facade.

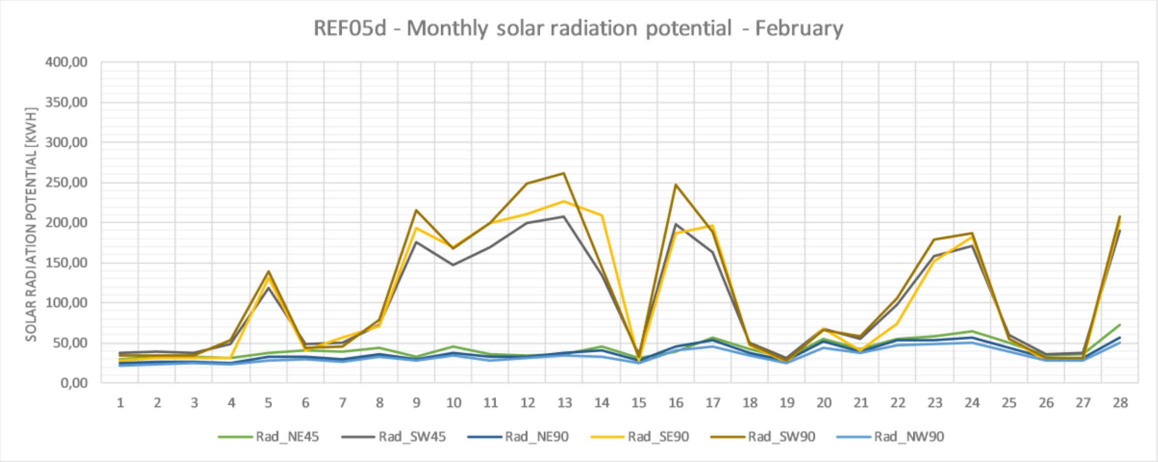


Figure 59: Monthly solar radiation potential per surface of the reference design in kWh of the month of February

The north-east roof, north-east facade and north-west facade get no direct sunlight resulting in a potential that is constantly equal to the base potential. On sunny days, the south-west facade almost always has the highest potential, sometimes slightly less than the south-east facade. This probably has to do with a difference in amount of sunlight in the morning and afternoon. The south-west roof shows a similar profile to the south-west facade, but always with slightly lower potential.

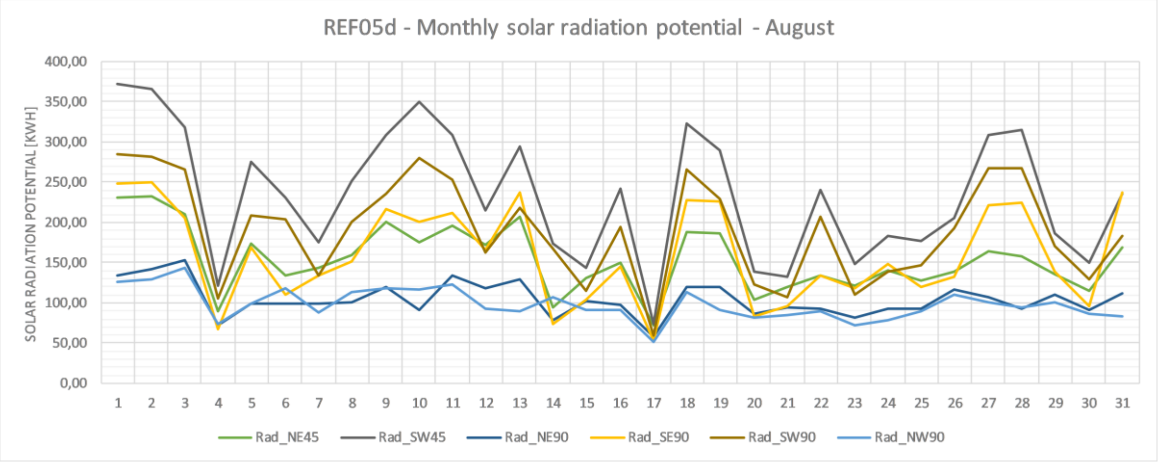


Figure 60: Monthly solar radiation potential per surface of the reference design in kWh of the month of August

The base potential is 50 to 90 kWh and can only be derived from the cloudiest day (17th of August). The highest peaks range from 330 to 370 kWh. Both the base potential and peak potential are thus approximately 1.5 to 2 times higher than in February.

The south-west roof always has the highest solar potential. The north-east and north-west facades almost always catch the least solar radiation, resulting in a lower potential that is slightly affected by the cloudiness. Sporadically, the solar potential of the north-west facade is higher than the south-east facade, probably caused by a bigger of amount of sunlight in the afternoon and evening.

Lastly, the daily differences and the surface mutual differences are more whimsy than in February.

Daily solar supply potential analysis

The daily patterns per surface provide information on the potential related to the time of day. The hourly solar radiation potentials of a typical sunny day in February and in June are shown below.

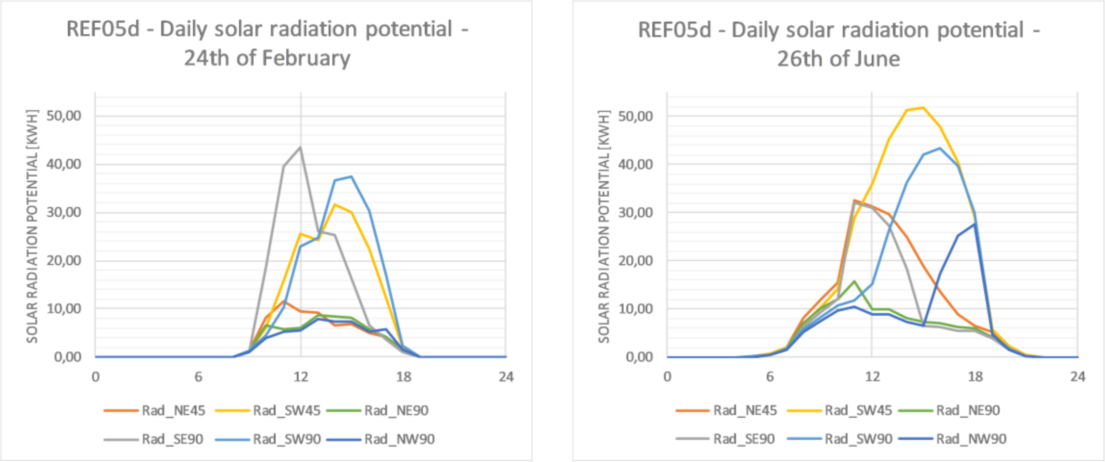


Figure 61: Daily solar radiation potential of the 24th of February and the 26th of June per surface of the reference design

In February, the southern facades have the highest potential, with the south-eastern facade having its peak in the morning and the south-western facade its peak in the afternoon. In June the timing of facade peaks is similar, though the potential on west-oriented surfaces is higher and the south-west roof surface has the highest potential of all surfaces.

Moreover, in February only the southern facades and roof surface have an increased potential by the direct sunlight. In June, all gain benefit from direct sunlight because of longer days.

Conclusion

The solar supply potential is studied for all surfaces of the reference design. The solar potential is summer is 6.5 times as high as in winter. Moreover, in summer the potential of northern facades and the south-west roof surface become significantly larger due to an extended solar path and a larger solar altitude.

In winter, the supply is strongly dependent on the alternation of cloudy days and sunny days. There is always a baseload from diffuse light of around 20-40 kWh per day per surface. In summer, there are more daily differences in supply and the differences per surface are bigger.

5.2.3 The mismatch

The previous two sections showed the characteristics of the demand and the supply profile. To gain insight in the mismatch, which is essential for energy-flatness, the demand and supply are compared to each other.

The energy-flatness aims for zero difference between demand and supply at any time. Some assumptions are made to translate the elaborate demand and supply analysis to two demand (i.e. heating and cooling demand) profiles and one supply profile. This way, a clear analysis of energy-flatness can be made.

1. Heating and cooling a building are generated differently. Combining both heating and cooling in a single demand value would result in a too simplified demand profile. A separate cooling profile and a separate heating profile are considered, and both separately compared to the supply profile. Only Q_{heat} and Q_{cool}, as described in the previous section, are considered for they represent the heating and cooling energy needed. All other passive gains (e.g. Q_{int}, Q_{solg}) and passive losses (e.g. Q_{inf}) are neglected because they are implicitly included in the resulting heating and cooling demand.

2. The supply-profile as described in the previous section considers the total solar potential. Not all solar potential can be used as effective energy to fulfil the demand. Moreover, having a much higher value for supply than demand, will inevitably result in a mismatch. In this comparison, the total solar potential is multiplied by 0.03 to result in the supply profile, which is an approximation based on the following considerations:
    a. the supply should roughly equal out the demand to make energy-neutrality possible. Energy-neutrality is a boundary condition for energy-flatness. For the reference design simulation (REF05d, see appendix 4), the total demand (7407 kWh) divided by the total solar potential (259786 kWh) = 2.9%. This is rounded to 3%.
    b. 3% of the solar potential also suggests the following in-practice situation:
        i. Covering 15% of each building surface with PV panels
        ii. And assuming an efficiency of 20% of all PV panels to convert solar power to electrical energy
        iii. And assuming an efficiency of 100% to convert the electricity to usable heat or cooling. N.B., the electricity system will have losses, but a heat pump could operate with a COP > 1. This will be regarded later.

    The above is a simplification; in a real situation, efficiencies would differ hourly because of PV temperatures, outside temperatures, differing COP’s and more. This will be discussed in 7.4.4 *Building services & translation to electricity flatness*, where a translation is made to a real-life situation. For the comparison of the reference design, this constant factor is assumed to be sufficient for a first approximation of the mismatch.

N.B.: the profiles now represent different types of energy: heating, cooling, and potential electricity output from solar radiation. The conversion of the heating and cooling demand to electricity use will be done later.

The annual mismatch is summarized with the values of total demand, supply and the key performance indicators.

Subject	Specification	Value
Heat	Total annual heating demand	3732.5 kWh
Cool	Total annual cooling demand	3675.1 kWh
Supply	Total annual supply potential	7793.6 kWh
KPI 1 - heat	Total mismatch for heating	-3323.6 kWh
KPI 1 - cool	Total mismatch for cooling	-1292.8 kWh
KPI 1 - supply	Total supply surplus	4902.3 kWh
KPI 2 - heat	Maximum heat shortage peak	-3.3 kW
KPI 2 - cool	Maximum cool shortage peak	-4.6 kW
KPI 2 - supply	Maximum supply surplus peak	5.0 kW
KPI 3	Maximum cumulative mismatch	2766.3 kWh

From the table above is derived that the reference design is nearly energy-neutral, assuming these supply potentials. The total surplus is almost equal to the total demand (i.e. heat plus cool). The total mismatch is 9518.7, which is 128% of the total demand and 63% of the total flow of energy (i.e. supply plus heat plus cool), which should be completely compensated to achieve energy-flatness.

Yearly mismatch analysis

The yearly mismatch provides information on the seasonal mismatch of supply and demand. Figure 62 shows the demand and supply profile, which provides insight on the timing of the mismatch. Figure 63 shows the cumulative mismatch, which provides insight in the development of the mismatch; the steeper profile means a quicker increasing mismatch.

Figure 62 shows that the demand profile shows a ‘’W’’-pattern, with high heating demand in mid-winter and high cooling demand mid-summer, and lower demands in autumn and spring. The supply profile shows a hill-pattern, raising fluently from low supply in winter to high supply in summer. In winter, the supply is much lower than the heating demand. In summer the supply approximately equals the cooling demand, though the demand has a clear peak in July whilst the supply has a more fluent ‘peak’ from May till August. From March till June and from September till October there is a clear surplus. In October, both heating and cooling loads occur.

From Figure 63 is derived that the summer is relatively energy-flat. In April there is a large supply surplus, whilst the biggest shortage occurs in December.

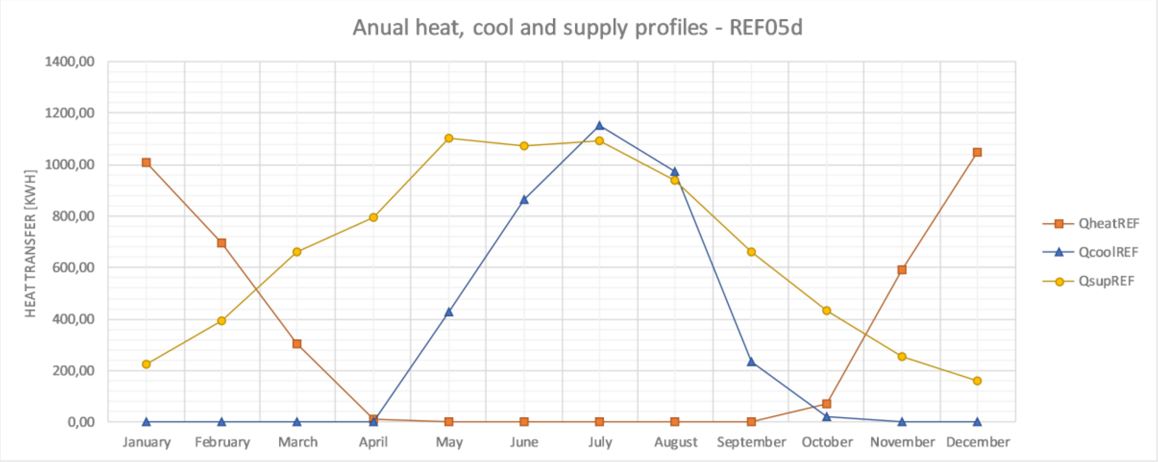


Figure 62: Annual heat, cool and supply profiles and their mismatch

In terms of energy-flatness, it is beneficial to decrease the demand profile in winter. Moreover, the energy supply in spring and autumn should be decreased or shifted. Another option is to increase the demand, preferably in such a way that it compensates the shortage of the winter. The summer is approximately flat and merely requires fine-tuning.

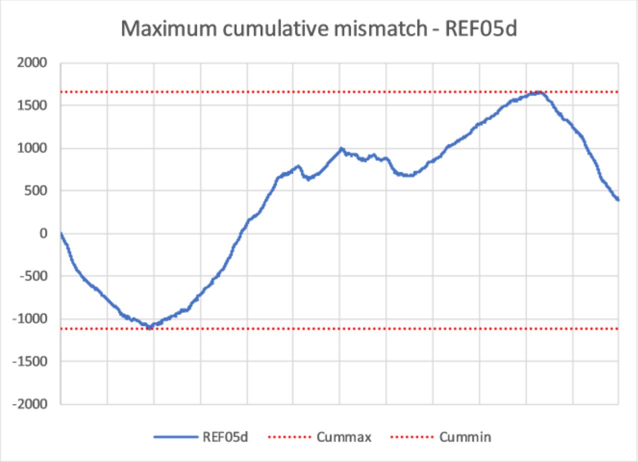


Figure 63: The cumulative mismatch of supply and demand shows the development of the mismatch over the year

Monthly mismatch analysis

The monthly mismatch shows how the mismatch differs per day. The month October, which has both a cooling and a heating load, and the month December, which has the biggest mismatch, are respectively shown in Figure 64 and Figure 65.

In October, the cooling load occurs in the beginning of the month. The first heating load starts two weeks later. October 25 and October 30 show a heating shortage. It proves that the large supply surplus that is suggested by the annual chart (Figure 62), does not mean that no shortage occurs.

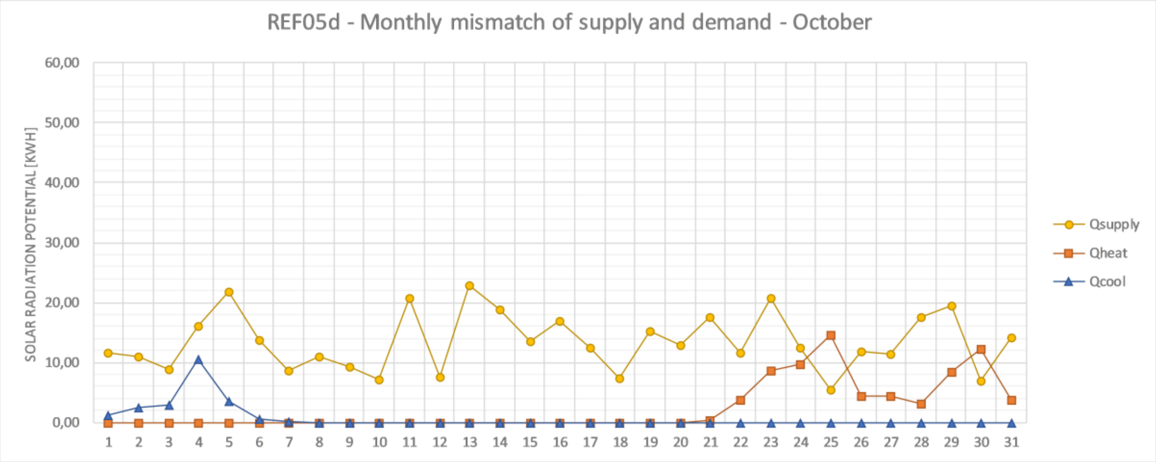


Figure 64: The monthly mismatch in October

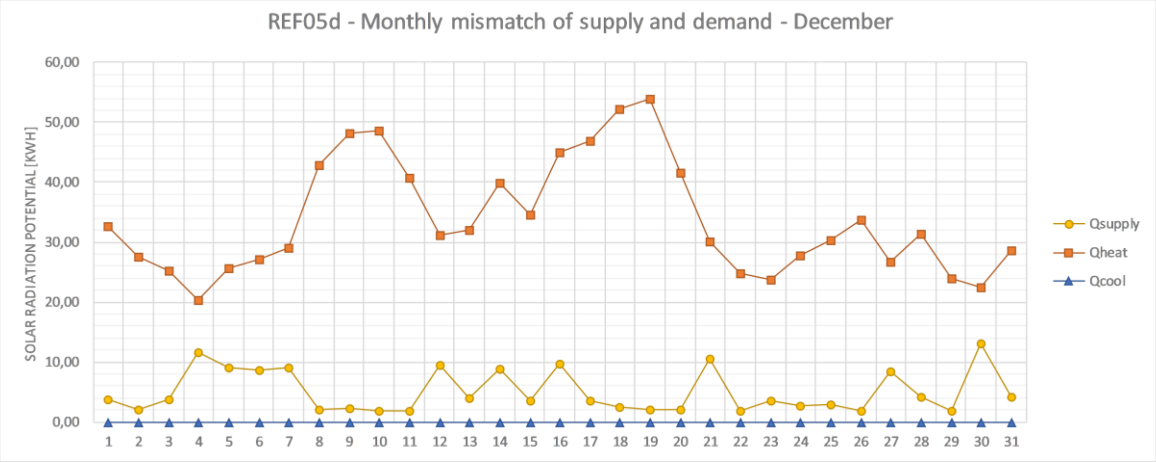


Figure 65: The monthly mismatch in December

In December, the supply is rather low and is never higher than 15 kWh per hour. Roughly half the month has a supply of 3 kWh per day. This is low compared to the demand, ranging from 20 to 55 kWh per day. Moreover, the demand in some cases is a mirrored profile of the supply; when demand is increases the supply decreases and vice versa. This might be the result of warmer days (i.e. lower heating load) occurring when the sun shines (i.e. more supply). This is not occurring every day.

For both months, the daily mismatch is high, though the size of the mismatch changes greatly from day to day. In terms of energy-flatness, it can be concluded that daily differences are high for both energy shortage as for energy surplus. To achieve energy-flatness, supply and demand should be predicted and adapted to each other. In October, this would mean reducing the supply almost to zero. In December, either the supply should be greatly increased, or the demand should be greatly reduced.

Weekly mismatch analysis

The weekly mismatch shows the differences between day and night and the detailed differences between one day and the next. In Figure 66 the weekly mismatch of the 21st till the 28th of February is shown.

The demand profile shows a clear recurring pattern, with a high peak in the end of the night. During noon the profile has a dip an in the evening it rises again. The daily differences are limited within this time frame of one week.

The supply profile shows a clear peak every day, starting around 10AM and lasting until 6PM. The size of the peak differs greatly per day. The smallest peaks can be seen at 26th and 27th of February, which probably represent the 'base load'.

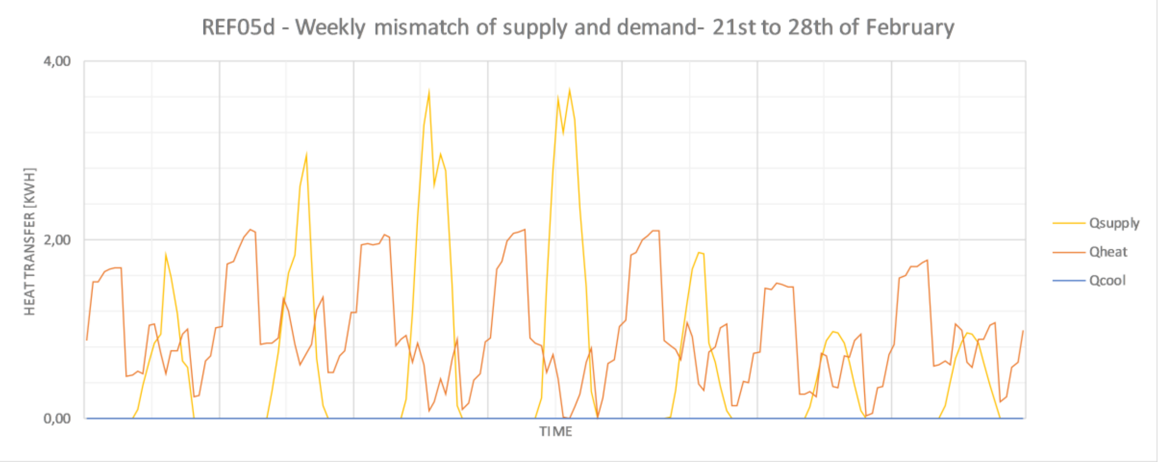


Figure 66: The weekly mismatch of the 21st till 28th of February

For energy-flatness, one of the greatest challenges is the complete absence of supply in the night. Moreover, high peaks of supply most often go accompanied by lowered heating demands as a result of passive solar heating, resulting in an energy surplus, even in winter. It would be desired to use the daily surplus to compensate for the nightly shortage. Nevertheless, days without energy surplus occur as well and should be considered.

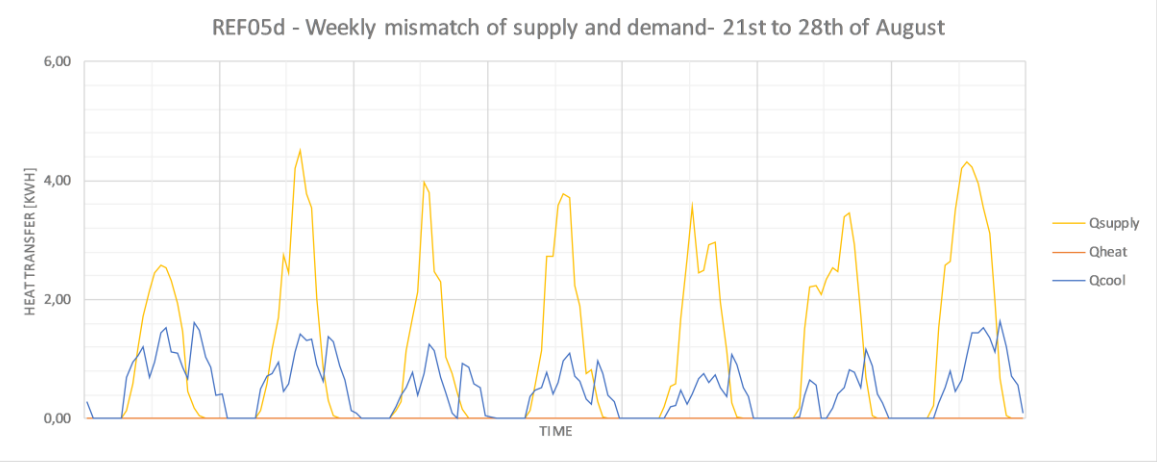


Figure 67: The weekly mismatch of the 21st till 28th of August

Figure 67 shows that in summer, the demand profile matches the supply profile approximately. Demand occurs between 6 am and 12 pm, supply occurs from 6 am till 10pm, resulting in a small shortage every day between 10 pm and 12 pm. Moreover, there is a daily surplus between 10am and 6pm, because the supply is higher than the cooling demand. The cooling demand is almost every day represented by three successive peaks, with dips in between. These peaks are partly caused by the internal gains; they occur based on a repetitive schedule as explained in *12.1.3 Loads & schedules*.

5.3 CONCLUSIONS

The energy demand, supply and their mutual mismatch of the reference design are analysed by using the output of the dynamic simulation model. The reference design is based on the SenterNovem Referentiewoning (DGMR, 2016) and represents a detached villa. This reference design only considers building geometry, constructions and building installations.

The mismatch of the reference design is studied by analysing the results generated with the energy-flatness simulation. Three profiles are studied to determine the mismatch; the heating profile, the cooling profile and the supply profile. The demand is characterized by a high heating peak in winter and a high cooling peak in summer. Ventilation and transmission through glazed surfaces are the biggest energy losing flows in winter. In summer, high nocturnal outdoor temperatures result in the disability to dispose superfluous heat and results in a cooling load at daytime. The solar potential is extremely high compared to the demand. Supply levels are very whimsy can differ a lot from day to day. The daily supply profile is characterized by a single 'hill', which always has a peak around 2 PM. Southern facades have the highest potential in winter, whilst in summer the northern facades and south roof surface become more important due to longer days and higher solar altitude.

For the mismatch in the reference design, the following conclusions can be drawn.

- Considering the seasonal mismatch, there is an energy shortage in winter, a supply surplus in autumn and spring, and an approximate match of supply and cooling demand in the late summer.
- Looking at the monthly balance period, the mismatch differs a lot from day to day. This is the result of all loads being heavily subject to climate conditions. Creating energy-flatness can only be done if the loads can be predicted or if the loads can be made more or flexible.
- Summer days are characterised by a cooling load occurring during daytime. This matches the supply potential in terms of timing, although the size and type of energy of the cooling load and the supply differ.
- Winter days are characterised by a heating load occurring from the beginning of the evening to the early morning. This results in a supply surplus at daytime and a heating shortage at night-time. For energy-flatness, there is a need to shift this load.

From this chapter is derived that there is a need to adapt all the three energy flows; heating, cooling and supply. The adaptations should be found in both shifting, increasing, decreasing and flattening the profiles. In the next chapter, building parameters are simulated to study their effect on the energy flows.

6 EFFECTS OF PARAMETER CHANGES ON THE MISMATCH

For every new building design, there are thousands of design possibilities, which will result in different aesthetics and different energy performances. This inherently means that there is no way to check all possible designs and that therefore there is a need to generalize the design principles of a building that affect the energy performance.

This chapter describes the parameter study that is done to explore the effects of architectural parameters on the energy-flatness of a building. Nine parameters are studied and compared to the reference as described in *5.2 Analysis of the current residential mismatch*. One parameter affects both supply and demand, seven parameters affect the demand profiles and one parameter only affects supply.

All design parameters are quantitative, linear parameters, in favour of the scalability and the applicability of their effects on all future designs. Figure 68 shows the nine parameters that are studied.

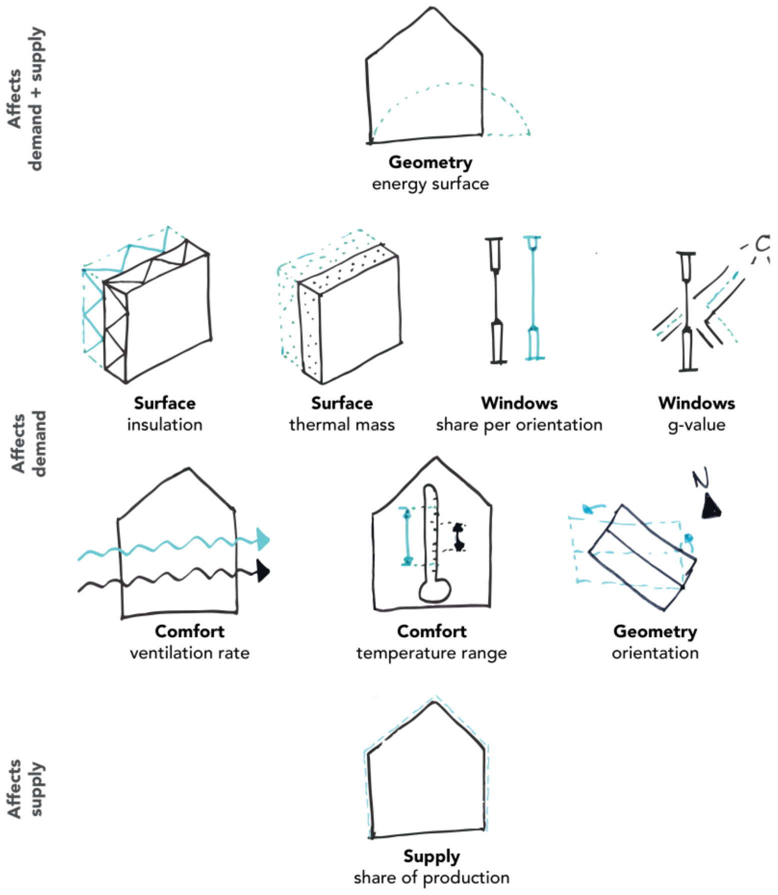


Figure 68: the nine parameters that are studied on their effect energy-flatness

The parameter study variables are chosen such that, for every parameter, the lowest and highest value are as broad as possible (to show the effects more clearly), though within reasonable limits. Moreover, all other building properties are constant relative to the reference, unless indicated otherwise.

In the next section, every parameter study is explained and analysed in more detail. For every parameter study, some short background information is given. Then is explained what the changes for the parameters are and why they are chosen. Next, the results are provided in graphs and text, which is then interpreted. Then, a conclusion is given that answers the questions of what the most energy-flat solution would be for that specific parameter and if or how it should be achieved in architecture.

The complete overview of input and results in a grid view of all the parameter studies can be found in Appendix 4.

6.1 GEOMETRY: ENERGY LOSING SURFACE

6.1.1 Background

This parameter analyses the effect of a change in energy-losing surface, whilst keeping the usable floor area constant.

The ratio between the building skin and the usable floor area influences the energy performance. Some of the elements of the energy balance are influenced by building skin surface area. The smaller the surface, the less the energy transfer will be. However, a building always requires a minimum amount of floor surface. Also, the shape of a building (including the skin/floor-ratio) is highly subject to architectural design.

*The abbreviation of this variant is **GeoSrf**, which is used as name for the simulations.*

6.1.2 Parameter change

Changing the building skin surface area is impossible without changing the shape of a building. Inevitably, some parameters and building properties will change with the change of shape. Where possible, other parameters are kept constant. The following considerations are made:

- the glass surface is kept constant at the same area in square meters per surface as in the reference.
- the roof angle is kept constant, except from variant A, in which a flat roof is required to achieve the lower building skin surface.
- none of the other energy-influencing parameters are scaled with the building volume. For example, the ventilation air change rate is not constant (which would induce an increase in air flow when the volume increases), but the total amount of m^3/h is constant.
- an evolutionary solver (Genome, Grasshopper) is used to get the geometry, such that the building skin surface area is as required and the usable floor area is constant.

- The parameters differ a factor 1.2 from each other. The reference is variant B, because it is not possible to achieve a shape that has less than 83% of the original building skin surface area, considering a minimum floor height and constant floor area.

	unit	GeoSrf_A	REF05d	GeoSrf_C	GeoSrf_D	GeoSrf_E
Parameter change						
Building skin surface area	m^2	306.6	367.9	441.5	529.8	652.7
Relative change	%	83.33 %	100.0 %	120.0 %	144.0 %	172.8 %
Inevitable side changes						
Volume	m^3	512.6	674.1	831.6	771.7	1146.6
Thermal mass	10^{6}* J/K	96.0	110	120	130	160

Figure 69 shows the geometry of the four variants and the reference building. The change in building volume, the consistent roof angle and the constant window area per surface becomes extra clear in these images.

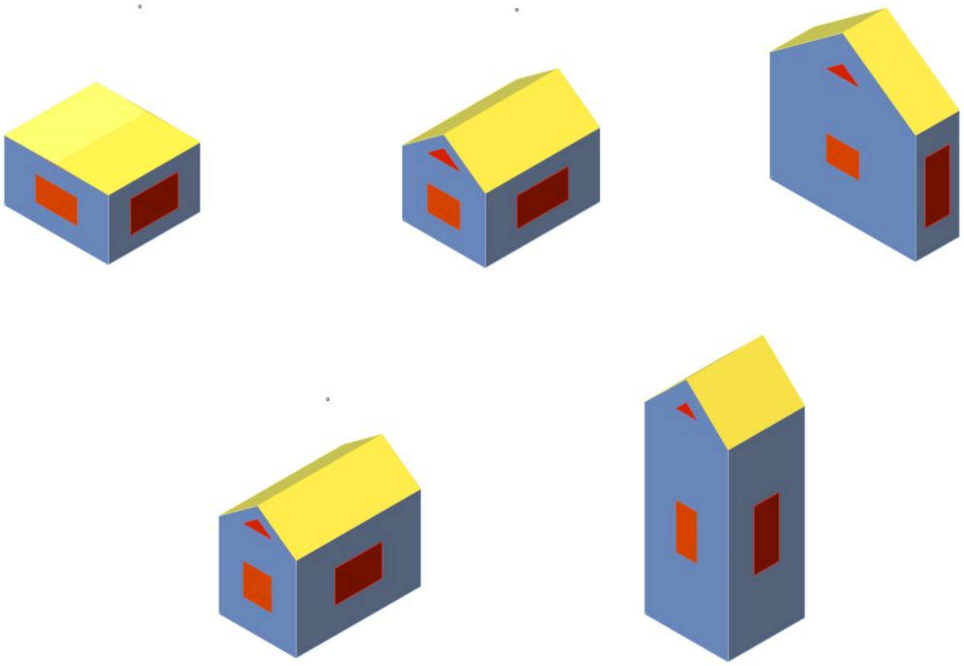
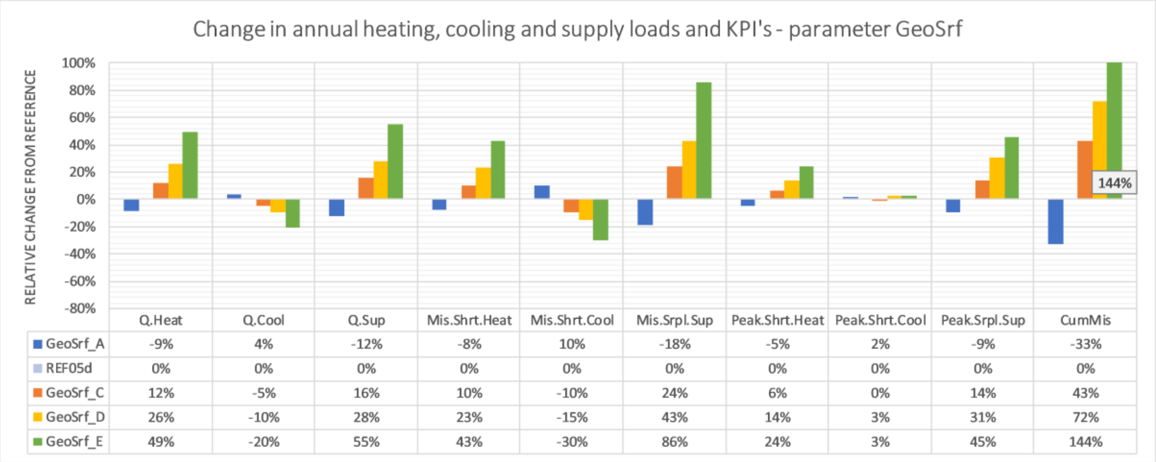


Figure 69: The geometry of variant A (top left) to E (bottom right) of the parameter study for building skin surface area

6.1.3 Results

Figure 70 shows the effect of changing the building skin surface area on the heating load, the cooling load and the performance indicators. It shows that changing the building skin surface results in a similar pattern for almost all KPI’s; the mismatch becomes bigger as the building skin surface increases. The effect is inversed for the cooling load and the mismatch by cooling. For the maximum shortage in cooling, the effects are very small.

Important to notice, is that the effect on the supply is bigger than the effect on the heating and cooling loads. This parameter study aims to analyse the effect on a change in energy-losing surface, but the effect on supply is bigger than on demand.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
GeoSrf_A	-9%	4%	-12%	-8%	10%	-18%	-5%	2%	-9%	-33%
REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
GeoSrf_C	12%	-5%	16%	10%	-10%	24%	6%	0%	14%	43%
GeoSrf_D	26%	-10%	28%	23%	-15%	43%	14%	3%	31%	72%
GeoSrf_E	49%	-20%	55%	43%	-30%	86%	24%	3%	45%	144%

Figure 70: The effect of changing the building skin area on the heat, cool and supply flows and the performance indicators

The monthly heating and cooling loads, see Figure 71, show an increase of heating loads and a decrease of cooling loads when increasing the building skin area. The effect is bigger on the heating load than on the cooling load, both in absolute and relative terms. The figure shows that the mismatch in summer becomes smaller when decreasing the building skin area, because of the increasing cooling load and decreasing supply. In winter, this results in a smaller mismatch, because the heating load decreases is bigger than the supply decrease.

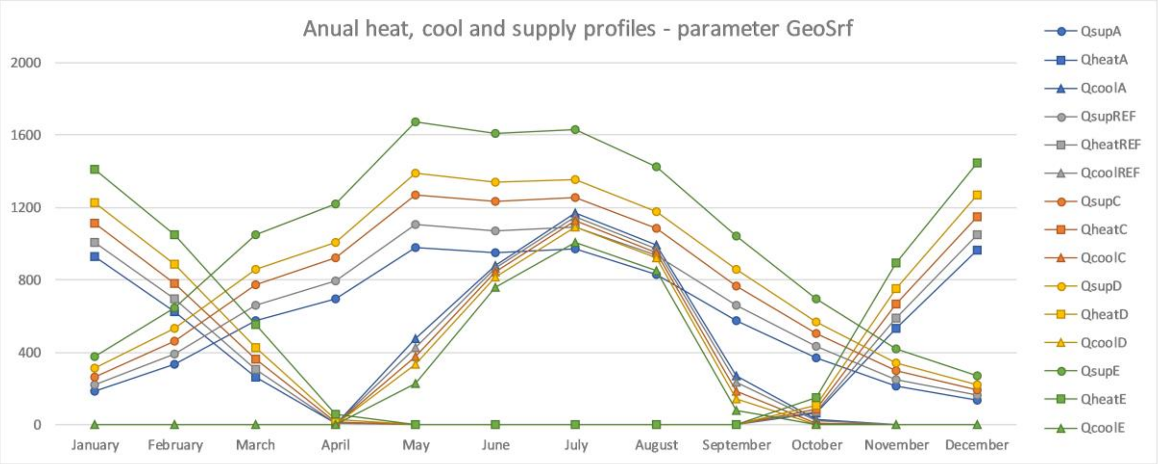


Figure 71: The effect of changing the building skin area on the annual heat, cool and supply profiles

6.1.4 Interpretation

The increased heating load in winter is a logical result of the increased energy losing surface. Because the winter is characterized by a bigger difference between indoor and outdoor temperature, the effect on heating is bigger than on cooling in summer. In the reference design, it was concluded that in summer the building heats up fast and has little chance to dispose its heat during the nights, because of the high insulation values.

The larger energy losing surface results in a lower cooling load in summer; the building can more easily dispose its heat surplus resulting in lower cooling loads. This effect is significantly stronger on variant E, which probably is a result of the vertical shape.

The decreased energy supply in summer for variant A, is the result of the decreased roof surface. The evolutionary solver created a shape that has more total skin surface, but a relatively smaller roof surface. This results in a smaller surface and a more tilted projection of solar radiation. The opposite happens for the other variants, in which the building skin area increases.

The cooling shortage peak is not influenced by this parameter, means that the supply increases nor the demand decreases at the moment of the cooling peak. It means that the cooling peak occurs at a moment when supply is not present, and the size of the peak is not depending on the surface area.

That the effect on supply is more dominant than the effect on demand, can be explained by the build-up of supply and demand. Demand is the result of different types of energy losses, of which transmission is one. The supply is linearly the result of the surface area of outside surfaces. In other words, increasing the surface area only partly affects the demand whilst it linearly influences the supply.

The increase of the supply peak and the cumulative mismatch is the result of the decreased cooling load in summer and increased supply. The energy supply increases because of the increased surface, while the cooling load drops, resulting in an increasing effect on the KPI’s in two ways.

6.1.5 Conclusion

The parameter study provides a more or less linear effect on the KPI’s for energy-flatness, which means a preference for energy-flat design can be made.

For almost all cases, variant A is the only variant resulting in a decrease of the mismatch. The exceptions are the slight increase for cooling load, as a result of decreased ability of redundant heat disposal and the increase in total cooling mismatch as a result of increased supply combined with lower cooling loads. Increasing the energy-losing surface has a bigger effect on the supply than on the demand in this parameter study.

It is concluded that:

- Decreasing the energy losing surface is preferred when aiming for energy-flatness.
- Decreasing the energy losing surface results in a decrease of potential supply surface and a lower capacity of heat disposal in summer.

In terms of architecture, decreasing the energy losing surface is feasible, though it requires design skills to achieve this without handing in on comfort, aesthetics or building organization. Minimizing the energy losing surface is a parameter that is hardly change-able for existing buildings and thus should be incorporated in an early design stage.

6.2 SURFACE: INSULATION

6.2.1 Background

This parameter changes the insulation values of all surfaces that are in contact with the outside air by increasing the thickness of the insulation layers.

Thermal insulation decreases the speed at which heating energy can flow through a surface. Increasing the insulation value of a construction thus results in less energy transfer between inside and outside. Depending on the temperature difference and the requested indoor temperature this energy flow can be either beneficial or unwanted. In practice, increasing insulation values regularly induces higher costs (i.e. insulation material is expensive) and thicker constructions. Moreover, precision on preventing cold-bridges and air-leaks becomes more important.

*The abbreviation of this variant is **SrfIns**, which is used as name for the simulations.*

6.2.2 Parameter change

The reference knows three different types of surfaces that are in contact with the outside air; the walls, the windows and the roof. The ground floor is kept constant in this parameter study, for it behaves differently than the other surfaces and would create 'noise' in the results. The g-values of the windows are kept equal at 0.6.

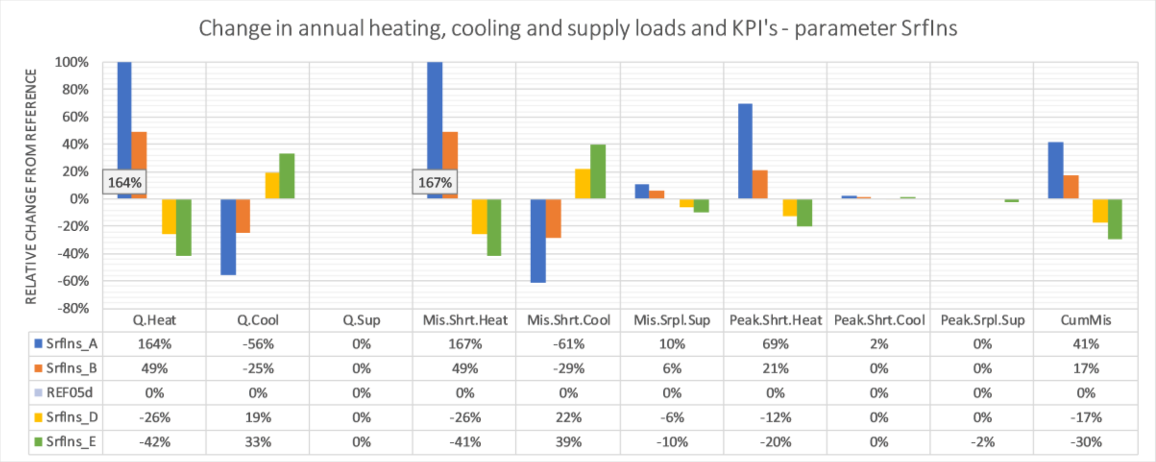
In the reference model, all these surface types have a unique insulation value, respectively 7.0, 0.8 and 9.0 m^2K/W for the walls, windows and roof. In this parameter study, these values are changed in steps of 30% relative to the reference values. Variant A and B are respectively 60% and 30% lower than the reference, variant D and E are respectively 30% and 60% higher than the reference.

	unit	SrfIns_A	SrfIns_B	REF05d	SrfIns_D	SrfIns_E
Parameter change						
Insulation window	m^2K/W	0.31	0.54	0.77	1.00	1.23
Insulation wall	m^2K/W	2.80	4.90	7.00	9.10	14.40
Insulation roof	m^2K/W	3.60	6.30	9.00	11.70	14.40
Average building U-value	W/ m^2K	0.06	0.10	0.15	0.19	0.23
Relative change	%	40 %	70 %	100 %	130 %	160 %
Inevitable side changes						
None						

The total U-value of the total building skin surface changes with the same steps, because the total U-value is the sum of the products of the surfaces and their corresponding U-values, divided by the total surface.

6.2.3 Results

Figure 72 shows the effect of changing the insulation value on the heating, cooling and supply load and the KPI’s. An increase of the insulation value results in lower heating loads and higher cooling loads. The shortage for heating becomes smaller as the insulation increases, and so does the energy surplus. The shortage for cooling increases with higher insulation. The effect of changing the insulation values has a much bigger effect on the heating and cooling loads than on the supply surplus. The peak KPI’s are barely affected by this parameter change. The maximum cumulative mismatches changes more or less linearly with the insulation change and becomes smaller as the insulation value increases.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
🟦 SrfIns_A	164%	-56%	0%	167%	-61%	10%	69%	2%	0%	41%
🟧 SrfIns_B	49%	-25%	0%	49%	-29%	6%	21%	0%	0%	17%
■ REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
🟨 SrfIns_D	-26%	19%	0%	-26%	22%	-6%	-12%	0%	0%	-17%
🟩 SrfIns_E	-42%	33%	0%	-41%	39%	-10%	-20%	0%	-2%	-30%

Figure 72: The effect of changing the insulation values on the heat, cool and supply flows and the performance indicators

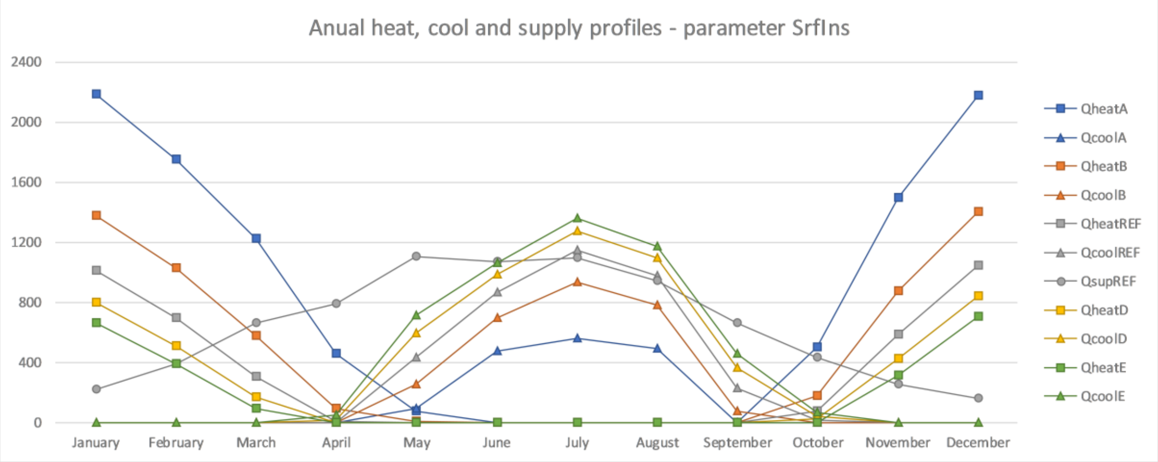


Figure 73: The effect of changing the insulation values on the annual heat, cool and supply profiles

The heating and cooling loads become respectively lower and higher as the insulation increases, as can be seen in Figure 73. The effect on the heating and cooling loads seems to show an ‘asymptotic’ figure, meaning the effect of increasing insulation values is smaller when insulation is already high. It can be derived that the supply profile is not affected by the insulation values, which makes sense because the supply is purely based on facade surface area and solar radiation. The figure shows that increased insulation brings the demand profile closer to the supply in winter, whilst doing the opposite in summer. Moreover, it shows how the demand profile drops below the supply profile for the low insulation variants in summer.

6.2.4 Interpretation

The decreased heating load and increased cooling load are a logical result of the lower flow of energy through facade surfaces when implementing increased insulation values. In winter, less heat flows ‘away’ through the surface, whilst in summer the increased insulation value results in the inability of the building to dispose its heat surplus.

The lower total supply surplus mismatch is a result of the increased cooling load. The (cooling) demand is highest when the energy supply is highest as well; on very warm days. In that sense, the increased cooling load ‘matches’ with the increased supply. However, the cooling mismatch is bigger in this case. This might also mean that The lower heat mismatch is the result of lowered heating demand values in winter.

The asymptotic effect of the decrease in heating loads can be explained by the share of energy transfer through the wall in relation to other energy loss flows; as the insulation becomes higher, the heating losses become more depending on other energy losses like ventilation and infiltration. This also shows that decreasing insulation to low levels has a very high impact on the mismatch and on heating loads.

6.2.5 Conclusion

The parameter study shows a significant effect of changing the insulation values on the mismatch between supply and demand. The effect is opposite for heating and cooling loads.

Variant E, which has the highest insulation value, results in a lower mismatch for all KPI’s, except the cooling mismatch. The effect on the peak cooling and peak supply mismatch is very little. Moreover, the increase of insulation results in an increase of cooling loads. Also, the effect of increasing insulation becomes less when insulation is already a high value, because the heating losses are to a greater extent determined by other building properties in that case.

It is concluded that

- Increasing the insulation value is preferred for energy-flatness
- However, increasing insulation increases cooling loads. These cooling loads are partly matched by the increased supply in summer season, but should not become excessive.
- Decreasing insulation to low levels has a very high impact on the heating loads and should be avoided.

Implementing higher insulation values in architecture is achievable, though it will affect the building construction in terms of thickness. Increasing the insulation value in an existing building is not always possible. Moreover, extremely high insulation values in existing buildings bring a risk of mould and humidity problems in existing building joints because of cold bridges. The increased cooling loads as a result of higher insulation might also disturb the indoor comfort, so the effects should be considered.

6.3 SURFACE: THERMAL MASS

6.3.1 Background

This parameter changes the thermal mass by increasing the thickness of all structural layers of the layers with a structural function (i.e. floor, walls, roof).

Thermal mass regards the ability of a material to (temporarily) store heat. Usually, increasing the thermal mass induces a so called damping effect; the mass takes time to heat up while slowly withdrawing heat from a zone. Similarly, the mass also takes time to cool down, slowly disposing its heat to a zone. Because the temperature of air in a zone can change quicker than the thermal mass, the mass usually mitigates the change in temperature.

Implementing thermal mass in a building can be done by using more heavy materials (i.e. a higher specific heat). Another option is implementing Phase Change Materials, which can absorb a high amount of energy at a certain temperature because of a phase change.

*The abbreviation of this variant is **SrfThm**, which is used as name for the simulations.*

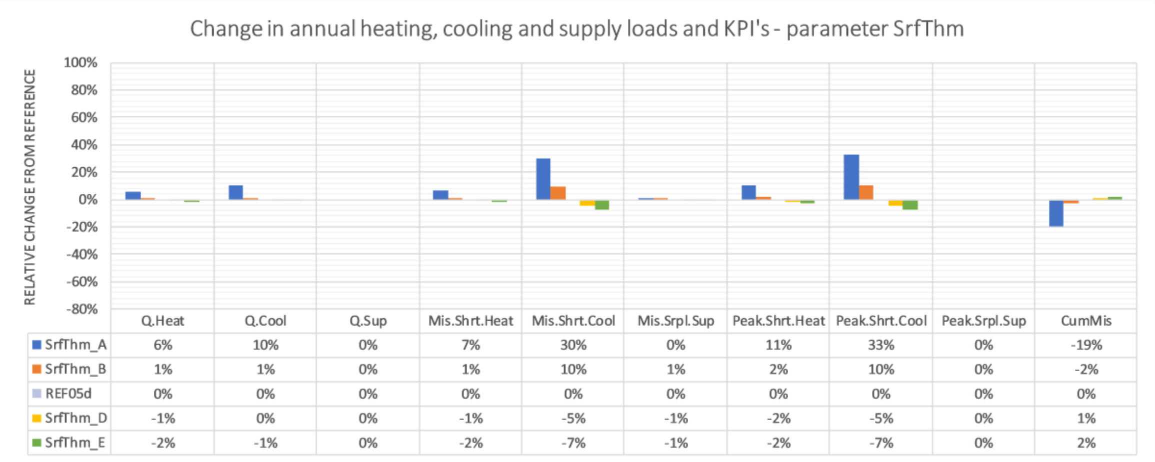
6.3.2 Parameter change

The thickness of the structural layers of the floor and roof in the reference is 15 cm, the thickness of the similar layer in the wall is 10 cm. In this parameter study, these values are changed in steps of 40% relative to the reference values. Variant A and B are respectively 80% and 40% lower than the reference, variant D and E are respectively 40% and 80% higher than the reference.

Changing the thickness of the structural layers has a small side effect on the insulation values of the surfaces; after all, also structural materials insulate. The resulting parameter change is as follows;

	unit	SrfThm_A	SrfThm_B	REF05d	SrfThm_D	SrfThm_E
Parameter change						
Thermal mass	J/K	21.5e6	64.5e6	110e6	150e6	190e6
Relative change	%	20 %	60 %	100 %	140 %	180 %
Inevitable side changes						
Insulation (walls)		6.90	6.95	7.00	7.07	7.12
Insulation (roof)		8.83	8.92	9.00	9.09	9.18
Insulation (floor)		5.93	5.97	6.00	6.05	6.10

It should be noted that the air inside a building also functions as thermal mass. In this parameter study, however, only thermal mass from structural materials present in the building is counted. The effect of thermal mass of air is different, for air is constantly moved and replaced in a zone.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
SrfThm_A	6%	10%	0%	7%	30%	0%	11%	33%	0%	-19%
SrfThm_B	1%	1%	0%	1%	10%	1%	2%	10%	0%	-2%
REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
SrfThm_D	-1%	0%	0%	-1%	-5%	-1%	-2%	-5%	0%	1%
SrfThm_E	-2%	-1%	0%	-2%	-7%	-1%	-2%	-7%	0%	2%

Figure 74: The effect of changing the thermal mass on the heat, cool and supply flows and the performance indicators

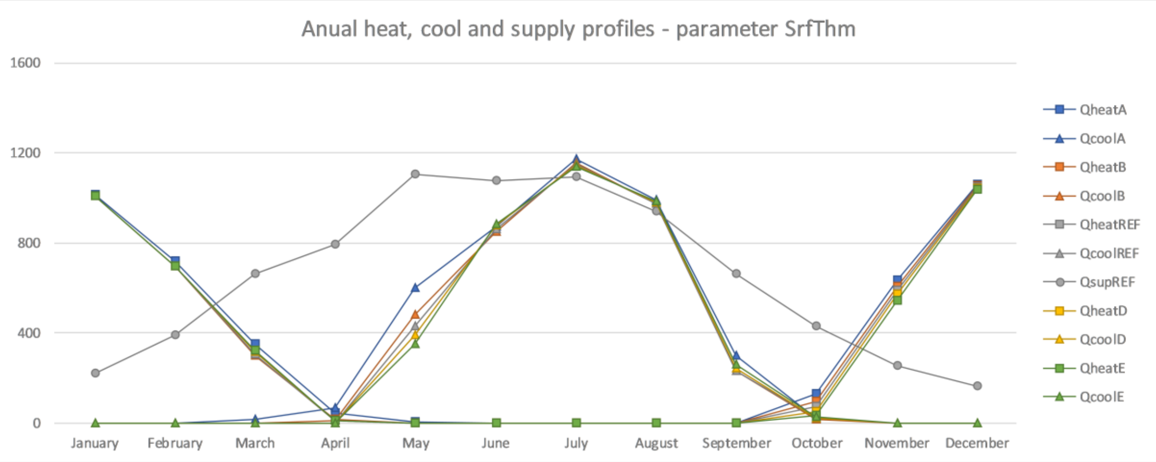


Figure 75 : The effect of changing the thermal mass on the annual heat, cool and supply profiles

6.3.3 Results

Figure 74 shows that the effect on the total heating and cooling values is very little, though variant A (with the least thermal mass) stands out by significantly increasing both the heating and the cooling load. The effects on the KPI’s is little as well, although in all cases variant A has a bigger effect than the other variants. A clear effect is clear on the total cooling mismatch and the peak cooling shortage. This is remarkable, because the cooling load itself is not much affected. Regardless the effect being small, in almost all cases increasing the thermal mass decreases the mismatch. The exception is the cumulative mismatch, that decreases with the lowered thermal mass.

Figure 75 confirms that the effect of changing thermal mass is very little on the monthly heating and cooling values. Nevertheless, the effect is the biggest is the inter-seasonal months May, October and November. Increasing the thermal mass logically has no effect on the supply profile. The demand profile shows that less thermal mass results in a higher heating and cooling demand, especially in the months between summer and winter; March, April, May and September, October, November.

6.3.4 Interpretation

The low effectiveness on the monthly values might be explained by the fact that the functionality of thermal mass is more present in smaller timesteps than represented by the graphs, namely a day or a week. This is confirmed by the decrease in total cooling mismatch for variant D and E, whilst the total cooling load does not change in these variants. A study with a smaller timestep might be useful to find out the effects of thermal mass on a daily pattern.

The big effect on the mismatch and heating loads when decreasing the thermal mass, compared to the smaller effect of increasing the thermal mass, might be explained by the damping effect of the mass. Thermal mass becomes less functional after a certain thickness, because the energy has no time to get in or out, and the mass more or less takes a constant temperature. Moreover, the high insulation values of the wall and roof increase the ability of the ‘deep’ thermal mass reaching a constant temperature. Adding more superficial thermal mass, might show the effect of an increase in effective thermal mass. This could be done by adding a while inside the building, instead of increasing the thickness of the outdoor surfaces.

The bigger effects of changing thermal mass in the months between summer and winter, might have to do with the heating and cooling setpoints compared to the indoor air temperature. In winter, the temperature is almost always at the heating setpoint, resulting in a constant heat demand. In summer, the temperature is almost always at the cooling setpoint, resulting in a constant cooling demand. Thermal mass mitigates temperature changes and thus has a bigger effect in autumn and spring, because the air temperature than ‘floats’ somewhere between the setpoints. The thermal mass mitigates the fluctuations and thus the amount of time a setpoint is reached, resulting in a heating or cooling load.

6.3.5 Conclusions

This parameter shows a similar effect on all KPI’s, meaning a big increase of mismatch when decreasing the thermal mass and a small decrease in mismatch when increasing the thermal mass.

Variant E show the biggest decrease for all KPI’s, including the total heating and cooling load. However, the effect is very limited because of the damping effect of thermal mass. To achieve the beneficial effect of thermal mass, more superficial thermal mass should be added in the building.

It is concluded that

- increasing the amount of thermal mass has a positive effect on decreasing the mismatch between supply and demand.

- However, the thermal mass becomes less effective as it is further away from the inside surface of the construction. Therefore, superficial thermal mass is what should be aimed for. (Ps. the design studies in *7 Energy-flat building design* show that ‘deep’ thermal mass also is beneficial for achieving energy-flatness)
- Moreover, the effect of thermal mass is the biggest in the inter-seasonal months, as a result of the outdoor temperature being closer to the indoor accepted temperature range.

The implementation of thermal mass in architecture is achievable. Every building will contain thermal mass because every material has a certain specific heat. The selection of materials, however, has a great influence on the total thermal mass. Heavy materials, with a high heat capacity, can increase the thermal mass. Superficial thermal mass acts quicker and has a bigger effect on the minimizing the mismatch. This could be achieved by also taking into account indoor walls when considering thermal mass. Moreover, phase change materials could be used in a building to increase thermal mass at a desired temperature range.

6.4 COMFORT: VENTILATION RATE

6.4.1 Background

This parameter changes the amount of outside air that enters and leaves the building by changing the ventilation rate.

Ventilation is an essential part of creating a comfortable indoor environment for the users of a building. Air has mass and thus a specific heat, which means that in- and outgoing air carries energy, resulting in an energy loss or gain for the zone. The amount of air going in and out building is subject to users opening and closing windows and in case of a mechanical ventilation system, changing air rates based on outdoor and indoor temperatures. Changing the ventilation rate of a building is relatively easy, because it does not require (much) changes in a building's construction. Completely controlling the ventilation rate, however, is hard because of users wanting to open and close windows whenever they like.

The abbreviation of this variant is ***CmfVen****, which is used as name for the simulations.*

6.4.2 Parameter change

In the reference model, there is a constant ventilation rate of 150 m^3/h. This is based on the need of an individual to have around 50 m^3/h of fresh air. The reference model considers no natural ventilation or night ventilation, for the sake of the simplicity and to improve the validity of parameter studies. The ventilation rate changes with a factor 2 per step, resulting in the following parameter values:

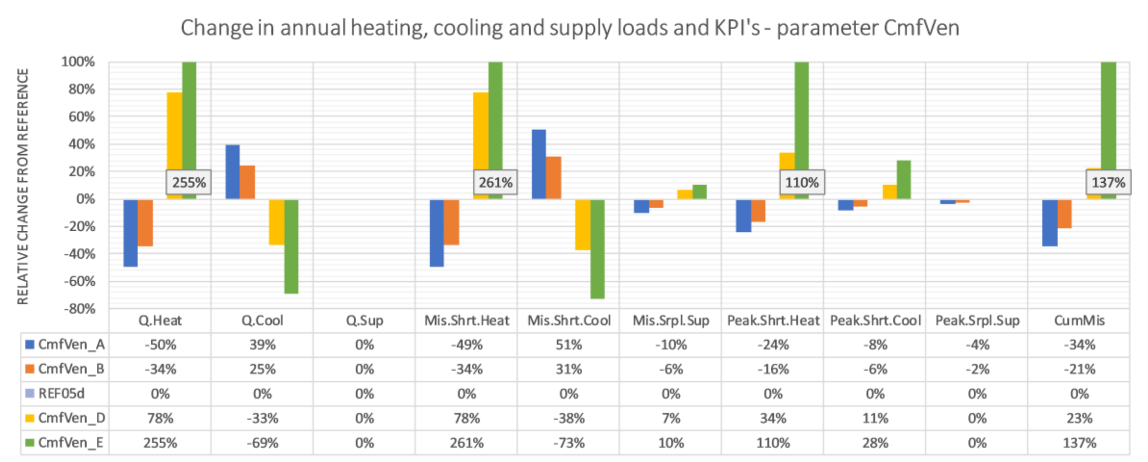
	unit	CmfVen_A	CmfVen_B	REF05d	CmfVen_D	CmfVen_E
Parameter change						
Ventilation rate	m^3/h	37.5	75.0	150	300	600
Relative change	%	25 %	50 %	100 %	200 %	400 %
Inevitable side changes						
None						

No other parameters are affected by changing the ventilation rate.

6.4.3 Results

Increasing the ventilation rate results in higher heating loads and in lower cooling loads, as can be seen in Figure 76. The total heating shortage and the supply surplus increase when the ventilation increases, though the effect is stronger for the heating value. The shortage for cooling decreases with higher ventilation rates. Decreasing the ventilation rate has a smaller effect than increasing the ventilation rate on all performance indicators, but this might be explained by the exponential increase of the parameter. The shortage peak for both heating and cooling, and the maximum cumulative mismatch increase when increasing the ventilation rate. The change of ventilation rate barely affects the supply surplus peak or total surplus.

Figure 77 shows the big effect of changing the ventilation rate. Increasing the ventilation rate results in much higher heating values in winter, and lower much cooling values in summer. For the decreased ventilation variants, the mismatch is lower from September till February. In March and April the increased ventilation variants result in a lower mismatch, in May and June decreased ventilation is optimal and in July and August the reference situation is optimal.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
CmfVen_A	-50%	39%	0%	-49%	51%	-10%	-24%	-8%	-4%	-34%
CmfVen_B	-34%	25%	0%	-34%	31%	-6%	-16%	-6%	-2%	-21%
REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
CmfVen_D	78%	-33%	0%	78%	-38%	7%	34%	11%	0%	23%
CmfVen_E	255%	-69%	0%	261%	-73%	10%	110%	28%	0%	137%

Figure 76: The effect of changing the ventilation rate on the heat, cool and supply flows and the performance indicators

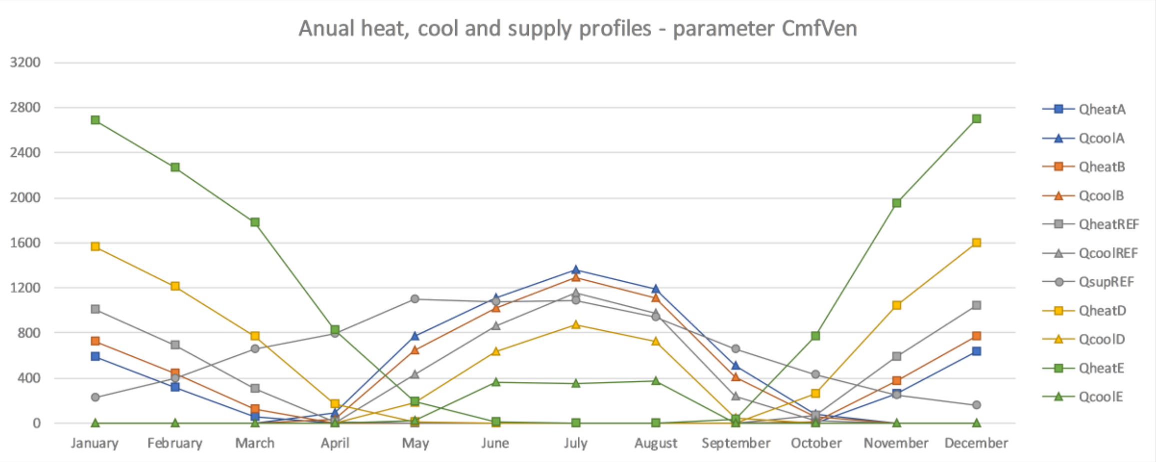


Figure 77: The effect of changing the ventilation rate on the annual heat, cool and supply profiles

6.4.4 Interpretation

Air is an energy carrier, thus an increase in ventilation means a higher energy exchange between indoors and outdoors. In winter, this results in a higher heating load, because all the extra air that comes in the building must be heated up, while all the energy in the exhaust air withdraws energy from the zone. In summer, this results in a lower cooling load, because the ability of the zone to dispose its superfluous heat increases. Practically, the increased ventilation also brings in more heat in summer during daytime if the outdoor temperature is higher than the indoor temperature, which would result in a higher cooling load. However, the increased disposal of heat during the nighttime has a bigger effect than the slightly increased heat gain during daytime.

The increased supply surplus as the ventilation increases, is explained by the diminished cooling load in summer. The increased heating shortage is explained by the increased heating load in winter. In other words, the seasonal effects on the mismatch become stronger.

The fact that increasing the ventilation rate has no effect on the surplus peak, probably is because the maximum cooling load peak originates from a high solar radiation load, which is present at the time that the outdoor temperature is not much lower (or even higher) than the indoor temperature. In other words, the diminished overall cooling load occurs at night, whilst the maximum peak cooling load occurs at daytime which is unaffected by the ventilation rate.

The increase in maximum cumulative mismatch is logically caused by the excessively increased heating load.

6.4.5 Conclusion

Changing the ventilation rate has a significant effect on the heating and cooling loads and KPI's.

Variant A, with the lowest ventilation rate, results in the smallest overall mismatch. This low amount of ventilation, however, results in higher cooling loads in summer because of the diminished ability of the building to dispose its superfluous heat. This increased cooling load is beneficial from April till June, because it matches the supply. In summer, it results in a slight shortage due to excessive cooling loads. Increasing the ventilation rate is highly beneficial for decreasing the cooling mismatch.

It is concluded that

- a seasonal approach is beneficial when energy-flatness is aimed for.
- In winter, low ventilation results in low heating loads. From March till October, however, the ventilation can either decrease cooling loads or increase heating loads with increased ventilation, and increase cooling loads or decrease heating loads with reduced ventilation. Depending on the supply, a different ventilation rate should be chosen. Adjusting the ventilation rate to daily differences is probably an effective solution for solving daily mismatches.
- if it is not possible to have a seasonal approach, decreasing the ventilation rate all year long results in a lower total mismatch.

In terms of architecture, reducing the amount of ventilation can be critical. Any user desires a minimum amount of fresh air to assure a comfortable indoor climate. The timing of ventilation, however, might be adjusted. Mechanical ventilation systems can change the flow rate based on schedules, indoor air quality or outside climate conditions. If the volume of a building is large enough, ventilation (i.e. energy loss or gain) could be stopped temporarily by stopping the ventilation temporarily.

6.5 COMFORT: TEMPERATURE RANGE

6.5.1 Background

This parameter study changes the comfort temperature range by adjusting the heating and cooling setpoints, i.e. the indoor air temperatures at which heating or cooling activates.

The indoor air temperature is essential for a comfortable indoor climate. Decreasing the heating setpoint and increasing the cooling setpoint means that the indoor temperature can be closer to the outdoor temperature, resulting in a lower ΔT. Energy flow is linearly dependent on the ΔT in most energy balance flows, e.g. transmission, ventilation. Increasing the temperature range thus inevitably decreases heating and cooling loads.

Changing the indoor temperature range is relatively easy and does not require many building adaptions and in most cases can be done by simply adjusting installation settings. The ‘limiting’ factor is the user; every user has its own comfort standards, which must be achieved.

*The abbreviation of this variant is **CmfTmp**, which is used as name for the simulations.*

6.5.2 Parameter change

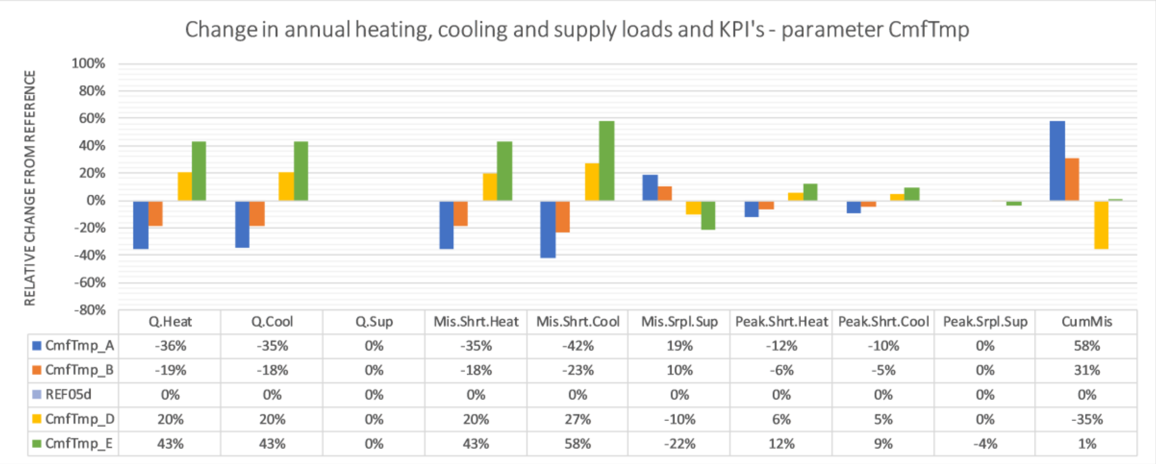
The reference model has a temperature range of 19-25 °C, meaning that every indoor air temperature between these values is accepted. In this parameter study, this range is broadened and narrowed in steps of 1 degree Celsius for both the cooling and heating setpoint. Like the reference model, there is no difference in night-time and daytime setpoints nor are setpoints based on presence of inhabitants. No other parameters are affected by this change, resulting in the following parameter study details;

	unit	CmfTmp_A	CmfTmp_B	REF05d	CmfTmp_D	CmfTmp_E
Parameter change						
Ventilation rate	°C	17 - 27	18 - 26	19 - 25	20 - 24	21 - 23
Relative change	%	167 %	133 %	100 %	67 %	33 %
Inevitable side changes						
None						

6.5.3 Results

The effect of changing the temperature range is consistent and significant on the heating loads, cooling loads and KPI’s, as can be seen from Figure 78. The effect is linear; for every step the change in KPI’s or loads is approximately equal. For all, except the supply surplus and cumulative mismatch, loads and KPI’s a smaller temperature range results in a bigger mismatch. The supply surplus is barely affected. The cumulative mismatch is highly affected, but the pattern is not consistent. Heating and cooling loads increase when the temperature range is smaller.

Figure 79 shows a clear linear increase for both the heating and cooling loads, in all months of the yea, in which the demand increases as the temperature range narrows. In the months of April, May, September, and October the effect is less linear, because of the heating and cooling demands reaching zero. Moreover, from March till June the narrowed range results in a higher cooling load, which is beneficial given the availability of supply.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
🟦 CmfTmp_A	-36%	-35%	0%	-35%	-42%	19%	-12%	-10%	0%	58%
🟧 CmfTmp_B	-19%	-18%	0%	-18%	-23%	10%	-6%	-5%	0%	31%
■ REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
🟨 CmfTmp_D	20%	20%	0%	20%	27%	-10%	6%	5%	0%	-35%
🟩 CmfTmp_E	43%	43%	0%	43%	58%	-22%	12%	9%	-4%	1%

Figure 78: The effect of changing the temperature range on the heat, cool and supply flows and the performance indicators

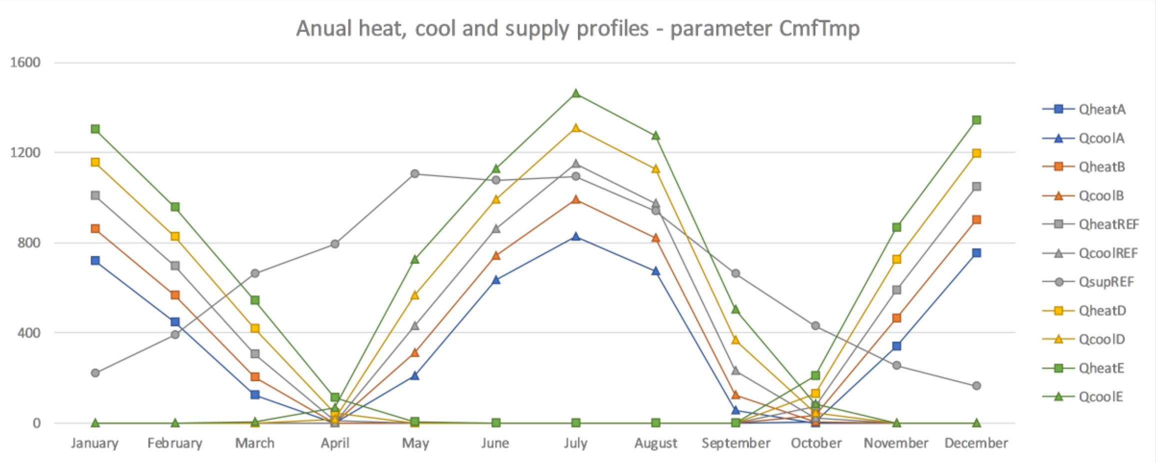


Figure 79: The effect of changing the temperature range on the annual heat, cool and supply profiles

6.5.4 Interpretation

The linear effect of changing the temperature range on the heating and cooling loads is logical, given the fact that most energy loss flows are linearly affected by the ΔT of indoor temperature and outdoor temperature. This translates to an increase of shortage; in winter time, when there is shortage because of lack of supply, the shortage gets bigger because of the increased heating load. In summer time, the surplus mismatch decreases when the range gets smaller, because a cooling load occurs in times of energy surplus.

The surplus peak is unaffected, meaning that the peak of energy supply is not at the same moment as the (peak) cooling load. This might be the end of the morning, when the sun is highest, but the building has not completely heated up yet. The shortage peak is only slightly affected, but the effect is linear. This might be explained by the difference in ΔT being relatively low; if the outdoor temperature is -5°C, a difference of 1 or 2 °C on the total temperature difference is relatively small.

The cumulative mismatch increases as the temperature range broadens. This is the result of the demand becoming higher whilst the supply stays constant; the supply (or surplus) then determines the annual cumulative mismatch. Variant D has the lowest cumulative mismatch because supply and demand are more equally spread out, and in variant E the demand (or shortage) becomes dominant.

6.5.5 Conclusion

Changing the temperature range results in a linear effect on most KPI's and on the heating and cooling loads. Narrowing the range increases both heating and cooling loads.

Variant A, with the widest temperature range, results in the biggest decrease in total mismatches for heating and cooling However, this variant increases the annual supply surplus and cumulative mismatch. In winter, a lower heating setpoint is beneficial for it decreases the heating load. From March till October it is more effective to have a lower cooling setpoint, because supply is superfluous.

It is concluded that

- A seasonal approach for heating and cooling setpoints is best for energy-flatness.
- In winter, a lower heating setpoint is desired. From March till October a lower cooling setpoint is beneficial, except from July and August. The cooling setpoint should be adapted to the available supply to achieve a minimized mismatch.
- The effect of a changed setpoint is characterized by linearity and consistency, which might contribute to matching supply and demand on small time steps.
- If a seasonal adaptive solution is not possible, the widest temperature range results in the lowest annual mismatch

In terms of architecture, changing the temperature range is easy for it can be done by changing installation settings. The user, however, should have a comfortable (and thus partly controllable) indoor climate. Solutions in terms of radiative heating or cooling by airflow might help to achieve comfortable indoor climates whilst having a more extreme air temperature.

6.6 WINDOWS: SHARE PER ORIENTATION

6.6.1 Background

This parameter analyses the effect of changing the share of window surface, by adapting the window area per orientation.

Windows are an essential element in architecture in terms of aesthetics, comfort and energetic performance. Windows can provide light, transparency, and sight. However, windows can also make architecture worse. Large windows can cause an uncomfortable climate due to low radiation temperatures and may decrease a feeling of privacy and intimacy. Moreover, windows affect the insulation value of a building, because windows always have much worse thermal insulation than closed facade elements.

Adjusting the window composition in an existing building is hard and should be avoided; it is costly and adapts the original intended architecture.

*The abbreviation of this variant is **Shr**, which is used as name for the simulations.*

6.6.2 Parameter change

In the reference model, the south-east and north-west facades have a window share of 15% and the south-west and north-east facades have a window share of 20%. In this study the share of window surface per orientation is changed twice; one study with 1% window surface and another with 90% window surface. A share of 1% represents ‘’no windows’’, but is preferred above 0% to keep the number of surfaces and modelling nodes constant and prevent biased results. A share of 90% is assumed to be realistic, for a facade of a villa will need some closed (structural) elements in most cases. Below, the two variants and the reference model are shown for the south-west facade.

Figure 80: The share of window surface of the SW facade of resp. the refence model, 1% window and 90% window surface

Inevitably, an increase in window surface results in a decrease of the average U-value. In this study, this decrease in insulation is not corrected, so that the realistic effects of increasing a window are taken into account. Also, the total thermal mass changes because of the change in closed facade surface. Below, the change in window size is shown, as well as the change in U-value and thermal mass.

Roof surfaces are neglected in this parameter study, because the reference model does not have any roof windows. The surfaces are named by their orientation (e.g. **NE01** is the window on the north-east facade, reduced to a share of 1% relative to the facade surface).

		REF05d	ShrNE01	ShrNE90	ShrSE01	ShrSE90	ShrSW01	ShrSW90	ShrNW01	ShrNW90
Parameter change										
NE window surface	m^2	13.64	0.68	61.38	13.64	13.64	13.64	13.64	13.64	13,64
SE window surface	m^2	9.20	9.20	9.20	0.61	55.15	9.20	9.20	9.20	9,20
SW window surface	m^2	13.64	13.64	13.64	13.64	13.64	0.68	61.38	13.64	13,64
NW window surface	m^2	9.20	9.20	9.20	9.20	9.20	9.20	9.20	0.61	55,15
Inevitable side changes										
Total U-value	W/m^2K	0,15	0.14	0.17	0.14	0.17	0.14	0.17	0.14	0.17
Thermal mass	J/K	1.1e8	1.1e8	9.7e7	1.1e8	9.8e7	1.1e8	9.7e7	1.1e8	9.8e8

6.6.3 Results

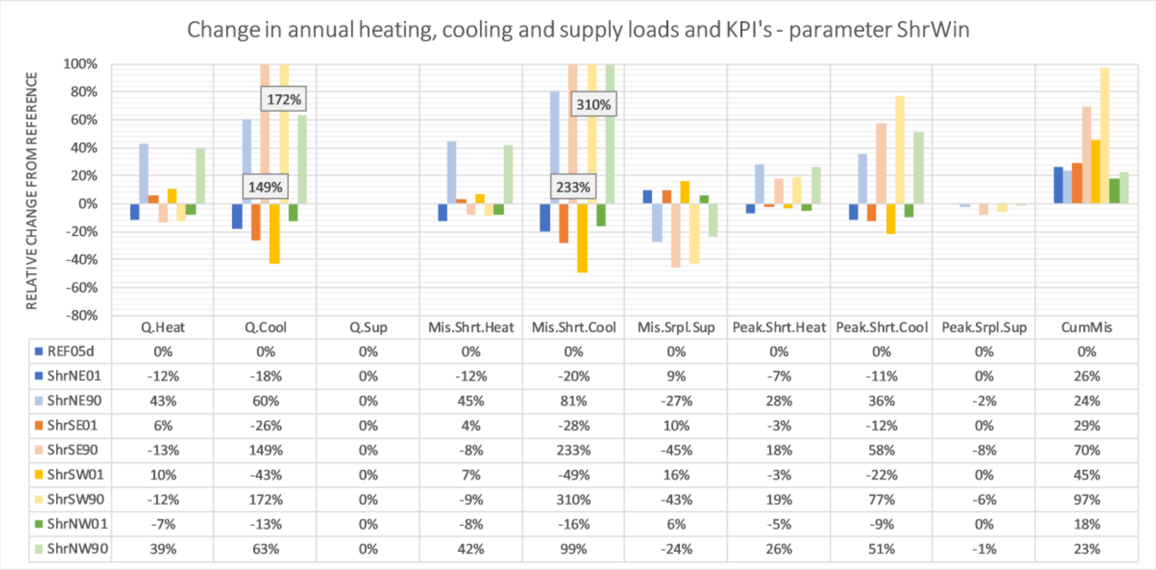
Figure 81 shows that the effect of changing the window size is similar on the north-east and north-west facades for the heating and cooling loads. The south-west and south-east facades also behave similar. Moreover, the effect of increasing the window size is always opposite to decreasing the window size in terms of heating and cooling demand, and increasing window size always has a bigger effect than decreasing it. Also, the effect in cooling loads and cooling KPI's is always bigger than the effect on heating loads and KPI's.

For the northern facades, decreasing window size results in lower heating and cooling loads. For the southern facades, decreasing the window size results in higher heating loads and lower cooling loads. The effect on cooling loads by increasing the window size on southern facade, is very large resulting in an increase of 149% 172% for respectively the south-eastern and south-western facade.

Increasing the window size on the northern facades results in a large increase of heating loads, and an even bigger increase of cooling loads. The total supply surplus decreases when increasing the window size on any orientation, the opposite happens for decreasing the window size although this effect is smaller.

Also, the peaks of heating shortage and cooling shortage increase with an increase of window share. The surplus peak is barely affected by the change in window share, although a slight decrease is visible when increasing the window surface on the south-west and south-east facades. The maximum cumulative mismatch increases in all cases. For northern facades, decreasing or increasing the window results in a similar effect. On the southern facade, increasing the window size has a larger effect.

In Figure 82, one can see that in winter the heating load stays approximately the same for almost every variant, except for three parameter variants. Increasing the window share on northern facades results in a significantly higher heating load. Increasing the window share on the south-western facade results in higher heating loads in midwinter December and January, but lower heating loads in November and February.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
■ REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
■ ShrNE01	-12%	-18%	0%	-12%	-20%	9%	-7%	-11%	0%	26%
■ ShrNE90	43%	60%	0%	45%	81%	-27%	28%	36%	-2%	24%
■ ShrSE01	6%	-26%	0%	4%	-28%	10%	-3%	-12%	0%	29%
■ ShrSE90	-13%	149%	0%	-8%	233%	-45%	18%	58%	-8%	70%
■ ShrSW01	10%	-43%	0%	7%	-49%	16%	-3%	-22%	0%	45%
■ ShrSW90	-12%	172%	0%	-9%	310%	-43%	19%	77%	-6%	97%
■ ShrNW01	-7%	-13%	0%	-8%	-16%	6%	-5%	-9%	0%	18%
■ ShrNW90	39%	63%	0%	42%	99%	-24%	26%	51%	-1%	23%

Figure 81 : The effect of changing the window surface on the heat, cool and supply flows and the performance indicators

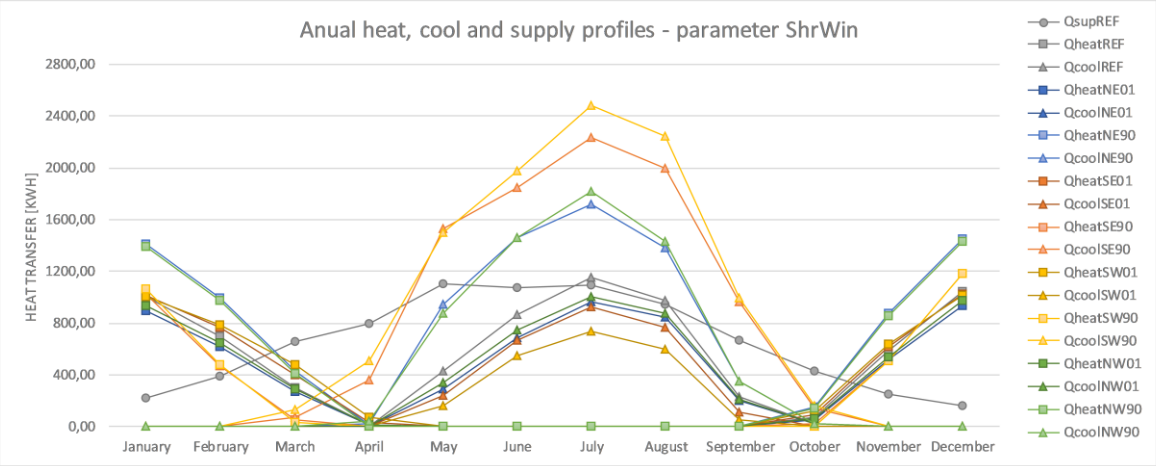


Figure 82: The effect of changing the window surface on the annual heat, cool and supply profiles

In summer, increasing window share results in a higher cooling load increase for all orientations. The effect on changing the window size is always the biggest on the south-west facade, slightly less on the south-east facade and the least on the northern facades. Only in May, the effect on increasing the window size is bigger on the south-east facade.

The effect on the cooling profile is in all cases much bigger than the effect on the heating profile. Increased cooling loads in summer result in a big shortage, lowered heating loads in winter result in a slight decrease of shortage.

6.6.4 Interpretation

Bigger windows result in a higher solar radiation gain. This decreases the heating load in winter. However, an increased window surface results in a lower U-value, resulting in higher heating losses. The study shows that depending on the presence of solar, either the energy gain by solar radiation or the energy loss by decreased insulation is dominant. Overall, the solar radiation gain is always stronger on south-facades than on north-facades, as is logically explained by the path of the sun at the Dutch latitude (i.e. 52°). In winter the solar radiation gain is slightly dominant to the increased energy loss whilst in summer the solar radiation gain is highly dominant.

The effect on the mismatches are very diverse for the three different energy flows; heating, cooling and supply. The heating mismatch is determined by orientation and thus mostly affected on the northern facades. Increased windows in summer result in much higher cooling loads, which inherently results in a lower supply surplus because a cooling load occurs in times of high solar radiation (i.e. high supply). The yearly change in total mismatch is little, because the effects per season are high, but they compensate each other.

Northern facades catch less solar radiation, especially in winter, resulting in a higher heating load when increasing the window surface. Southern facades have a high solar potential, which is beneficial in winter, but results in excessive cooling loads in summer due to excessive solar gain.

6.6.5 Conclusions

This parameter study shows clear and explainable results, it shows that adjusting window size affects energy gain by solar radiation and energy loss by transmission and is highly dependent on season and orientation.

Adjusting the window share has two major effects; increasing solar radiation gain and increasing energy loss by transmission. Depending on the orientation, season and hour of the day, this has different effects on the key-performance indicators. Moreover, southern facades are more affected by solar radiation. The preferred option thus differs per orientation and timing.

It is concluded that:

- An approach for energy-flatness should consider both orientation and season. Increasing window share results in higher energy transmission and higher solar radiation gain, both of which are desired on undesired depending on the differences between indoor and outdoor climate.
- In winter, when solar radiation is present, a large window share on the southern facades is desired. During the night, the losses caused by higher U-values should be minimized. All other facades should have a high insulation in winter.
- In summer, solar radiation should be blocked from all facades. Summer nights could benefit from the heat loss by lowered insulation values. This, however, could also be achieved easier by other parameters (e.g. ventilation)

For architecture, the above proposition is challenging. Windows are known for their low insulation values as a result of their transparency. A window that has a high insulation value is desired. Because the need for high insulation is most often not at the same time as the need for solar radiation gain, a dynamic solution could be designed in which the surface changes from transparent solar radiation gain surface, to a highly insulated, non-transparent surface.

6.7 Windows: g-value

6.7.1 Background

This parameter analyses the effect of changing the g-value of a window surface.

The g-value is a measure for the share of solar energy that is transmitted to a window surface. The total solar energy transmitted consists of energy directly entering the building as radiation, and energy indirectly entering the building as a result of heat absorption by the glass. The g-value is a factor, meaning it theoretically ranges from 0 (no solar transmittance) to 1 (100% transmittance of solar radiation). The required g-value differs per situation; in some cases, high solar gain is desired to increase the passive heat gain. In other cases, e.g. hot climates, it is more beneficial to have a g-value that is as low as possible.

The abbreviation of this variant is ***Gvl****, which is used as name for the simulations.*

6.7.2 Parameter change

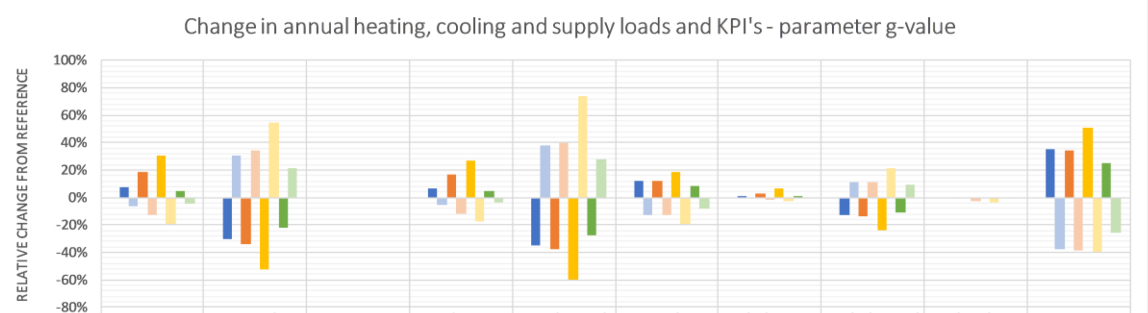
The g-value of the reference model is 0.6 for all windows. In this parameter study, the g-value is changed to 0.05 and to 0.95 for all surfaces individually, resulting in eight different result studies. The values of 0.05 and 0.95 are assumed to be extreme but realistic. Changing the g-value does not affect other parameters, resulting in the following parameter study overview:

		REF05d	GvlNE05	GvlNE95	GvlSE05	GvlSE95	GvlSW05	GvlSW95	GvlNW05	GvlNW95
Parameter change										
NE window g-value	-	0.60	0.05	0.95	0.60	0.60	0.60	0.60	0.60	0.60
SE window g-value	-	0.60	0.60	0.60	0.05	0.95	0.60	0.60	0.60	0.60
SW window g-value	-	0.60	0.60	0.60	0.60	0.60	0.05	0.95	0.60	0.60
NW window g-value	-	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.05	0.95
Inevitable side changes										
none										

6.7.3 Results

Looking at the total heating and cooling values, Figure 83 shows that a change of g-value has an opposite effect on heating and cooling loads. Heating loads increase when the g-value decreases. In all cases, the effect is the biggest on the south-west facade, followed by the south-east facade. Moreover, the effect on the cooling load is higher than on the heating load.

The changes in total heating and cooling shortage follow the changes in respectively the heating and cooling loads, meaning a higher g-value results in a lower heating shortage and higher cooling shortage. The supply surplus increases when the g-value decreases. The effects on the heating shortage peak and supply surplus peak are limited. The cooling peak is affected by the g-value change. A higher g-value results in a much smaller maximum cumulative surplus, a lower g-value does the opposite.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
■ REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
■ GvlNE05	7%	-31%	0%	7%	-35%	13%	1%	-13%	0%	35%
■ GvlNE95	-6%	31%	0%	-5%	38%	-12%	-1%	11%	0%	-37%
■ GvlSE05	19%	-34%	0%	17%	-38%	12%	3%	-14%	0%	34%
■ GvlSE95	-13%	34%	0%	-12%	40%	-13%	-2%	12%	-2%	-39%
■ GvlSW05	30%	-52%	0%	27%	-60%	18%	6%	-24%	0%	51%
■ GvlSW95	-19%	55%	0%	-17%	74%	-19%	-2%	21%	-4%	-39%
■ GvlNW05	5%	-22%	0%	5%	-27%	8%	1%	-11%	0%	25%
■ GvlNW95	-4%	22%	0%	-4%	28%	-8%	0%	9%	0%	-26%

Figure 83: The effect of changing the g-value on the heat, cool and supply flows and the performance indicators

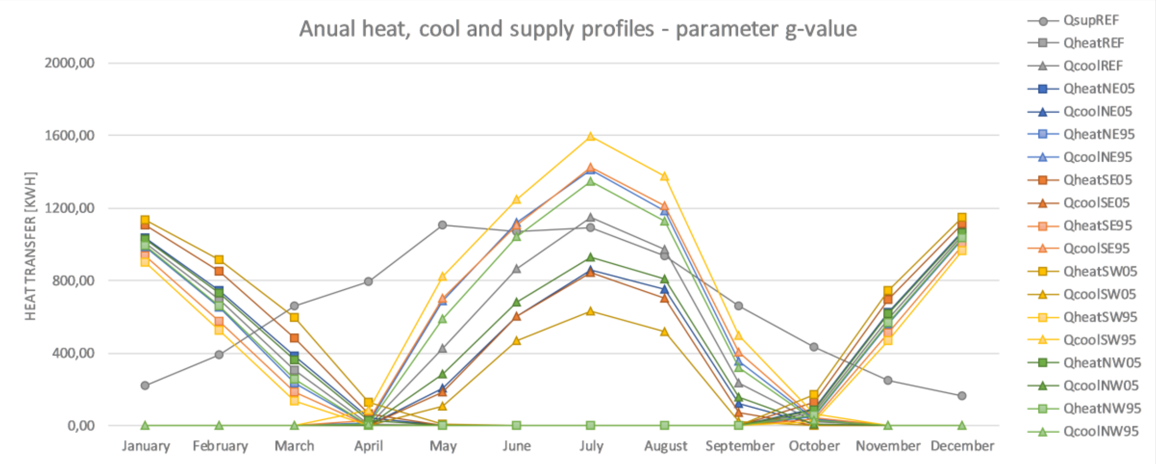


Figure 84: The effect of changing the g-value on the annual heat, cool and supply profiles

Figure 84 shows that the effects of changing the g-value are bigger in summer than in winter. In all cases, the effect of changing the g-value is the biggest on the south-west facade and the least on the northern facades. A decrease in g-value results in a higher heating load and lower cooling load. The decreased demand because of a higher g-value in winter is beneficial for decreasing the mismatch. The increased demand because of a higher g-value in September and May is beneficial as well, because the supply is higher in than the demand in the reference. In the middle of the summer, the higher g-value makes the mismatch worse, by causing excessive cooling loads. In the months of October and April, heating and cooling loads occur simultaneously for the low g-value variants.

6.7.4 Interpretation

The decreased heating loads at higher g-values are the result of an increased solar gain. These increased solar gains result in higher cooling loads in summer. The high cooling loads make use of the availability of energy supply in summer, resulting in a lower energy surplus when a higher g-value is applied.

The supply surplus peak and heating shortage are barely affected. For the supply surplus peak, this means that it does not occur simultaneously with a cooling load. For the heating shortage peak, it means that this peak does not occur in times of supply, which means it occurs during the nighttime.

The cumulative surplus decreases in all cases where the g-value increases, and increases in all cases of a decreased g-value. This is the result of lowered heating values with the decreased g-value. The increased effect of changing the g-value on the southern facades, is because the g-value affects the solar energy transmittance. The amount of solar energy is the highest on the southern facades, and thus results in a bigger effect of the change.

6.7.5 Conclusion

The parameter study provides clear results on the effect of changing the g-value of windows for different orientations. Increasing or decreasing the g-value gives opposite effects in all cases. Moreover, the effect on the south-west facade is the biggest in all cases.

The effect on the heating and cooling mismatches are opposite, but the effect on the cooling mismatch is always bigger. Also, the effect is always biggest on the south-west facade. Peaks for heating shortage and supply surplus are barely affected by this parameter change, but the cooling peaks are affected significantly. The differences between the effect on heat and cool, suggest that a dynamic solution is preferred.

It is concluded that:

- An approach that differs per season is desired for energy-flatness and the biggest effects can be achieved when adapting the south-west facade
- Increasing the g-value on the south-facade results in higher solar gains, resulting in lower heating loads and higher cooling loads.
- A high g-value is desired on the southern facades to reduce heating loads in winter. A high g-value is effective from March till October to increase cooling loads to match the surplus of supply, except for the months of June, July and August in which this causes excessive cooling loads.

Changing the g-value of a window is a technical challenge. Whilst the g-value for conventional windows is determined by adding coatings and layers, modern technique have shown that windows with adaptable g-values can be produced, by electronically changing the colour and transparency of a window. Another solution would be to implement sun shading, which practically has the same effect on net passive solar gain. Also, sun shading is available in adaptable forms.

6.8 GEOMETRY: ORIENTATION

6.8.1 Background

This parameter analyses the influence of the orientation of a building by rotating the north direction of the reference design three times in steps of 45°.

The orientation of a building influences the solar gain, shadows and wind loads on the different facades by changing itself in relation to the sun's azimuth. Where in other parameter studies certain building elements were changed per facade (i.e. per orientation), in this study the whole building rotates itself. Since the building is symmetrical, all possible configurations with a rotation size of 45° are studied.

Changing a buildings' orientation is most often not possible after a building is build. In new building projects, most often there are limitations to a buildings orientation due to urban context. Some examples of actively rotating homes can be found (see for example *2.6.2 ReVolt - TU Delft Solar Decathlon entry 2012*).

*The abbreviation of this variant is **ChNrth**, which is used as name for the simulations.*

6.8.2 Parameter change

In the reference model, the southern roof face is oriented to the south-west direction. According to the SenterNovem Reference design documentation (DGMR, 2016), this is the logical result from the villa being autonomous and thus able to orient itself to the sun. In this parameter change, the north direction is changed in steps of 45° three times such that 4 different orientations occur. Since the building is symmetrical, these are all possible orientations assuming a minimum mutual change of 45°. Figure 85 below shows how the north angle changes.

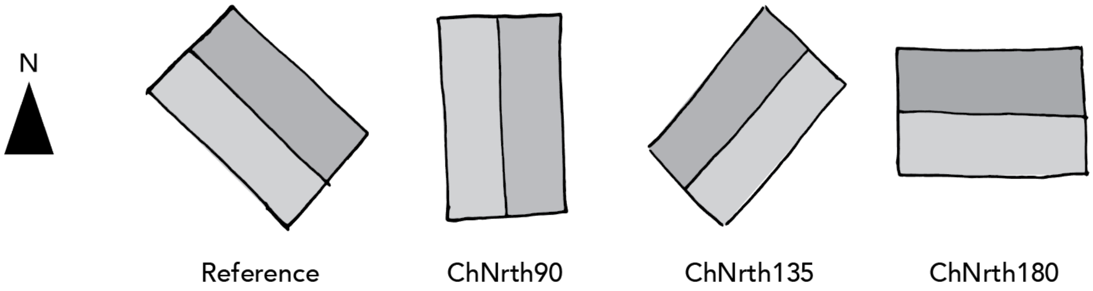
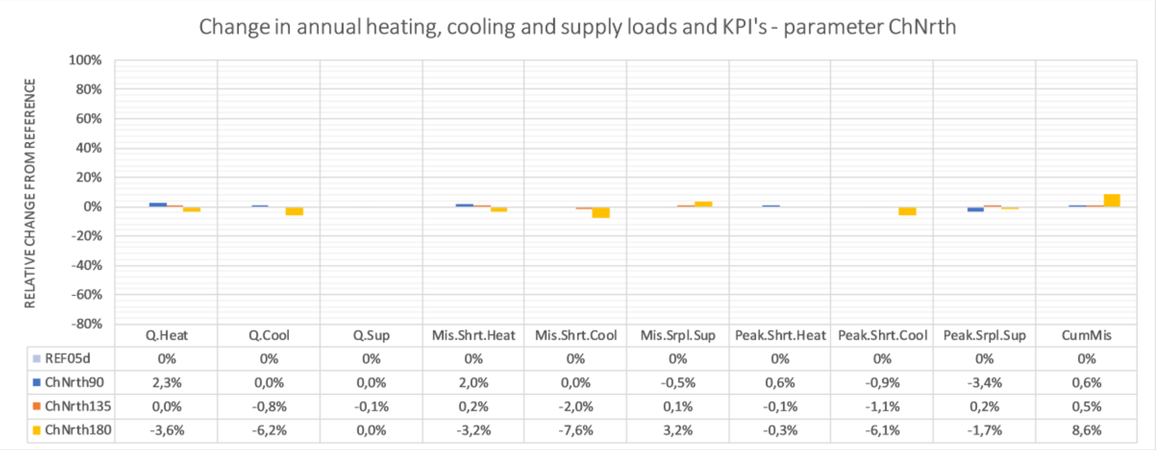


Figure 85: The reference design is rotated in steps of 45°, resulting in all possible orientations considering a symmetric design and steps of 45°

6.8.3 Results

From Figure 86 it becomes clear that adjusting the rotation of the reference design has very little effect on the heating, cooling and supply loads and the KPI's. In all cases, the variant ChNrth180 (which is rotated 135° compared to the reference) has the biggest effect on the KPI's. For all KPI's this variant results in a lower mismatch, except for the supply surplus mismatch and the cumulative mismatch. Figure 87 shows that the effect of changing to variant ChNrth180 is biggest for cooling. The effect on the mismatch is limited and becomes most clear from May till August.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ChNrth90	2,3%	0,0%	0,0%	2,0%	0,0%	-0,5%	0,6%	-0,9%	-3,4%	0,6%
ChNrth135	0,0%	-0,8%	-0,1%	0,2%	-2,0%	0,1%	-0,1%	-1,1%	0,2%	0,5%
ChNrth180	-3,6%	-6,2%	0,0%	-3,2%	-7,6%	3,2%	-0,3%	-6,1%	-1,7%	8,6%

Figure 86: The effect of changing the orientation on the heat, cool and supply flows and the performance indicators

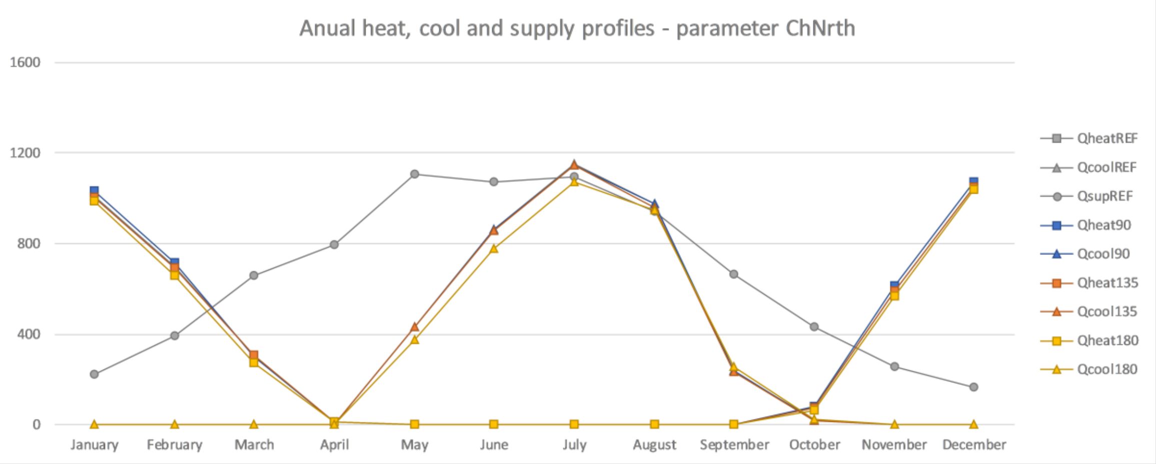


Figure 87: The effect of changing the orientation on the annual heat, cool and supply profiles

6.8.4 Interpretation

The rotation of the complete building has very little effect with this design. It should be noted though, that this probably is the result of the symmetric design. The reason that variant ChNrth180 results in a lower mismatch, is because of the decreased heating load in winter and the slightly decreased cooling load in times of no supply. This reduced heating loads are the result of a larger window surface orienting to the south-direction, in which solar radiation is most powerful. The effect on the cooling loads is smaller, because the window is oriented straight to the south; the point where the sun is high, especially in summer.

6.8.5 Conclusion

The parameter study shows that the effect of changing the orientation of the reference design is very limited.

Variant ChNrth180, in which the longest side is oriented straight to the south, has the lowest mismatch. The difference compared to the reference, however, is very little. Changing the orientation has the biggest effect in summer, probably because of the biggest window orienting straight to the south, i.e. the moment when the solar radiation is most powerful.

It is concluded that:

- Changing the orientation of the complete building is not very effective for achieving energy-flatness. This might be the result of the symmetrical reference design. Therefore, the effect of changing orientation on other designs should be studied separately.
- A little mismatch decrease is achieved when orienting the building straight to the south, because it results in a lower heating load in winter.
- It is expected that orientation is more effective for other building specific parameters like windows and supply surfaces.

Changing a buildings orientation is most often difficult, due to urban restrictions and limitations. For existing buildings, it is rather impossible. In the case of a new, autonomous building with little urban restrictions, the orientation might be changed to the preferred direction. However, when designing a new building, elements might be placed at certain facades based on their orientation, resulting in not changing the complete buildings orientation, but rather tactically placing building elements. The earlier this is considered in the design phase, the easier it is to implement it.

6.9 SUPPLY: SHARE OF ENERGY PRODUCTION PER ORIENTATION

6.9.1 Background

This parameter study analyses the effect of increasing the supply per surface, by multiplying the initial 3% of the total solar radiation potential by a factor of 8 per surface (see 5.2.3 The mismatch for more information on the 3% supply factor).

In this research, a share of the solar potential represents supply. This way, no preliminary direction is given to how the supply should be used, meaning it can be still be transformed to passive heat energy (e.g. windows), electricity (e.g. photovoltaics) or active heat energy (e.g. solar collectors). Solar energy supply is orientation dependent and thus the extent to which solar supply can be introduced on a buildings surface highly depends on the architecture and the type of supply desired.

The abbreviation of this variant is ***Sup****, which is used as name for the simulations.*

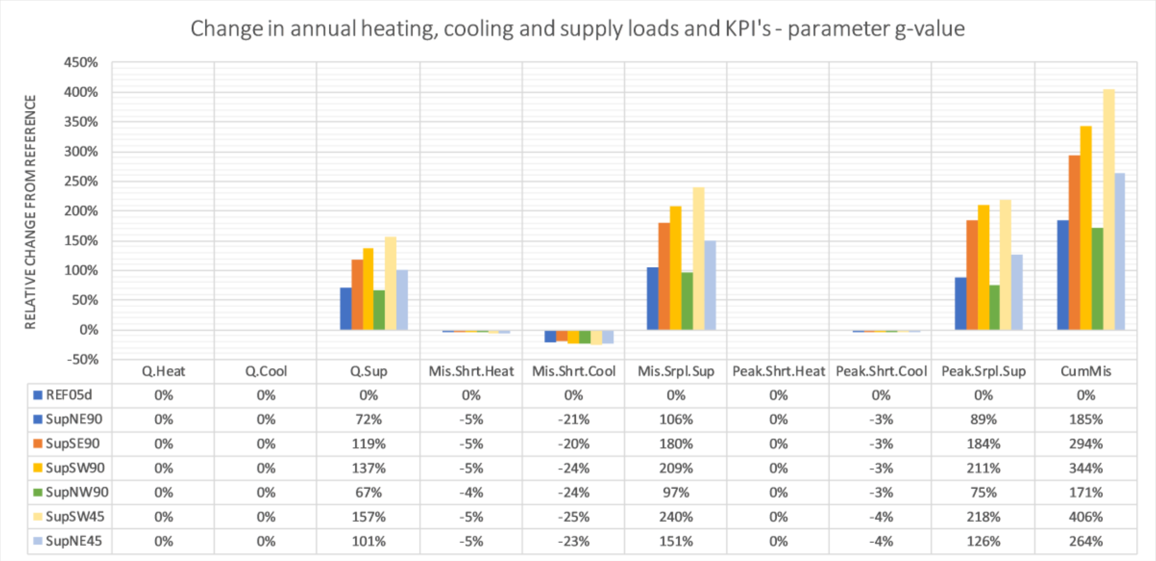
6.9.2 Parameter change

Section 5.2.3 The mismatch describes how the solar potential is multiplied by a factor of 0.03, in this parameter study this factor is multiplied by 5 resulting in a factor of 0.15. The variant study, one facade has an increased supply factor. This provides results in which the effect of increasing the supply of one facade becomes visible. The surfaces are named by their orientation and their angle relative to the ground (e.g. NE90 is the north-east wall and NE45 is the north-east roof surface). The following variants are studied.

		REF05d	SupNE90	SupSE90	SupSW90	SupNW90	SupSW45	SupNE45
Parameter change								
NE90 supply factor	-	0.03	0.15	0.03	0.03	0.03	0.03	0.03
SE90 supply factor	-	0.03	0.03	0.15	0.03	0.03	0.03	0.03
SW90 supply factor	-	0.03	0.03	0.03	0.15	0.03	0.03	0.03
NW90 supply factor	-	0.03	0.03	0.03	0.03	0.15	0.03	0.03
SW45 supply factor	-	0.03	0.03	0.03	0.03	0.03	0.15	0.03
NE45 supply factor	-	0.03	0.03	0.03	0.03	0.03	0.03	0.15
Inevitable side changes								
none								

6.9.3 Results

In contrast to the other parameter studies, changing the supply factor does not affect the heating or cooling loads. From Figure 88 it becomes clear that for the supply flow and all supply KPI’s the southern facades, SE90 and SW90, and the southern roof SW45 have the biggest impact. Next is the northern roof NW45, followed by the northern facades. For the heating and cooling shortage mismatches, the effect is approximately equal for a change in any surface. The effect on cooling shortage, however, is bigger than on heating shortage. The variants result in a decrease of cooling shortage of 20 to 25% and a decrease in heating mismatch of 4 to 5%. The peak shortage for heating is not affected by this parameter, and the peak shortage for cooling only slightly. The cumulative mismatch is affected the most extreme by this parameter change.



	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
🟦 REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
🟦 SupNE90	0%	0%	72%	-5%	-21%	106%	0%	-3%	89%	185%
🟧 SupSE90	0%	0%	119%	-5%	-20%	180%	0%	-3%	184%	294%
🟨 SupSW90	0%	0%	137%	-5%	-24%	209%	0%	-3%	211%	344%
🟩 SupNW90	0%	0%	67%	-4%	-24%	97%	0%	-3%	75%	171%
🟨 SupSW45	0%	0%	157%	-5%	-25%	240%	0%	-4%	218%	406%
🟦 SupNE45	0%	0%	101%	-5%	-23%	151%	0%	-4%	126%	264%

Figure 88: The effect of changing the supply factor on the performance indicators (N.B. deviant scale)

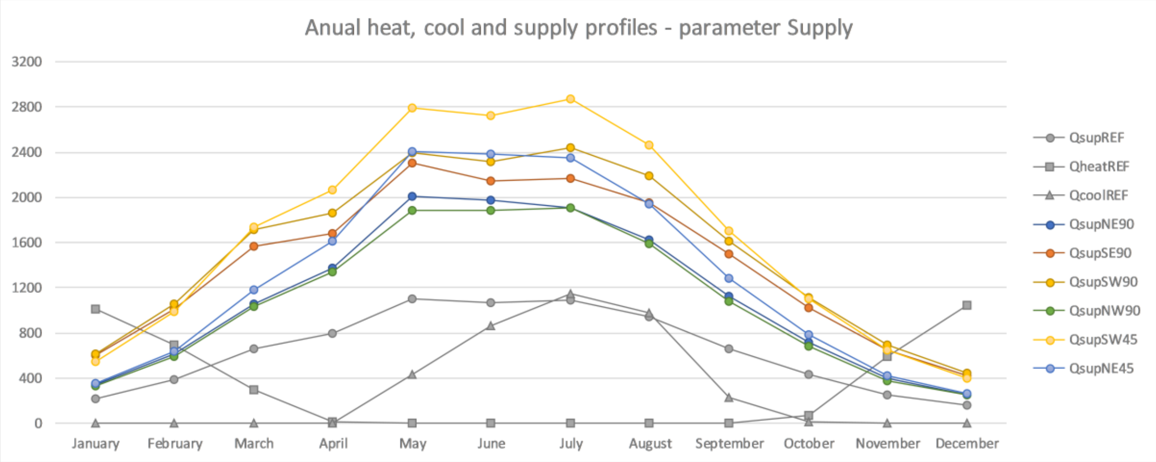


Figure 89: The effect of changing the supply factor on the monthly demand and supply profiles

Figure 89 shows that the shape of the supply curve stays more or less equal compared to the reference. The shape changes the most for NE45, which has low supply in winter and a high increase of supply in summer. In all cases, the effect on increasing the supply is the least for the northern facades NE90/NW90 and the highest on the south-west roof SW45. The effect is approximately equal for the other faces. Moreover, the increase in supply in from November till February still does not match the demand, though it does decrease the energy shortage.

6.9.4 Interpretation

The big effect on the supply surplus compared to the effect on the heating and cooling shortages is explained by the increased solar radiation in the summer. Supply surplus occurs mostly in summer months, and the relatively high amount of solar radiation in these months is multiplied by a factor five per surface. The shortage becomes smaller because of the increased supply in winter, though the figures show that the increase of a factor 5 for one surface is still small and not enough to diminish the monthly mismatch in November, December, and January.

The reason that for all KPI's the increase patterns for the surfaces is equal, is the logical result of the linear multiplication of the supply per surface. The southern roof surface SW45 is the affected the most, because of its orientation to the sun's most powerful direction. For the same reason, the northern facades are affected the least. The increased effect on surface NE45 in summer, has to do with the solar altitude, which is higher in summer.

All variants increase the mismatch. This is explained by the fact that this parameter change is the most affect in summer, a period in which energy surplus already exists. The surplus greatly increases because of the increased supply. The small supply increase in winter, which diminishes the shortage, does not compensate the increased surplus in summer.

6.9.5 Conclusion

Increasing the supply surface directly and linearly affects the supply for every surface, though the amount at which the supply increases differs per surface orientation.

All the variants increase the mismatch, because the effect of changing supply is the biggest in summer, when a supply surplus is already present in the reference design. The shortage is slightly decreased, whilst the energy surplus is highly increased. The effect of this parameter is the biggest on the south-west roof and southern facades, followed by the north-eastern roof. The effect is the lowest on the northern facades.

It is concluded that:

- A seasonal approach is desired for energy-flatness. Increasing the supply surface diminishes the heating shortage in winter. An increased supply surface in summer, however, results in a big supply surplus.
- The effect of changing the supply surface is the biggest on the south-western roof surface, followed by the southern facades.
- Supply should be increased in the months of November till February

In terms of architecture, adjusting supply requires some definitions on installation types and efficiencies. In this study, the supply side is simplified to a single number by multiplying the solar potential with a factor 0.03. This factor represents a 15% coverage of surface and a PV efficiency of 20%. In that sense, increasing the supply surface with a factor 5, is achievable by increasing the PV surface area.

While doing this, factors like user sight, architectural design and orientation should be considered. Not all walls can have a 90% coverage of PV for example, simply because it would take away the ability to place windows. Moreover, supply could also be represented by other types of energy collection. See 5.2.2 for more information of the type of energy supply that could be used.

6.10 CONCLUSION

A set of nine parameters was studied in this chapter. For every parameter study, the effects on the heat profile, cool profile and supply profile and the KPI's were analysed. Most parameters provide different and significant effects on the demand and supply profiles. Below, the main findings are discussed, as well as the resulting input for the energy-flat design studies, as well as a short reflection on this parameter study in particular.

6.10.1 General findings

Almost all parameters result in a significant effect on the KPI's. The only exceptions are the orientation parameter and the thermal mass. The orientation shows very little effect on any of the KPI's, although one orientation (ChNrth180) relatively has the biggest effect. The thermal mass showed a clear pattern when it was decreased to 40% compared to the reference. Increasing the thermal mass, however, resulted in a very small effect on the KPI's. It was concluded that thermal mass is effective, but only if it is superficial, effective mass.

For the parameters GeoSrf, SrfIns, SrfThm, CmfVen and Sup, the KPI's behave equally on a change in parameter, meaning that all KPI's decrease as the parameter changes, or all KPI's increases if the parameter changes in the other direction.

For the other parameters, CmfTmp, WinShr, WinGvl and Orientation, the KPI's of surplus and shortage behave oppositely, meaning that an increase in surplus mismatch of a parameter change, automatically results in a decrease of shortage mismatch and vice versa. These parameters are also characterized by little effects on the annual mismatch, because changes in surplus and shortage compensate each other.

The seasonal characteristics largely determine the effect of parameters, with a high heating load and low supply in winter, and a high cooling load with high supply in summer. For almost all parameters, a different approach in winter and summer is desired to diminish the mismatch of supply and demand. Moreover, for most parameters that desire a different approach in summer and winter, also a different approach for day and night is beneficial.

6.10.2 Input for energy-flat design

For every parameter, the most optimal solution for energy-flatness is selected. These solutions will be combined in the first energy-flat design, as discussed in the next chapter.

	Best for energy-flatness	**Climate dependent**	**Remarks**
Geometry - energy losing surface (GeoSrf)	Minimize energy-losing surface		Has a bigger effect on supply (unintended) than on demand

Surface - insulation (SrfIns)	Maximize thermal insulation		
Surface - thermal mass (SrfThm)	Maximize thermal mass		Focus on effective thermal mass, i.e. superficial mass
Comfort - ventilation rate (CmfVen)	Minimize ventilation rate	Winter; minimize Summer; maximize when Tout < Tin	Minimizing ventilation results in higher heating loads when Tout<Theat and higher cooling loads when Tout>Tcool
Comfort - temperature range (CmfTmp)	Maximize temperature range	Winter; lower heating setpoint Mar-Oct, exc. Jul/Aug; lower cooling to increase demand	Consider comfortable indoor climate
Windows - share per orientation (Shr)	Minimize window share on northern facades	Winter; increase share solar oriented windows when sun is present (not at night or cloudy days) Summer; increase window share to generate cooling load	Window surface increases solar radiation gain, but also increases heat losses
Windows - g - value per orientation (Gvl)	Maximize g-value	Winter; maximize g-value on solar oriented windows Summer; minimize g-value on solar oriented windows to prevent excessive cooling	Increasing g-value increases solar radiation gain The south-west facade has the biggest influence
Geometry - orientation (ChNrth)	Orient to south		Very little effect
Supply - share of energy surface (Sup)	none	Winter; maximize supply surface Mar-Oct, exc. Jul/Aug; lower supply depending on demand	The supply is a simplification of real supply, and may be changed depending on installation efficiencies

The table above shows that for every parameter there is one single solution to minimize the mismatch, but that for five out of nine the mismatch can be decreased more by having season-dependent parameters. How this should be translated into design will be explained in the next chapter.

6.10.3 Reflection

In this study, the results are only analysed on the annual scale with monthly values and annual totals. The energy studies done to provide these values, also contain hourly values. A more elaborate analysis in different timesteps (e.g. week, day) might provide new insights. Such analysis is useful, but does (unfortunately) not fit within the timeframe of this research.

Four variants are set-up per parameter study and from this the relation is explained. Mathematically seen, a set of four variants is insufficient to prove a certain correlation. Nevertheless, most variants show a logical pattern that can be explained. Therefore, it is assumable that the conclusions made in this chapter are a funded base for further research. If one would want to use these parameters for other designs, it is recommended to do a more elaborate study with more variant per parameter, different reference designs and mutual relations of parameters.

The list of parameters is not exhaustive; a designer could come up with more parameters that might influence the buildings energy performance. The parameters studied in this chapter, however, are assumed to cover the most influencing and possible building properties in terms of energy.

7 ENERGY-FLAT BUILDING DESIGN

This chapter goes into the final energy-flat building design. The final product is an example of an almost completely energy-flat design. According to the initial methodology, the first energy-flat design is made in three design steps, of which the first two are a separate approach to adapting demand to supply and vice versa. The knowledge of these two preliminary designs in translated into an energy-flat design toolbox, containing design principles that contribute to energy-flat design. After this, the final design is described elaborately, including performance, building installations and a reflection. This chapter is an elaborate section that provides insight in the design by research approach.

7.1 DESIGN 1A - DEMAND ADAPTED TO SUPPLY

In the first design, the demand is adapted to the supply. The supply is assumed to be unadaptable. The design is made by doing several iterations; the starting point is the conclusion from the previous chapter, in which for every parameter study the most optimal value is chosen. Then the design is optimized by constantly finetuning the parameters. Conclusions on optimal demand-adaptation solutions are drawn from this optimization iteration. The conclusions are summarized and translated in an overview of demand-oriented design principles.

7.1.1 Optimization

The optimization iteration is essential for finding energy-flatness solutions whilst simultaneously learning from the intermediate results. The complete optimization analysis is described in Appendix 5. Below, the most relevant changes per optimization step and the conclusions are described.

	Changes	Analysis & conclusions
1A_DEM_v1	- All based on conclusions parameter study	1. Excessive cooling loads by high southern window share with high g-value 2. Winter heating demand can be as low as supply on monthly timescale
1A_DEM_v2	- Lower southern window share - Nocturnal insulated blinds added - Solar shading added in summer	1. Low cooling and heating loads result in monthly supply surplus 2. Nocturnal heating demand peaks cause mismatch in winter 3. Cooling load occurs after sunset
1A_DEM_v3	- Thermal mass is added	1. Superficial thermal mass is effective for mitigating daily differences 2. Thick thermal mass is effective for

		bridging temperature differences over multiple days
1A_DEM_v4	- Incorrect input, corrected in next design	
1A_DEM_v5	- ventilation schedule is with minimized night ventilation in winter - sunshades are active till 21:00h - higher southern window share	1. ventilation schedule in winter results in a lower heating load 2. without nocturnal ventilation, the only two significant heat flows are infiltration and transmission through glazing. 3. sunshading adaptations result in lower cooling load 4. heating mismatches still occur in the same day as supply surpluses. Loads should be shifted.
1A_DEM_v6	- pre-heating and pre-cooling in times of supply surplus - ventilation maximizes when $T_{out}<T_{in}$ and cooling load is present.	1. pre-heating and –cooling is very effective for energy-flatness 2. overall heating and cooling loads are higher, but the peaks are smaller

7.1.2 Conclusions

From the optimization process, the following conclusions have been made in regard to energy-flat design. These conclusions are translated into design principles in *7.3 Energy-flat design toolbox*

Pre-heating and pre-cooling are very effective

Extra heating (i.e. bringing the indoor temperature above the heating setpoint) and extra cooling in times of sufficient supply is a very effective measure for matching supply and demand. It increases demand in times of high supply and decreases demand in times of little supply. There are two major boundary conditions. The first one is that temperatures should be kept between comfortable limits. Experience and personal preferences will determine what these limits are. The second boundary conditions is the availability of sufficient thermal mass to store the heat temporarily.

A downside of this approach is that the actual outdoor temperatures and potential supply cannot be predicted precisely, while a higher predictability results in a more effective functionality.

Thermal mass is effective

Both superficial and deep thermal mass are effective. The superficial thermal mass mitigates peaks within a time-period of approximately 24 hours. Deeper thermal mass (from 15-30cm) is effective for mitigating peaks over several days.

Nocturnal ventilation cooling in summer is effective

Using natural ventilation at night in summer effectively cools a building, resulting in lower cooling loads during the next day. Especially the morning peak and evening peak, which are fatal for energy-flatness, are mitigated.

Minimizing winter heat load in general is necessary

Apart from time-related approaches, for energy-flatness it is required to reduce the heat demand in winter. Even if matching the heat demand would be easily possible, the total amount of supply available is still not able to match the demand. This means that most state of the art energy-saving measures will also apply to energy-flat housing.

Shifting ventilation during winter is effective

Having an adaptive ventilation rate in winter is effective. Ventilation should increase in times of a low temperature difference between indoors and outdoors (i.e. the afternoon) and ventilation should be minimized in times of a high temperature difference (i.e. midnight). In all cases, a comfortable indoor climate should be considered.

Minimizing infiltration and minimizing glazed transmissions in winter is essential

In demand-optimized situations, nocturnal infiltration losses and glazing transmission losses become significant in the heat balance. To achieve energy-flatness, these two energy-flows should be minimized.

Adaptive systems in general are essential

Adaptive installations are a great solution; lots of mismatches occur based on differences between indoor and outdoor temperatures and can be minimized if a building adapts to that. To achieve this, a self-learning, smart system with sensors indoors and outdoors and weather analysis is required.

7.2 DESIGN 1B - SUPPLY ADAPTED TO DEMAND

In this design, the supply profile is adapted and the demand is assumed to be unadaptable. A design iteration is done with several variants in order to find the most optimal solutions for adapting supply. Adaptation of supply in this case, only considers adapting the share of use of solar potential on the surfaces of the reference design. The solutions are summarized and translated into design principles.

7.2.1 Optimization

The optimization iteration consists of several design variants, in which parameters are adjusted one by one to find the optimal solutions. The intermediate conclusions provide insight in the functionality of the parameters. The complete iteration analysis is found in Appendix 6. Below, the most relevant changes per optimization step and the conclusions are described.

The starting points are the reference design and the conclusions of the parameter study for supply. One change is made compared to the reference design; the orientation is set to 0°. The parameter study showed that this has very little effect on the supply and demand, but this orientation improves the easiness for modelling and makes the references more clear and short.

	Changes	**Analysis & conclusions**
1B_SUP_v1	All surfaces have the following share-schedule: 0.1 in Nov,Dec,Jan,Feb 0.015 in Mar,Apr,May,Jun,Sep,Oct 0.03 in Jul,Aug	1. the supply potential in the morning should be used more effectively to fulfil heating and cooling demands 2. the late evening supply should be increases as much as possible
1B_SUP_v2	East and west share is 0.1 all year South and south-roof share is zero	Heating shortage increases in this variant. However, the supply profile is more similar to the demand profile. Southern supply is essential for winter demand, but eastern and western supply provide a better matching profile.
1B_SUP_v3	Evolutionary solver with an annual value per share, and the following aim: *Min[heat short + cool short + supply surplus]*	When supply surplus, heating shortage and cooling shortage are valued equally, the lowest total mismatch is achieved by reducing the supply. This results in an annual energy shortage (not energy-neutral).
1B_SUP_v4	The same evolutionary solver, but now supply is only value 20%. Resulting in: *Min[heat short + cool short + supply surplus]*	A relative high share of supply potential on the north surfaces results in a lower mismatch. This is probably the result of the bigger share of diffuse supply potential, which is more stable, on these surfaces.
1B_SUP_v5	Evolutionary solver to find the inevitable mismatch. Supply surplus is not considered a problem. Resulting in: *Min[Heat short + Cool short]*	1. The heating shortage is determined by the nights 2. On cloudy days, the supply potential of the building is not sufficient to match the demand. 3. On cloudy days, the supply potential per surfaces is not dependent on the orientation

7.2.2 Conclusions

From the optimization process, the following conclusions have been drawn in regard to energy-flat design. These conclusions are translated into design principles in *7.3 Energy-flat design toolbox .*

Southern façade has the highest potential, but east and west match the demand

In winter, the southern facade is the most effective for supply potential per m^2. However, the east and west facade are most effective for matching the supply profile with the heating demand. For energy-flatness, east and west supply is desired, but the reduced supply potential per m^2 should be considered.

In summer, the southern facade provides a higher supply per m^2, but this extra supply is not needed to achieve sufficient daily supply. The solar power on eastern and western orientations is sufficient for matching the daily demand. However, the southern supply should not be completely eliminated, because that results in a drop of supply in times of high cooling loads in summer.

Achieving the smallest mismatch for cooling, heating and supply results in a situation that is not energy-neutral

When supply surplus, heating shortage and cooling shortage are valued equally and only supply adaptations are considered, the lowest total mismatch is achieved by reducing the supply. It results in an annual energy shortage; a situation that is not energy-neutral. This is probably the result of the high supply surplus that occurs in summer when the supply surface is slightly increased in favour of the winter; decreasing the share of solar supply results in a big reduce of supply surplus, and a small reduce of heating shortage.

From an optimization point of view, a higher share of northern supply surface is beneficial, as is shown by the evolutionary solver.

A relatively high northern supply share results in a better match. This is probably the result from the north oriented surfaces providing a stable amount of (diffuse) supply and do not result in a high supply surplus because they are not oriented towards the solar power side. In other words; the higher share provides desirable supply potential in winter, whilst not causing excessive supply loads in summer. However, it should be noted that in the simulation diffuse and direct solar power are valued equally as potential supply. Depending on the energy transforming system, direct solar power might be more valuable and in that case this conclusion applies to a lesser extent.

Supply-oriented solutions counteract eachother

When comparing all the variant studies, it is concluded that better values for one KPI often result in worse values for the other KPI’s. Variant 2 in which east and west supply are increased, for example, results in a very low heating mismatch, but has higher supply and higher cooling mismatches. Variant 7, which optimizes for all mismatches, results in a, but the values clearly show that it is one way in between.

The mismatch that is unsolvable by supply

In the night, there is simply no solar potential hence no supply available, if solar is considered the only supply source. To achieve energy-flatness, both heating and cooling loads that occur after sunset and before sunrise, should be eliminated.

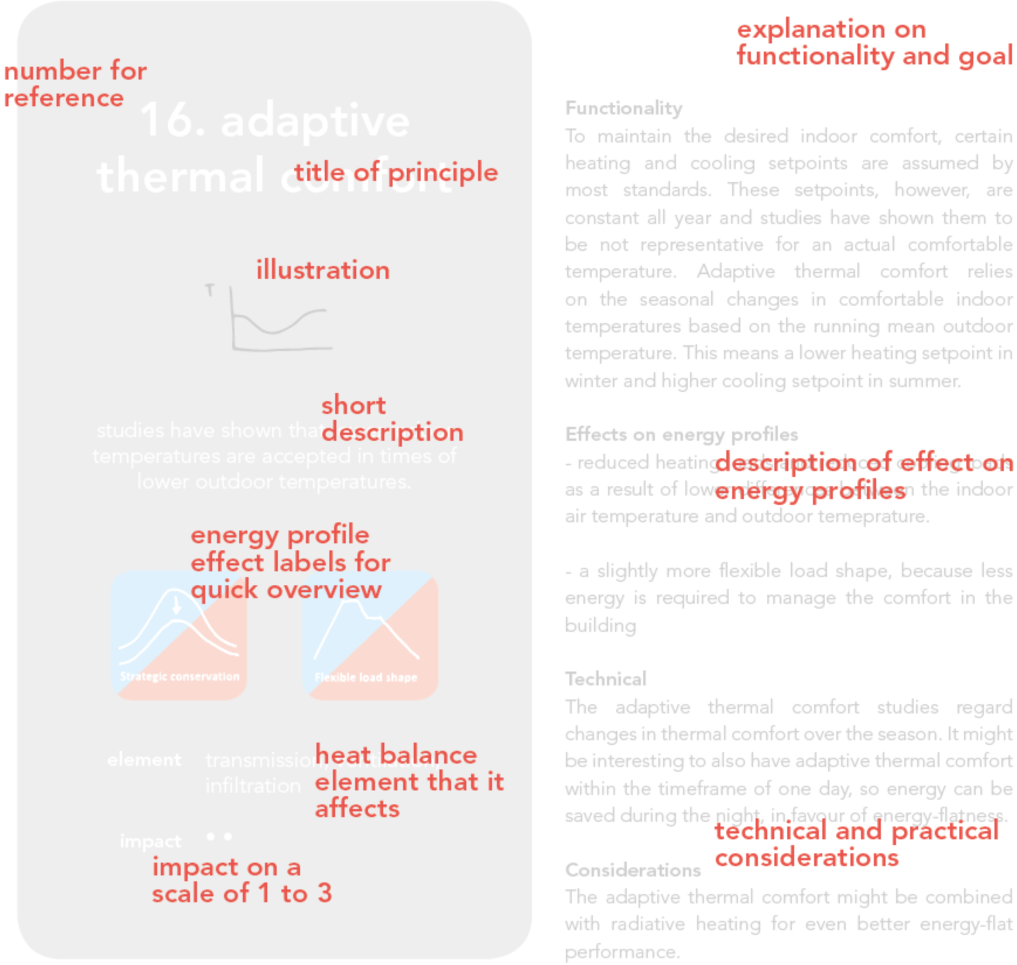
A study is done in which supply surplus is neglected. This automatically results in a design in which heating and cooling shortage are diminished as good as possible. The remaining heating and cooling shortage are considered inevitable in a situation where only supply can be adapted. The inevitable heating shortage is 2843,3 kWh with a maximum peak of 3.3 kWh in one hour. The inevitable cooling surplus 763.8 kWh with a maximum peak of 4.0 kWh.

7.3 ENERGY-FLAT DESIGN TOOLBOX

The residential energy mismatch can be solved partly by architectural design. The previous research on energy-flatness has shown which energetic goals should be achieved for energy-flatness. The related goals can be found in the conclusions of the parameter study (6.10), and the two preliminary energy-flat designs (7.1.2 and 7.2.2). Based on these goals, a set of principles is described which could contribute to achieving these goals. Next, these principles are linked to the previously mentioned energy-flatness goals. Thereafter, two examples of integrated design concepts are shown, which serve as an inspiration for designers and as means to explain the relation of some principles.

7.3.1 The design principles

In total, 35 design principles in favour of energy-flatness are described. Because showing all the principles in this chapter would interrupt the flow of the report, the set of principles is to be found in Appendix 8. The design principles are organized using a simple, intuitive format, which is explained in Figure 90.



studies have shown that [illegible] temperatures are accepted in times of lower outdoor temperatures.

Functionality

To maintain the desired indoor comfort, certain heating and cooling setpoints are assumed by most standards. These setpoints, however, are constant all year and studies have shown them to be not representative for an actual comfortable temperature. Adaptive thermal comfort relies on the seasonal changes in comfortable indoor temperatures based on the running mean outdoor temperature. This means a lower heating setpoint in winter and higher cooling setpoint in summer.

Effects on energy profiles

- reduced heating [illegible] as a result of lower difference [illegible] the indoor air temperature and outdoor temeprature.

- a slightly more flexible load shape, because less energy is required to manage the comfort in the building

Technical

The adaptive thermal comfort studies regard changes in thermal comfort over the season. It might be interesting to also have adaptive thermal comfort within the timeframe of one day, so energy can be saved during the night, in favour of energy-flatness.

Considerations

The adaptive thermal comfort might be combined with radiative heating for even better energy-flat performance.

Figure 90: Explanation of the design principle format, which is used in the appendix

The energy profile effect labels are based on the six load shape objectives, as designed by Gellings and Smith (1989). These objectives are more elaborately explained in *2.3.1 Energy flexibility in the energy system*. Every load shape objective can be applied on every energy profile, resulting in 18 possible labels in total for cooling (blue), heating (red) and supply (yellow). See Figure 91.

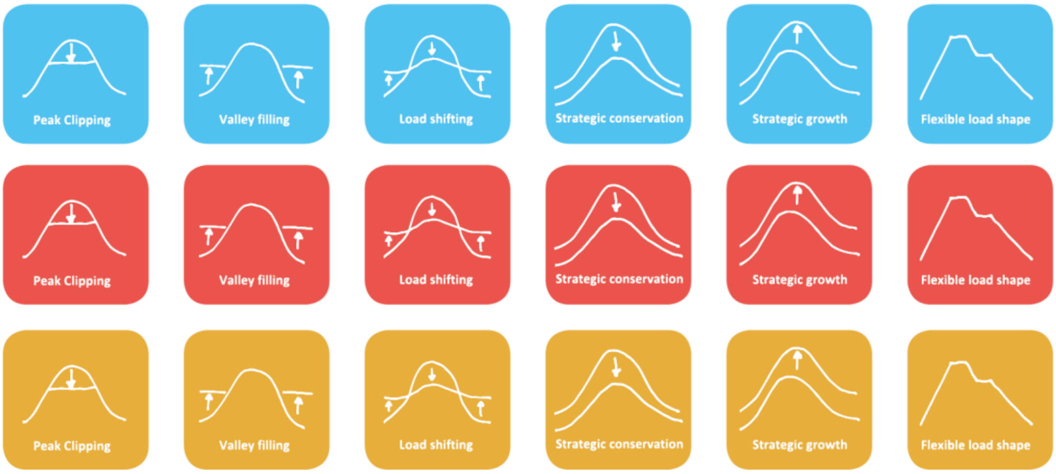


Figure 91: Overview of energy profile effect labels for cooling (blue), heating (red) and supply (yellow)

7.3.2 The design principles in relation to energy-flatness goals

This section forms a bridge between the energy-flatness goals, as concluded in chapter 6 and 7, and the energy-flatness design principles, as described in the previous section (7.3.1) and shown in Appendix 8. The energy-flatness goals are conclusions from elaborate research using the energy-flatness simulation tool and several parameter- and design studies. Though substantiated, they do not give much direction for energy-flat design by themselves. The design principles, on the other hand, have a very abstract nature. To what extent they influence the energy-flatness is hard to state. The effect strongly depends on the combination of principles and the total design, hence it can only be concluded by simulating a complete design. Because there is no quantified effect for every principle, they may seem a little bit random and there is a risk of them being used in the wrong way or for the wrong goal. By categorizing the design principles by the substantiated energy-flatness goals, it is clear how the energy-flatness goals could be achieved in design.

In the overview on the next pages, the design principles as described in the previous paragraph are linked to the energy-flatness goals that were concluded from concluded by quantified research of the previous sections. The principles are numbered, and elaborate explanations can be found in Appendix 8.

Conclusion	Source	Principles related
Minimize energy-losing surface	Parameter study	1 2 5 6 10
Maximize thermal insulation	Parameter study	3 4 5 6 7 10 18 19
Maximize thermal mass	Parameter study	1 2 8 9 10 11 12 27
Minimize ventilation rate or make it adaptive to seasons	Parameter study	17 24 25 26 27
Maximize temperature range or make it adaptive to season	Parameter study	14 15 16 17
Increase southern window share and decrease northern window share	Parameter study	5 18 19 20

Maximize solar gain on southern facades in winter, minimize in summer	Parameter study	13 18 20 21 22 23 32 35
Orient to south (has little effect)	Parameter study	13 14 32 33
Maximize supply share surface in winter and optionally lower in summer	Parameter study	32 33 34 35
Pre-heating and pre-cooling are very effective	Design 1A	2 8 9 10 11 12 14 25
Thermal mass is effective	Design 1A	2 8 9 10 11 12 27
Nocturnal ventilation cooling in summer is effective	Design 1A	25 26 27
Minimizing winter heat load in general is essential	Design 1A	1 3 4 5 6 7 14 15

		16 18 19 26 28 29 30 31
Shifting ventilation during winter is effective	Design 1A	25 26 27
Minimize transmission through glazing in winter	Design 1A	1 5 7 14 15 16 18 19
Adaptive systems are required	Design 1A	6 13 15 16 17 18 21 22 25 26 33 35
East and western façade have the highest potential match	Design 1B	13 33
A higher share of northern supply surface is effective	Design 1B	13 32 33 34

7.3.3 Design ideas for energy-flatness

In this section, three suggestions for energy-flat design in different context are described. Although the major share of this thesis focusses on quantifying the precise effect of certain parameters on the energy-flat performance, this section goes one step further and shows how the design principles of the toolbox could be combined in different contexts. Because it is mostly a look ahead, the detail level of this section is abstract.

When designing energy-flat buildings, the following steps should be considered:

1. Desires of the energy system

   What does the energy system, that compensates for the mismatch, desires? Is there a grid connection or a battery? And if so, what are the power and storage constraints?

2. Potentials of the context

   As with any architectural design, the potentials of the context should be investigated. Which can contribute to energy-flatness? And what are the constraints in terms of geometry and orientation?

3. Design using energy-flat design principles

   The concept design should contain energy-flat design principles. Energy-flatness is only possible if the design is adapted to it in early stages. This also is one of the reasons that the design principles are visualised at such an abstract level.

4. Simulate the design and improve by iteration

   The early concept design should be simulated using the energy-flatness simulation tool. With the results, the design can be optimized by reviewing the principles used and implementing new principles.

In this section, this approach is demonstrated for three different architectural and urban contexts. Only the second and third step are shown, because the first one depends on the actual context and its possibilities are explained in *3.3 Key performance indicators* and the fourth step is explained in the final design explanation. Explaining the second and third step with examples serves as an inspiration for designers and to show the relation between the design principles.

Example 1: a small floating district with floating homes

This example is inspired by the Amsterdam project *Schoonschip* (Stichting Schoonschip, 2018). This example is a group of six large houses floating on water, in the city of Amsterdam.

Potentials and threats of the context

Figure 96 shows a sketch of the context and its potentials. First of all, the group of homes floats, which allows for rotation of the buildings. This rotation can be used at building level for adaptive orientation. The floating also means that the homes will have one grid connection together. In other words, they do not have to be all flat by themselves; the buildings can use each other to create combined energy-flatness. Second, this shared grid connection and placement in the water also allows for the possibility to have collective renewable energy supply. This might be beneficial in terms of scale-efficiency. Lastly, there are not much shadow casting elements on the water, resulting in the possibility to make effectively use of the sun.

The biggest advantage of this location, also induces some disadvantages. The water results in a higher energy losses due to higher windspeeds

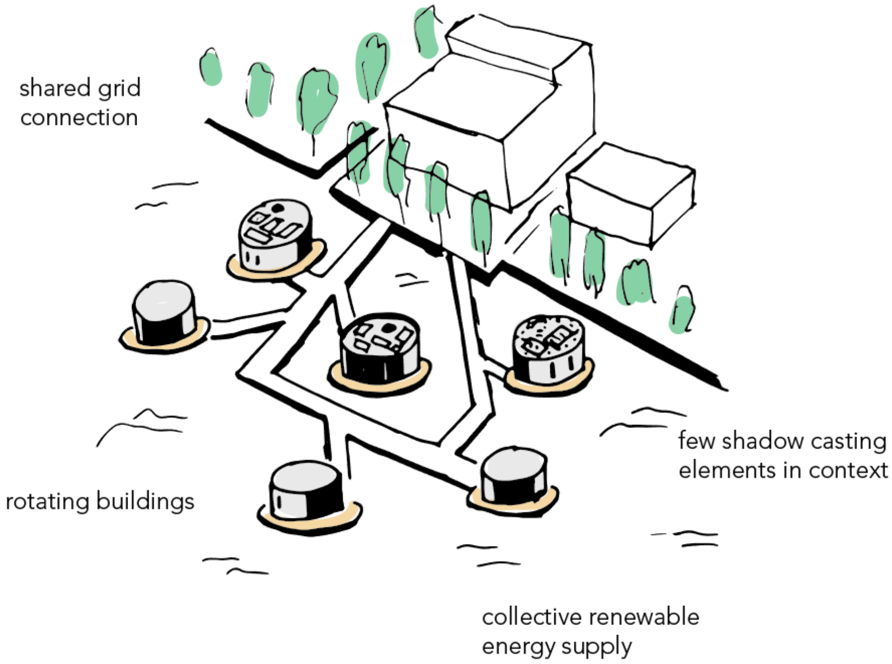


Figure 92: Context potentials of example 1; floating homes

<u>Design using energy-flat design principles</u>

Building in water creates some useful potentials in terms of energy-flatness. Figure 93 shows the overview of applied design principles in the design. Below, some considerations are described.

The possibility of the rotation of the building is extremely effective. Instead of having design principles that find a balance between solar gain in winter and solar blocking in winter, like the principles of '*high g-value glass on south'* and *'adaptive sunshading'*, now the complete building can rotate towards or away from the sun. The downside is the tactical orientation of PV for example. There is no optimal orientation for PV, because the building will rotate depending on the desire for passive solar gain.

Another interesting aspect is the floating on the water. The water serves provides an environment with a highly conductive material with a constant temperature. This will reduce heat losses in winter and optimize the use of a heat-pump for example. The downside is that a floating, rotating home cannot be too heavy, this will limit the possibilities in terms of thermal mass. This can slightly be compensated using PCM's.

Apart from these location specific properties, the building can be optimized using design principles that focus on the building itself; adaptive ventilation rates, radiative heating, natural ventilation, adaptive thermal comfort et cetera.

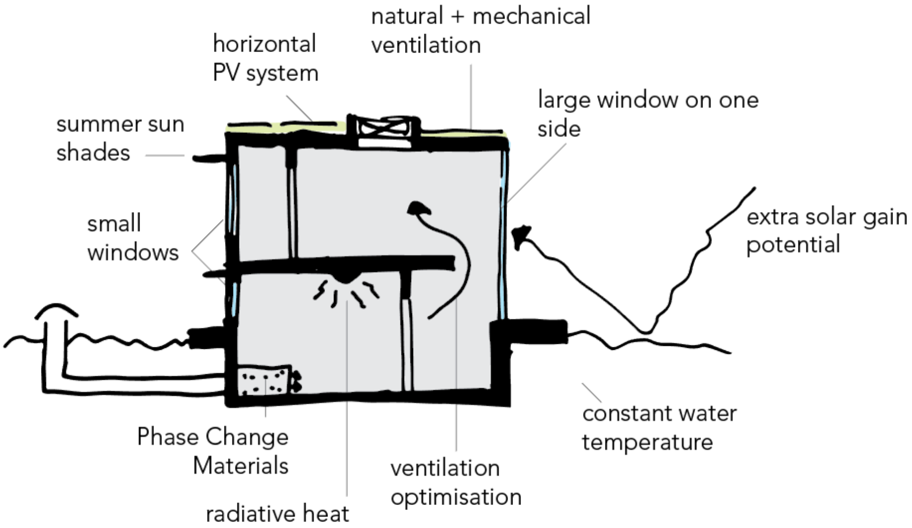


Figure 93: Sketch design for a detached energy-flat building on water

Example 2: typical Dutch rowhouses

This example considers the fact that in the Netherlands, only 1% of the total building stock is renewed every year. This means that building optimizations should also focus on the existing building stock. An existing typical Dutch row house is considered.

Potentials and threats of the context

Figure 94 shows the potentials of the context of this example. The main potential is the fact that the buildings are attached to each other on two sides (apart from the corner houses, of course). This results in a heat exchange between the buildings, resulting in a lower energy loss and a more stable temperature. The orientation of the building block highly determines how it should be adapted; a south-north orientation would be most beneficial for energy-flatness in terms of passive solar gain. The potential of the slanted roof surface also depends on the orientation. The fact that there are multiple buildings with repetitive elements may be a potential for a refurbishment; adapting multiple buildings at once may save costs, and creates potential in terms of energetic cooperation. A local energy storage system may become more cost-effective by this cooperation.

A threat of these existing row houses is the insulation. Low energy losses by transmission are essential for energy-flatness because of the lack of supply potential in winter and at night. The insulation of existing houses can be improved slightly, but it is hard to achieve modern standards. Inevitably, it will be hard to minimize the heat losses in winter and at night. Another challenge is the orientation; this is set. A non-south orientation will increase the challenge to achieve energy-flatness. Also the geometry of the building can be barely changed in a refurbishment.

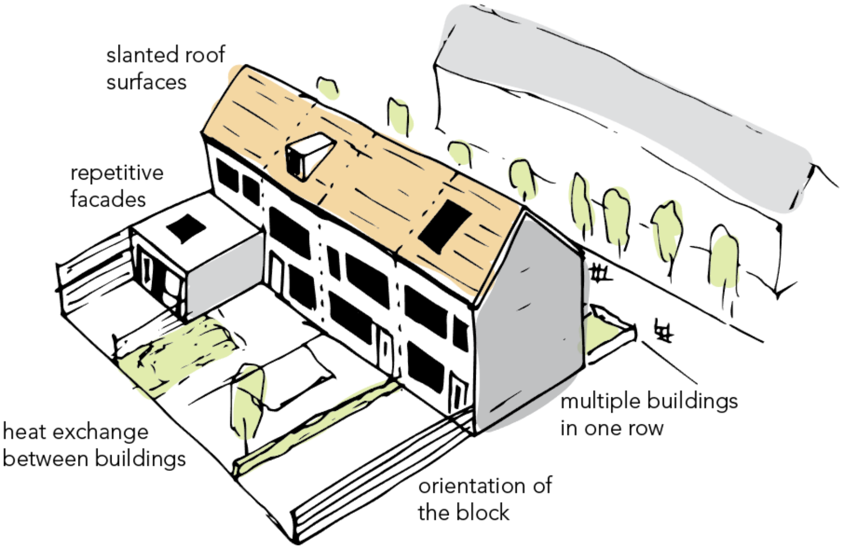


Figure 94: Context potentials of example 2; existing row houses

Design using energy-flat design principles

Since geometry and orientation of the building cannot be changed, mostly principles that focus on building installations and adaptive measures are used. Figure 95 shows a section of the sketch design for an energy-flatness approaching refurbishment. Pre-heating and -cooling is a very effective principle for energy-flatness, and it is a principle that can easily be used in existing buildings. A constraint for optimal use of this principle is a high amount of thermal mass. If a building consists of mostly wooden surfaces (e.g. floors, indoor walls), the mass is limited and pre-heating is only possible to a certain extent.

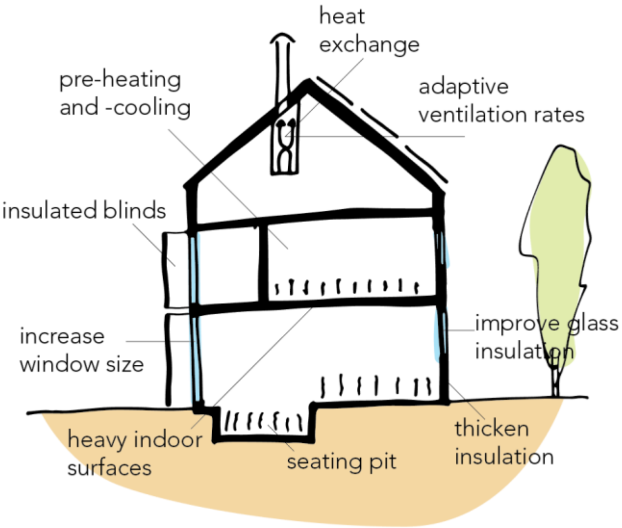


Figure 95: Sketch design for an existing rowhouse

Another potential is the ventilation of the building. Implementing a mechanical ventilation system can create possibilities for heat exchange and adaptive ventilation rates. The latter has proven to be very effective for energy-flatness. One constraint for this principle, however, is a decent distribution of air in the building. Lastly, if the orientation allows for it, the windows can be used as effective means to increase energy-flatness. Increasing window shares and their g-values on southern orientations allows for high passive solar gain. Northern windows can be replaced with highly insulated windows, to minimize transmission losses. On the south, the larger windows can be extended with adaptive insulated blinds, which block solar in summer and reduce transmission at night and at times the house is not used.

7.4 FINAL ENERGY-FLAT DESIGN: ADAPTING BOTH SUPPLY AND DEMAND

The final design serves as an example of energy-flat design. It brings the earlier mentioned principles and knowledge together in one single design. In that sense, this building should not be considered as the ‘typical’ energy-flat design, more designs are possible. Nevertheless, some iconic properties of the design are the result of essential energy-flat principles, hence other energy-flat design will show similarities.

This section describes the design with drawings and images, describes the main energy-flat principles and exaggerates on the energy-performance of this particular design. Finally, building services and considerations for achieving even better energy-flat performance are described.

7.4.1 Final design description

The final design is a non-typical kind of architecture, which is the result of design by research. The aim of the final design is to be energy-flat in the heat-balance. The floor space of the building (176 m^2) is equal to that of the reference design, to allow for a fair comparison with the reference design.

Figure 96: Visualisation of the final design

The design is a quarter elliptical sphere which is covered by a layer of earth. The south façade consist for 80 % of glazed surfaces. In front of the façade, there is an array of six rotating insulated solar blinds. In the back of the house, there is one shaft going through the layer of earth, providing light in the back of the house and ventilation possibilities. The house has two levels and almost all rooms are oriented to light of the south façade.

Design principles

As a result of the design by research approach, the final design is a mix of design principles that contribute to energy-flatness. Figure 97 shows an overview of the design principles that are applied in the final design. They are shortly described below.

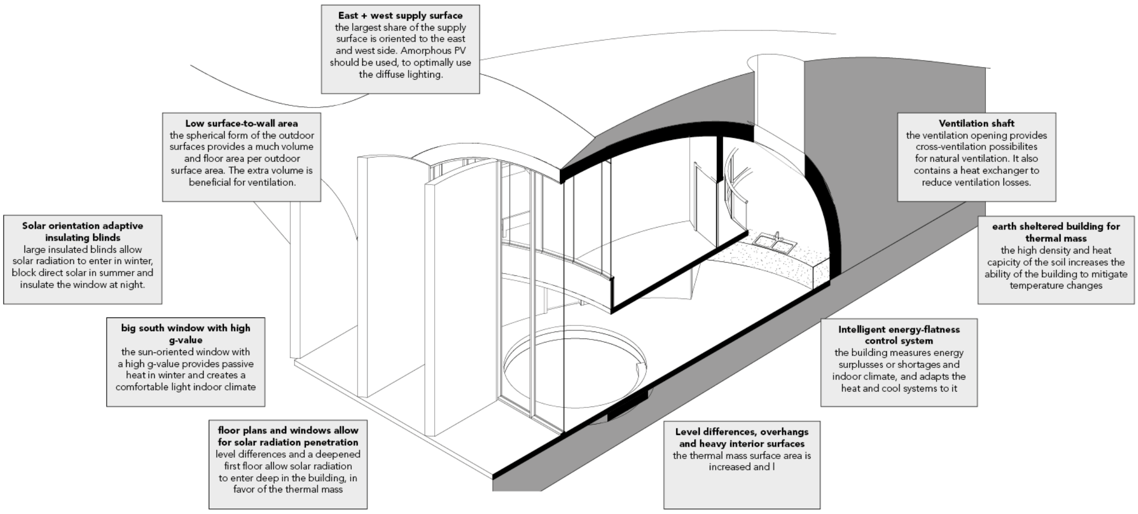


Figure 97: Overview of the design principles applied in the final design

Shape

The building has a spherical shape. This is the result of the ambition to have an energy-losing surface area that is as small as possible. Moreover, a larger volume results in the ability to 'pause' the ventilation longer. A sphere theoretically has the largest volume/surface-ratio. It is transformed to a elliptical sphere in favour of the size of the southern façade. One could argue that a smaller surface area can be approached if the roof surface is made flat; after all, a space does not have to have a ceiling height of more than approximately 3 meters. However, the slightly decreased surface area (in favour of reducing transmission) does not compete with the decreased volume (which counterworks to ability to control the ventilation rate).

Earth sheltered

One characterizing architectural element, is the cover of earth over the house. This earth layer is in favour of the amount of thermal mass; almost the complete zone boundary is thermally connected to the soil, thereby largely increasing the heat capacity of the building (see Figure 98) . This mitigates changes in air temperature on both the short term and long term. The exact amount of thermal mass is hard to calculate due to differences in heat capacity for different humidity levels in the soil.

Level differences and adapted floor plans

The floor plans are designed in favour of the functionality thermal mass. First of all, the first floor is offset from the south façade, allowing the solar radiation to enter deeper into the building (see . Second, the ground floor has some level differences, increasing the surface area of the thermal mass. Last of all, all the indoor wall and floor elements, are made out of concrete, in favour of the so-called superficial thermal mass.

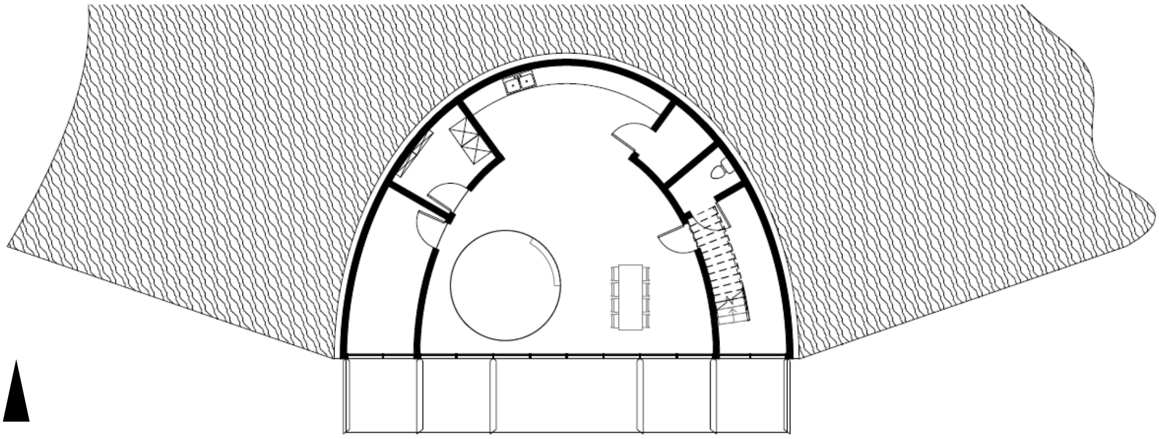


Figure 98: Plan of ground floor, not at specific scale

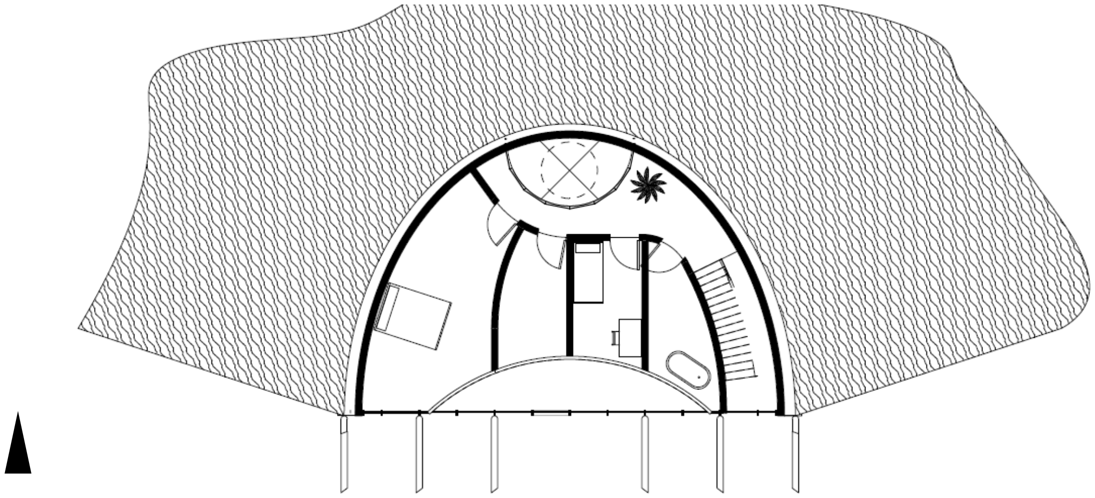


Figure 99: Plan of first floor, not at specific scale

Big southern window & solar blinds

On the south façade, there is a big window. The window has two main functionalities; allow the passive solar heat to enter and create architectural comfort. This window has a high g-value, combined with a high insulation value.

In front of the window, there is an array of six large rotating insulated solar blinds. These blinds have three functionalities:

- Insulate the window during cold nights in which transmission should be reduced
- Rotate with the direction of the sun to allow for optimal solar radiation penetration in the building
- Rotate against the direction of the sun in days that passive solar radiation is not desired (i.e. summer).

Figure 100 shows a 1 to 5 detail of the corner of the south window. In this, the insulation of the blinds, the rotation of the blinds and the connection of the window to the concrete wall are shown.

Ventilation shaft

In the northern side of the sphere, there is a shaft that goes through the earth layer. The shaft has two main functionalities:

- Allowing light to enter in the back of the house
- Facilitating both natural and mechanical ventilation with heat-exchange

The light that enters the building reaches both the first floor and the ground floor. This is done by a ‘gap’ in the first floor, allowing the light to reach the ground floor. The ventilation shaft is shown in Figure 101. In this figure that height of the shaft can be seen, which allows for a natural draft. The integrated heat-exchanger makes effectively use of the size of the shaft. By integrating the heat-exchanger in the shaft, both natural ventilation and mechanical ventilation are possible.

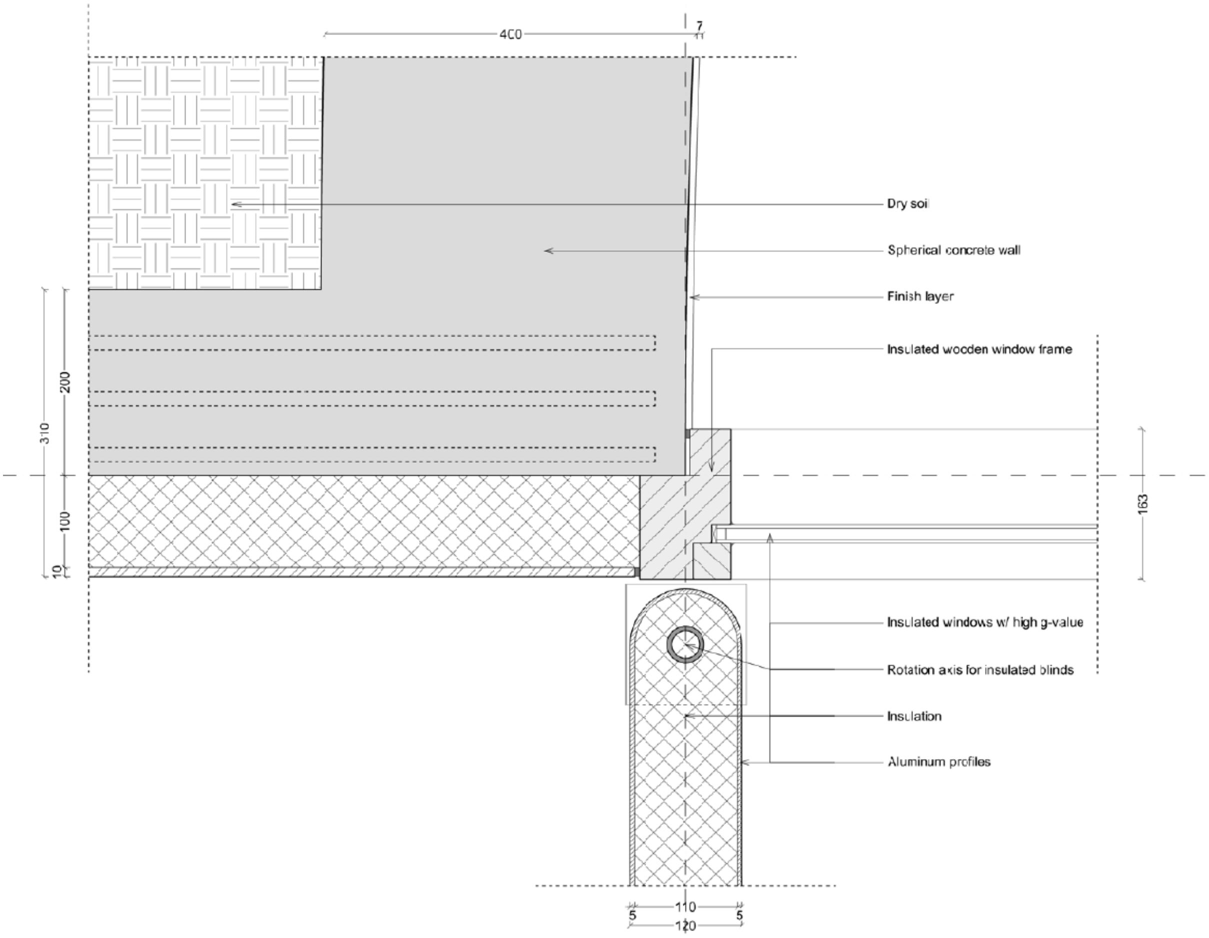


Figure 100: Detail of the connection of the south-west corner of the southern facade, showing the insulated blinds (no scale)

Intelligent control system

A design principle that is not visible in the drawings, is the implementation of a smart system. The building will contain multiple sensors, both indoors and outdoors, which measure the solar radiation, indoor and outdoor temperatures, CO_2-levels etcetera. Based on this locally measured data and online data (e.g. weather-predictions), it can effectively adapt the modes of building services. For example, if there is a heating load that is undesired, the ventilation rate can be lowered based on the CO_2-levels.

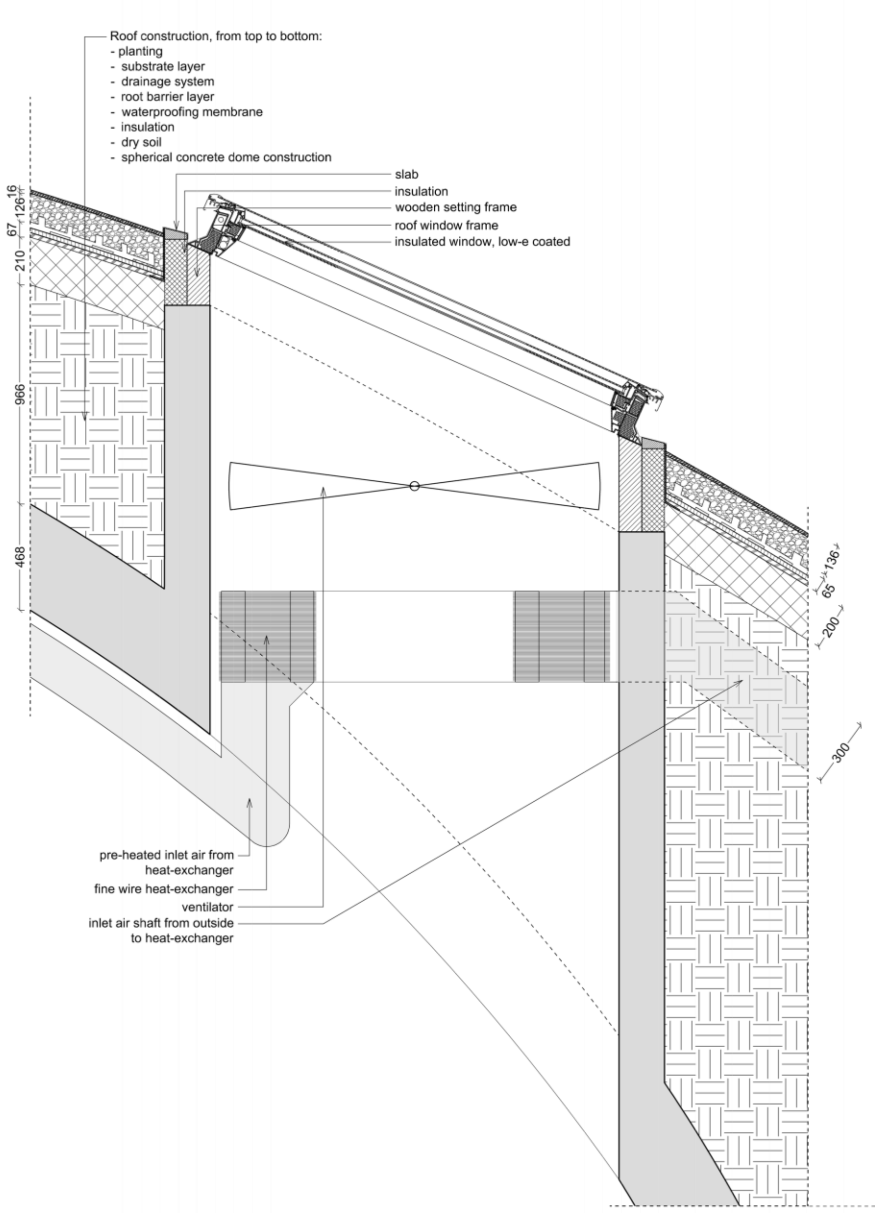


Figure 101: Detail of the ventilation shaft in the north side of the building (no scale)

Supply

The supply is for the largest share oriented on the east and west sides of the building. Since the building is covered by a layer of earth, rather than it has a façade, the solar panels are located on the ‘ hill’. An advantage of this is that the solar panels will be passively cooled by the green around it, increasing the efficiency of the panels.

7.4.2 Simulation of the final design

The energy performance of the final design is calculated using the same simulation as is used for all the parameter studies, as described in *4 Simulation of energy-flatness; the energy model*. However, the final design is so significantly different and more complex than the reference design that some adjustments and additions to the simulation tool are required. Moreover, not all design concepts of the final design are possible to simulate using this tool. This section shortly describes the adjustments, additions and the impossibilities in terms of modelling the design. Appendix 7 exaggerates on the details.

Meshed geometry

The final design contains a quarter of an elliptical sphere. EnergyPlus, the kernel of the Honeybee tool, is only able to calculated with planar surfaces. The geometry therefore is meshed into planar surfaces. Figure 102 shows the difference between the design and the input for the energy model.

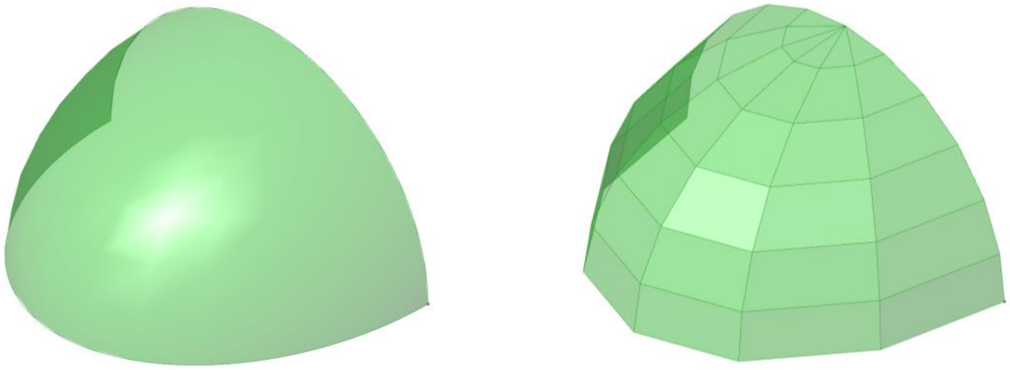


Figure 102: The adaptation of the geometry from the design elliptical sphere (left) to the meshed elliptical sphere (right)

Thermal massing

Key element in the final design is thermal mass. To increase the thermal mass in the final design the building is covered by a big layer of earth. In the simulation tool, the construction is simplified. All surfaces part of the sphere have the same construction which consists of one layer of concrete, one layer of soil and one layer of insulation. Apart from the thermal mass that is added to the buildings boundary surfaces, additional internal thermal mass is added using a Honeybee module, which represents the mass of all indoor floors and walls.

Insulating blinds

The final design consists of dynamic blinds which protect against direct solar radiation in summer, allow the solar radiation to enter in winter, and close during the night to cover the southern window with insulation. The rotation and insulation of the blinds are not completely modellable in the simulation.

This means two important adaptions are done:

- the blinds are simplified for solar radiation in summer and passive solar heating in winter to horizontal shades
- the insulating functionality of the blinds is implemented by a manual correction to the results, because it is essential for the energy-flat performance. The manual correction is a reduction of the transmission through glazing in times when the insulated blinds are shut according to schedule.

Solar absorption

In early versions of the simulation of the final design, a problem was encountered regarding the solar absorption. Solar absorption is the absorption of radiative solar heat by materials inside the zone. In a realistic situation, part of the solar radiation that enters a building through glazing is absorbed directly by the construction surfaces. The other part is not directly absorbed by these surfaces and warms up the indoor air. In the energy-model, the share of direct solar absorption was too high as a result of the single-zone modelling; by having no indoor walls, furniture or furnishings, almost all solar radiation was absorbed by the construction. This is corrected in the simulation with a correction factor.

Pre-heating and pre-cooling

The principle of pre-heating and pre-cooling was found to be one of the most effective solutions for energy-flatness. It considers increasing the heating setpoint when there is an energy surplus and lowering the cooling setpoint when there is an energy surplus.

The simulation tool does not allow for adaptive heating and cooling setpoints based on the presence of supply. It does, however, allow for scheduled heating and cooling setpoints. Hence, to simulate the adaptive setpoints a manual iteration is made in which the heating and cooling setpoint schedule is based on the mismatch of a previous simulation. This way, pre-heating and pre-cooling are activated in times of supply surplus.

Supply potential surface

In the reference situation, the supply surface was represented by the building surfaces of the design. In the final design, however, the zone boundaries are very different from the outer surface, because of a high amount of soil that is put on top of the building. Figure 103 shows the original surface shape, and the meshed supply potential shapes.

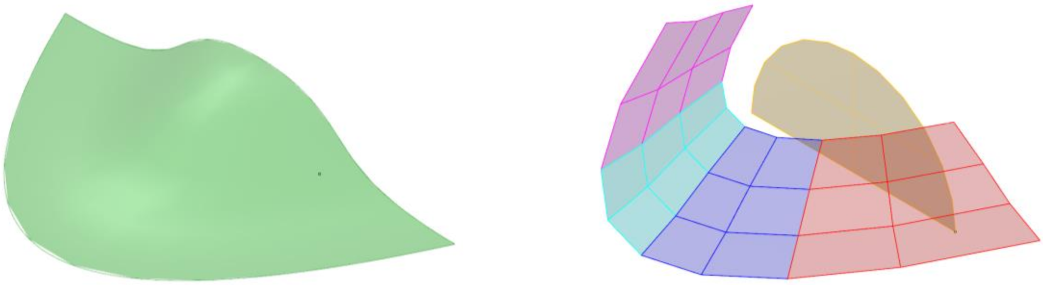


Figure 103: The outdoor sand surface (left) and the meshed supply potential surfaces (right)

7.4.3 Energy performance of the final design

The goal of the final design is to be a proof-of-concept and to be an example for an energy-flat design. This section describes the energy-flat performance of the final design.

When considering the energy-flat performance of the final design, it is important to keep in mind the meaning of KPI’s, as is described in *3.3.4 Meaning of the KPI’s in the heat and electricity balance*. In this design, the heat balance is considered, resulting in the KPI’s only being used as an optimisation tool and not giving any practical value in terms of battery size. Such properties could be found when elaborating more on the building installations. Figure 105, which more elaborately explained in the previously mentioned section, clarifies the meaning and purpose of the KPI's in the context of the heat balance.

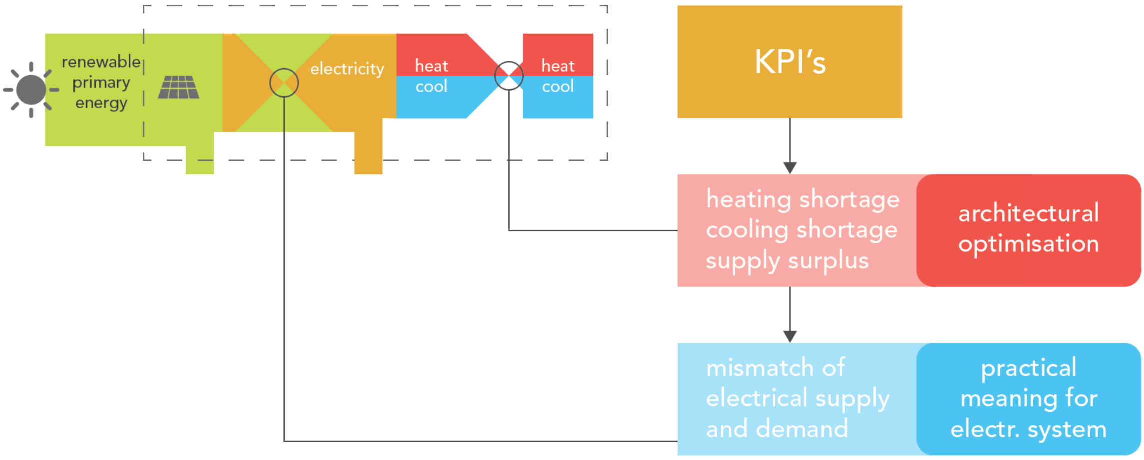


Figure 104: Different meaning, applicability and purpose of the KPI's in the heat balance and electricity balance

Total energy consumption and key-performance indicators values

Table 6 shows the total energy flows and the KPI's for the energy-flat design (N.B. design ID is 2_ARC_v7). All the loads and the KPI's are lower than the reference design. Please note, the reference design is a BENG building, as described in *5.1 The reference design*.

		unit	REF05d	Final design	Percentual change
Annual loads	Total heating load	kWh	3732.5	486.0	-87 %
	Total cooling load	kWh	3675.1	1759.4	-52 %
	Total supply	kWh	7793.6	2290.9	-71 %
KPI 1	Heating shortage	kWh	-3223.6	-356.4	-89 %
	Cooling shortage	kWh	-1292.8	-425.0	-67 %
	Supply surplus	kWh	4902.3	826.9	-83 %
KPI 2	Peak heating shortage	kW	-3.3	-2.4	-25 %
	Peak cooling shortage	kW	-4.6	-2.1	-54 %
	Peak supply surplus	kW	5.0	1.6	-68 %
KPI 3	Maximum cum. mismatch	kWh	2766.3	610.0	- 78%

Table 6: Total energy consumption and key-performance indicators of the reference design and final energy-flat design

The table shows that both the heating shortage and cooling shortage have decreased highly, 89% and 69% respectively. The decrease is big, but the values show that there still are times when there is no supply and there is a heating load (356.4 kWh in total) or a cooling load (425.0 kWh in total). Also, there still is an annual supply surplus of 826.9 kWh. This value is exaggerated on in the next section. The peak shortage have all decreased to reasonable values, 2.4 kW for heating and 2.1 kW for cooling.

To make the numbers of Table 6 somewhat more comprehensive, below some simple comparisons are made, all related to energy-flatness.

1. A BENG building has a total mismatch (heating shortage + cooling shortage + supply surplus) of 9419 kWh per year. The energy-flat design has a total mismatch of 1608.4 kWh per year.
2. If the total energy shortage would be compensated using a battery, the battery would have to be 2766 kWh in the BENG situation and should be 610.0 kWh in the energy-flat design. This is a reduction of 78%. A high-end Tesla Model S has a battery size of 100 kWh, meaning that roughly six Tesla's would be needed to compensate the heating shortage. This comparison, however, should not be taken too literally, considering the point made in Figure 104.
3. (N.B. determined by KPI3, neglecting self-discharges, efficiency and electricity-thermal transformation losses
4. The supply surplus has decreased from 4902.3 to 826.9 kWh. The surplus in the energy-flat design is relatively higher. Moreover, the supply surplus in the energy-flat design is for 75% 'produced' between March and May. Possible solutions for this centralized surplus are described in *7.4.5 Considerations for perfect energy-flatness*.

In the next section, the results are analysed on different timescales.

Analysis of the annual energy profiles

The annual mismatch becomes visible in Figure 105. The total heating load is lower than the cooling load and its peak is in the middle of the winter. The cooling load is higher than the heating load, occurs from April till November and has a peak in July and August.

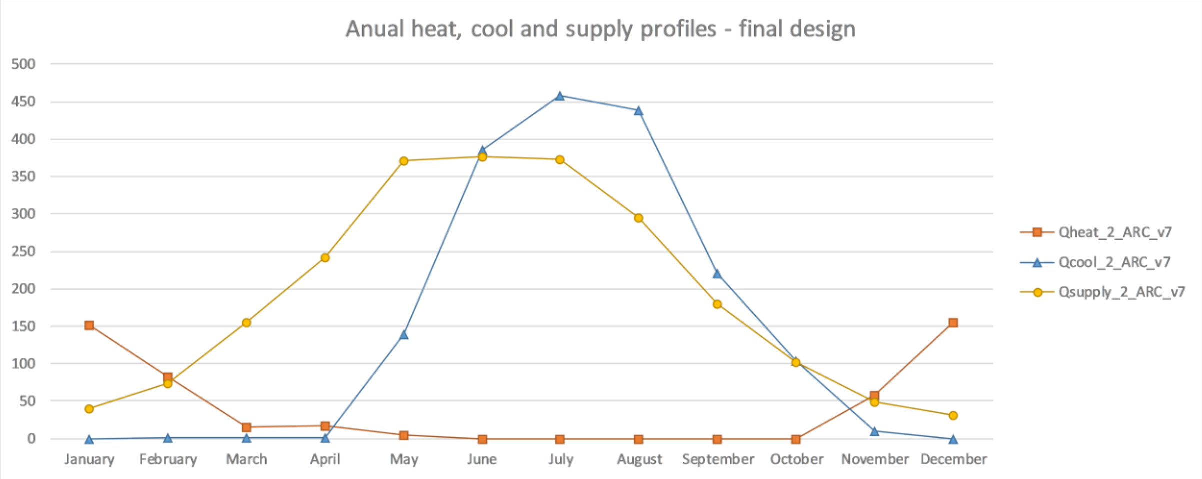


Figure 105: Annual heat, cool and supply profiles for the final design (2_ARC_v6)

The supply has its peak from May till July. The differing timing of the supply peak and cooling peak provokes a mismatch. The difference in timing of the peak might be the result of the high amount of thermal mass. The building takes some time to heat up, but eventually has a cooling load.

How the mismatch is built up over the year becomes clear in Figure 106, which shows the cumulative mismatch. This figure clear shows that the surplus mismatch is mostly present from March till May. August creates a small cooling shortage and December and January a small heating shortage. In the other months, the building is flat.

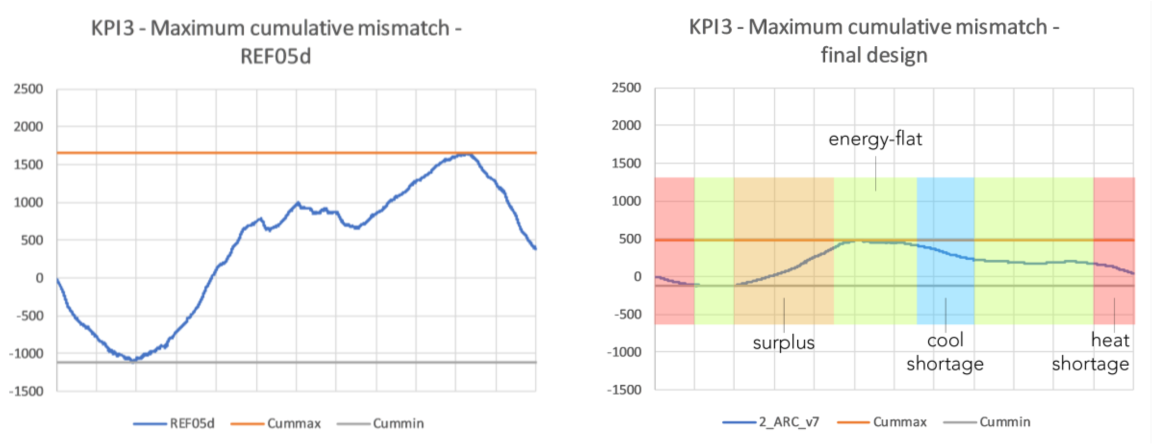


Figure 106: The maximum cumulative mismatch profile for the final design (2_ARC_v7), showing the critical timing for energy-flatness

Analysis of monthly and weekly energy profiles of August

A few things becomes clear by comparing the energy performance of a month with a good match, namely August, to the energy-performance of the reference design. This comparison can be seen in Figure 107. First of all, the loads are mostly lower, especially in times of former high loads. Second of all, especially the cooling demand profile has changed in shape. The supply loads are lower in the new design, but the profile is similar to the profile of the reference design.

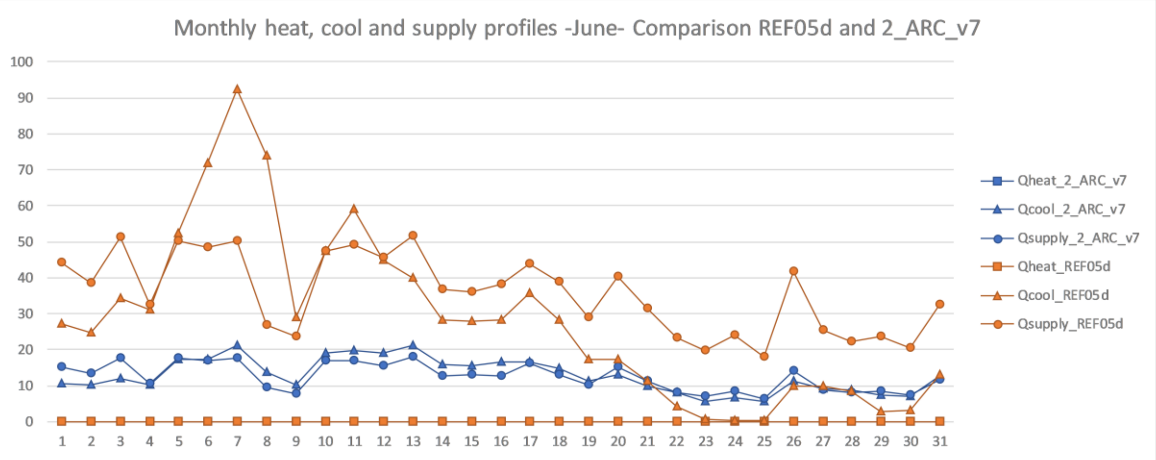


Figure 107: Comparison of the monthly heating, cooling and supply profiles of the reference design (REF05d) and the final design (2_ARC_v7) in June,, which is the best energy-matching month.

In general, the high peaks of the supply are flattened out, but the supply drops are still visible in the new profile. The cooling profile has adapted to this new supply profile. So, the cooling demand is adapted more to the supply profile than vice versa.

Figure 108 shows the hourly cooling and supply loads of one week of June. There are no cooling loads before sunrise or after sunset. Moreover, the cooling loads match the supply especially in the morning and afternoon. There are some supply or cooling peaks that miss each other, resulting in a small mismatch.

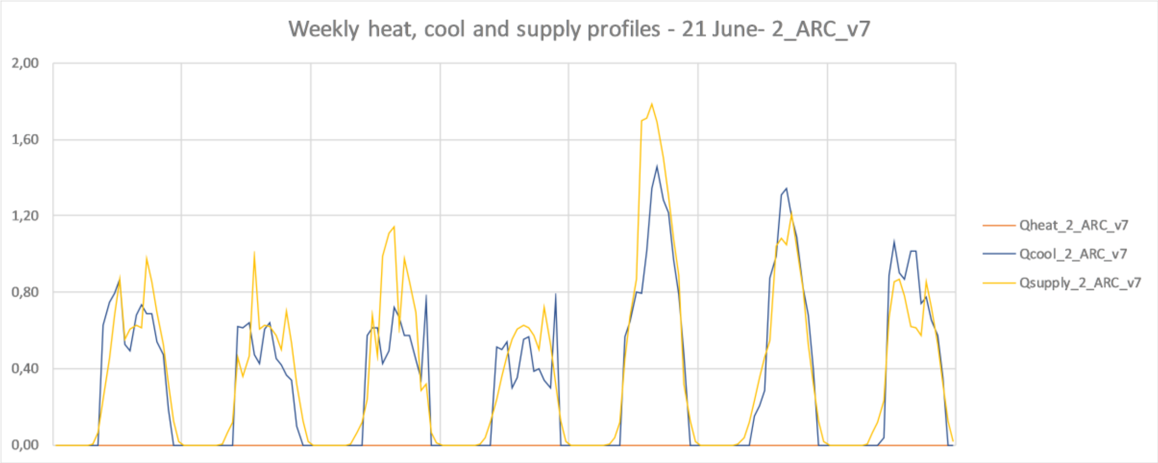


Figure 108: Hourly cooling and supply loads of the final design (2_ARC_v7) for the week of 21 June.

Analysis of monthly and weekly energy profiles of May

The month of April is the month that causes the biggest mismatch. Figure 109 shows its monthly heating, cooling and supply profiles. The cooling load is lower than the supply load on every day. Looking closely, it can be seen that the profiles do follow each other; peaks and valleys in the supply profile are followed by the cooling profile. The mismatch could be solved by reducing the supply load, but this affects the performance of other months. Considering the matches during the other months of the year and the fact that April is in the inter-season, there are few ways to reduce supply without affecting the other months. Solutions to solving this mismatch are discussed in 7.4.5 Considerations for perfect energy-flatness

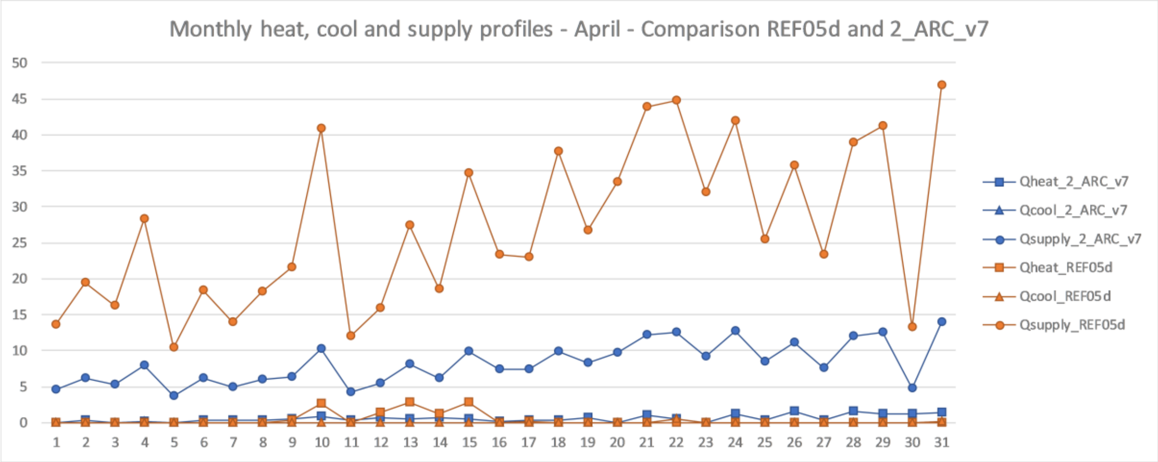


Figure 109: Comparison of the monthly heating, cooling and supply profiles of the reference design (REF05d) and the final design (2_ARC_v7) in April, which is the most mismatch-causing month.

Figure 110 shows the comparison of the weekly profiles for cooling and supply of the reference design and the final design in one week of April. The cooling shortages that occurred after sunset in the reference design are completely solved. Nevertheless, the cooling load has become lower and results in a higher supply surplus.

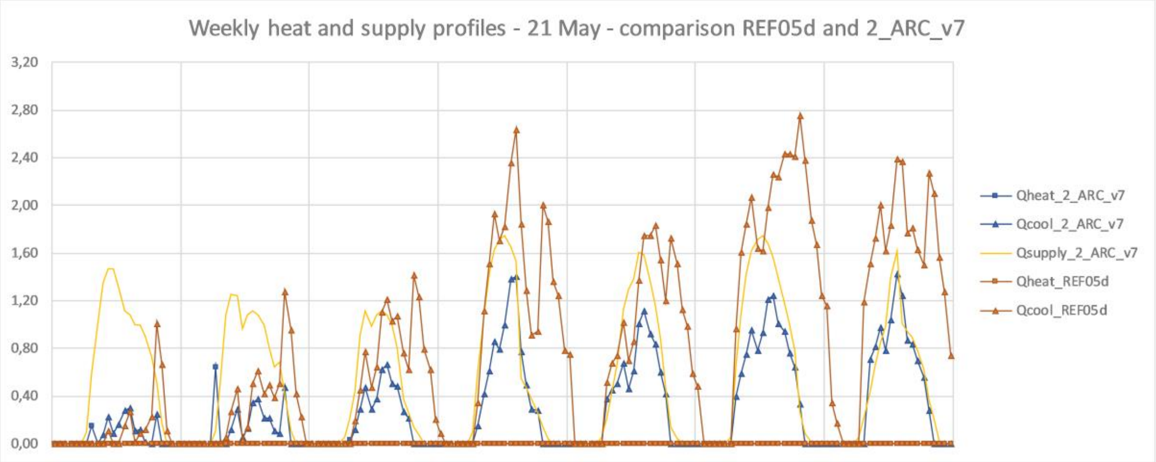


Figure 110: Comparison of the hourly heating, cooling and supply loads of the reference design (REF05d) and the final design (2_ARC_v7) in the first week of April, which is the most mismatch-causing month.

Analysis of monthly and weekly energy profiles of December

Another month worth considering is the month of December, which is the month in which the major heating shortage occurs. Figure 111 shows the comparison of energy-performance between this final design and the reference design for this month. The heating loads have highly decreased and the profile is mitigated. Nevertheless, the heating load is higher than the supply on every single day of the month. Also, successive high-heating days still occur, for example from 17 to 21 December.

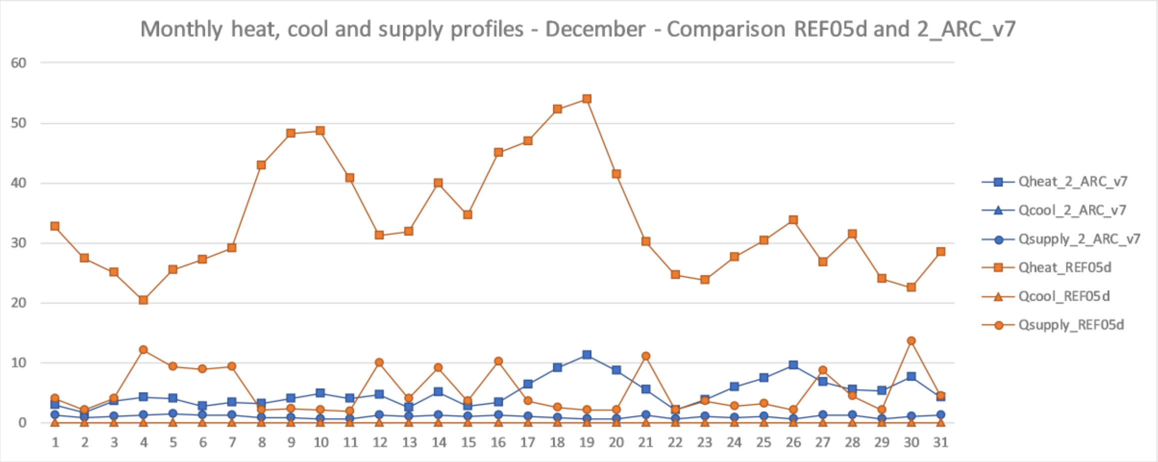


Figure 111: Comparison of the monthly heating, cooling and supply profiles of the reference design (REF05d) and the final design (2_ARC_v7) in December, which is the most heating shortage creating month.

In Figure 112 a comparison of the heating and supply profiles for the third week of December are shown for the reference design and the final design. The nocturnal heating demand peak is almost completely compensated, as a result of the reduced ventilation and insulated blinds. In some nights, there still is a small peak though. There are still heating peaks during daytime, which result in a heating shortage. In some cases (e.g. 16 December) there is a small surplus in the middle of the day. This is the result of inaccurate pre-heating and could be corrected in a situation with more precise pre-heating.

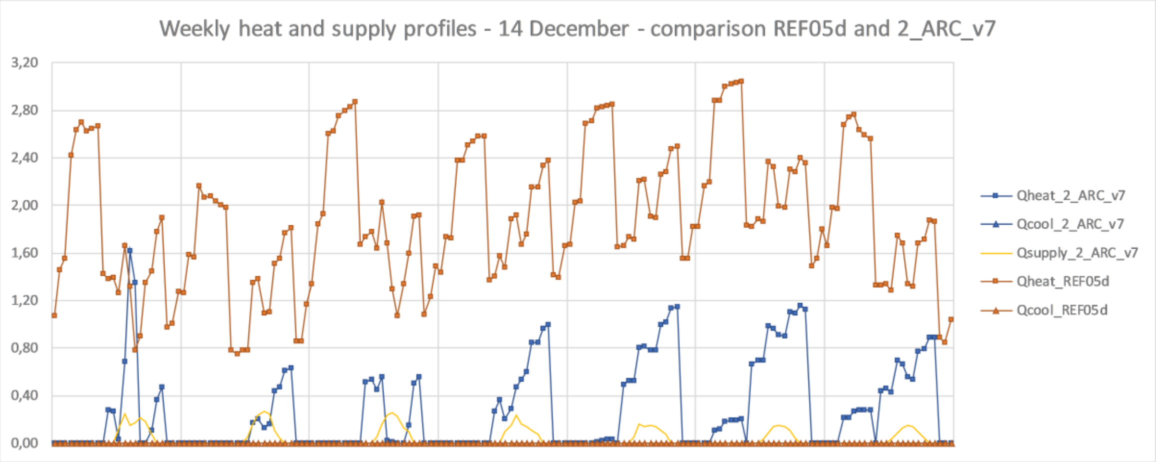


Figure 112: Comparison of the hourly heating, cooling and supply loads of the reference design (REF05d) and the final design (2_ARC_v7) in the third week of December, which is the most heating shortage creating month.

Conclusions on the energy-flat performance of the final design

The overall energy-flatness performance of the final design is much better than the energy-flat performance of the reference design. For every KPI, significant results are achieved. The total annual heating, cooling and supply loads are lower. From March till May, a surplus mismatch is built up caused by a lowered and shifted cooling loads as a result of much thermal mass. The other months are more or less energy-flat, except from December and January that cause a heating shortage.

The weekly profiles of several months prove the ability of the building to mutually adapt supply and demand. The supply profile is less controllable than the demand profile. Compared to the reference, the supply loads are lower, but the profile is more or less similar. The demand profiles are adapted to this supply profile. In all cases, though, the biggest peaks are mitigated.

The total heating shortage, cooling shortage and supply surplus are respectively 356.4, 425.0 and 826.9 kWh. If the aim would be to make the building off grid, a battery sized of 610 kWh (N.B. determined by KPI3, neglecting self-discharges, efficiency and electricity-thermal transformation losses) would be required to suffice the demand at any time. The building is now energy-neutral. It is noted that a higher supply, would result in a lower heating and cooling mismatches, but a higher surplus mismatch.

7.4.4 Building services & translation to electricity flatness

Heat energy-flatness and electricity energy-flatness should be distinguished, as is concluded in *3 What is energy-flatness?*. The parameter study focussed on the heat balance, because it is the most abstract and primitive form of energy-flatness. The final energy-flat design considers electricity flatness as well, because this is desired according to the problem statement. The design structure then looks as presented in Figure 113.

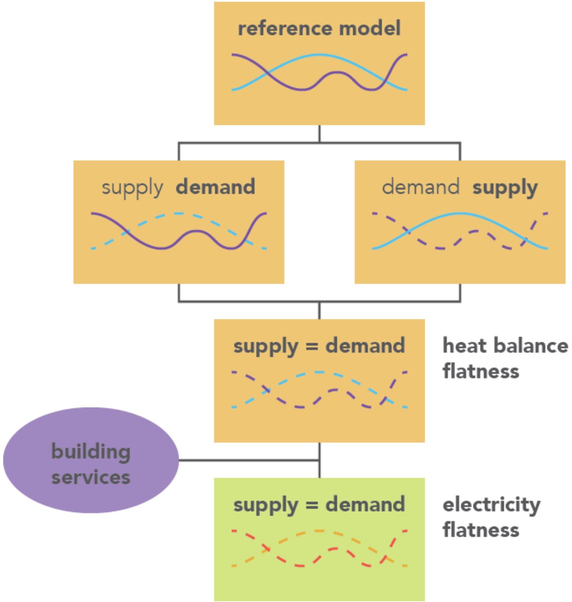


Figure 113: New design structure, also including electricity flatness

To translate the heat energy-flat design into the electricity-flat design, the type of building services that is used should be considered. This way, a realistic situation is presented that could be optimized. The translation of a heat and cool demand towards an electricity demand, relates to efficiencies and losses caused by distribution and transformation. Figure 114 shows how the initial heat, cool and supply flows are translated into electricity demand and supply flows.

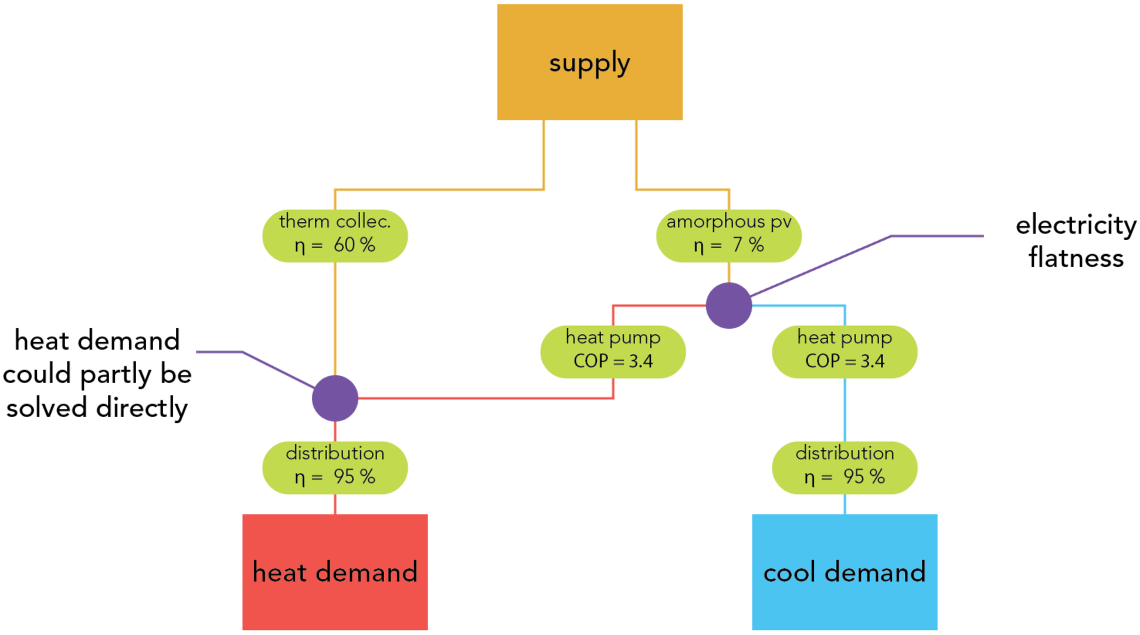


Figure 114: The translation of heat demand, cool demand and supply potential into electricity demand and supply

The efficiencies and losses of all building services are determined by the state of technology of these systems. Depending on the systems chosen and future technological developments, these efficiencies might differ. For now, a selection of existing building services and their corresponding efficiencies and losses is chosen and its effect on the heating and cooling demand and energy supply are described.

Heating and cooling

The heating and cooling loads of the final design are relatively low, which allows for a floor heating and cooling set-up. Floor heating and cooling consists of pipes running right below the floor or ceiling surface. Floor heating and cooling is a so-called low-temperature system. In typical systems, the heat source is around 35°C. The cooling source is around 17°C to prevent condensation.

Because low-temperatures are used, a heat-pump can be the heat and cool source. Figure 115 shows a schematic overview of the building services for heating and cooling in a section of the final design. In this case, a closed loop ground source heat pump is used. This type of source allows for a disbalance between heat demand in winter and cooling demand in summer, which is desired for this energy-flat design. Moreover, it provides a constant source temperature.

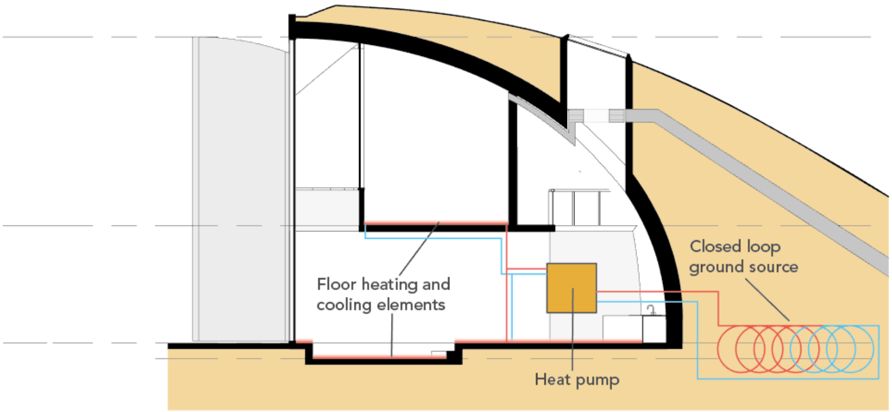


Figure 115: Schematic overview of the building services for heating and cooling

A heat pump provides heat or coolth by moving thermal energy from the source to the outlet. With little additional (electrical) energy, high thermal loads can be provided. Because of the use of this Carnot principle, it is possible to have efficiencies of above 100%. The so-called COP (coefficient of performance) of heat-pumps is basically derived from the efficiency of the Carnot engine, hence this COP depends on the temperature difference between the source temperature and the energy sink (i.e. the floor heating system). To increase the efficiency, both the source temperature can be increased or the sink temperature can be increased. Figure 116, by Meggers et al. (2012), shows the increase of the COP when decreasing the temperature rise. From this can be derived that a typical heat pump has a COP of around 5, assuming a situation of T_{out} = 5°C and T_{source} = 35°C.

Meggers et al. (2012) show the potential of low-exergy systems, systems in which the temperature rise is low. This final energy-flat design would suit for this kind of system. The heating load of the final energy-flat design is extremely low. Hence, it is possible to use a lower floor-heating temperature as a result. After all; the heat power of a floor heating system depends both on the temperature and the area of the distributing surface.

Moreover, by using a closed loop ground source heat pump, the source temperature in winter is relatively high; around 10 °C, the average ground temperature. Heat pumps with a fluctuating source temperature inherently have different COP's over the year. The closed loop ground source heat pump has a constant source temperature, hence a constant COP.

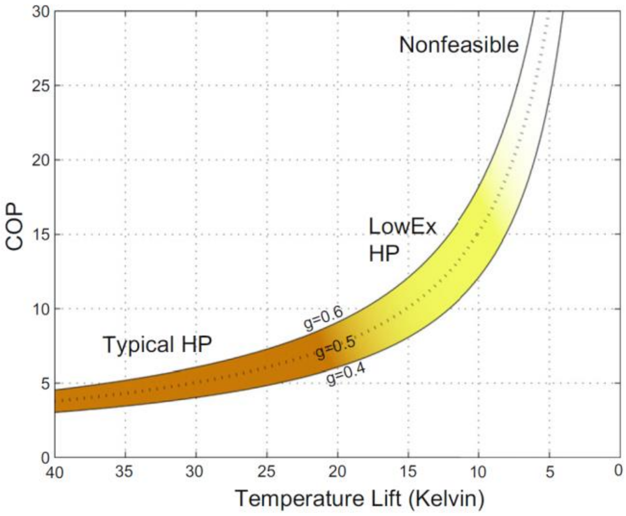


Figure 116: Variation of COP with decreasing temperature-lift. Below temperature-lifts of 20 K the COP increases rapidly. A typical range from g = 0.4 to 0.6 for exergetic efficiency for existing machines are illustrated (Meggers et al., 2012)

By using this ground source temperature of around 10°C and a floor-heating temperature of around 25-28°C, the COP of the system might reach up to 10. So, the use of a closed loop ground source heat pump results in an electrical load that is only a share of the thermal load, both for heating and cooling:

$$\mathbf{Q_{thermal;electrical} = Q_{thermal} / 10}$$

Apart from the COP of the heat pump, there are also some losses in terms of distribution. Part of the heat and cool energy may not be used as effective heating and cooling, due to losses in the spaces that do not need to be heated or cooled. The efficiency of the distribution is assumed to be around 95 %. This results in an adaptation of the formula above to:

$$\mathbf{Q_{thermal;electrical} = (Q_{thermal} / 10) / 0.95 = Q_{thermal} / 9.5}$$

The effect of the implementation of building services is more complex than just a linear scaling factor. A few other aspects should be considered when implementing this system. Firstly, the designs effectivity highly depends on the use of thermal massing. Floor heating and cooling are installed on the top of the massed surfaces, and might influence the effectivity of the thermal mass. Secondly, the loads for heating and cooling are high. A complete installation for fulfilling these loads might not be the most energy-effective solution. Strategic implementation of the heat and cool distribution might improve efficiency and comfort. Lastly, the closed loop ground source heat pump might also allow for the 'passive cooling' method. In that case, water is only transported from the source to the building, instead of being actively cooled in between. A more detailed study should show if this would suffice.

Supply

In terms of building services, the energy supply is provided by either photovoltaic panels or solar collectors. The supply as described in the heat balance of the final design (see 7.4.3 *Energy performance of the final design*) is a share of the solar radiation. This share is a representation of supply area per surface area and the efficiency of this supply area. Photovoltaics or solar collectors can either be separate systems, or they can be combined in one panel using PVT technologies.

It assumed that solar collectors are not effective in the case of the final design, considering the facts that both the heating load in the final design is low, and there already is a heat pump that is over-dimensioned because of the dominant cooling load. The efficiency of a solar collector ranges from 20-80% (see *2.5.7* Energy supply). This is higher than the efficiency of PV panels, but does not compensate for the earlier stated facts.

The efficiency of photovoltaics depends on aspects like panel type, but also on panel temperature, solar power, and conversion losses. In general, there are two main types of solar panels; crystalline silicone and thin-film. Crystalline silicone modules have, in general, higher efficiencies (i.e. conversion from solar radiation to electricity). Thin-film modules, however, are known for their relatively high ability to effectively use diffuse light. The energy-flatness parameter study showed that the diffuse light is essential for creating a stable supply profile. The overall efficiency of a thin-film module is around 7%-13%. The lower efficiency of the thin-film modules might be compensated by the decreased heating and cooling loads (i.e. there is enough surface for the panels). So, the use of thin-film photovoltaics is most effective for the final design.

	Potential surface area [m^2]	**Share of solar radiation considered supply [-]**	**Actual area of PV modules required [m^2]**
South (orange)	80.5	0.005	4.7
West (red)	68.6	0.008	6.5
North-west (dark-blue)	45.9	0.007	3.8
Nort-east (light-blue	45.9	0.007	3.8
East (magenta)	68.6	0.008	6.5
TOTAL	**309.5**		**25.3**

Table 7: Translation of supply potential shares of the simulation to actual PV module areas

Apart from the thin-film module efficiency, there are also conversion losses in the conversion from DC to AC. A typical efficiency for this conversion is 85%. Combining these efficiencies, the electrical energy supply provided by solar radiation is:

$$P_{supply;electrical} = P_{solar} * 0.1 * 0.85 * A$$

In the model, the supply was already a linear factor of the surface area and solar potential. In Table 7, these 'shares' are translated into actual required surfaces of PV modules.Detailed calculations, that include factors like module temperature and conversion efficiencies based on power levels, would provide a more accurate and fluctuating efficiency pattern over the year. For this scope, however, the linear factor is assumed to suffice.

Ventilation

The ventilation system has the main goal to refresh the air in the building. Both natural and mechanical driven ventilation is possible for both the inlet and the outlet. In the final design, a combination of natural ventilation and mechanical ventilation is used.

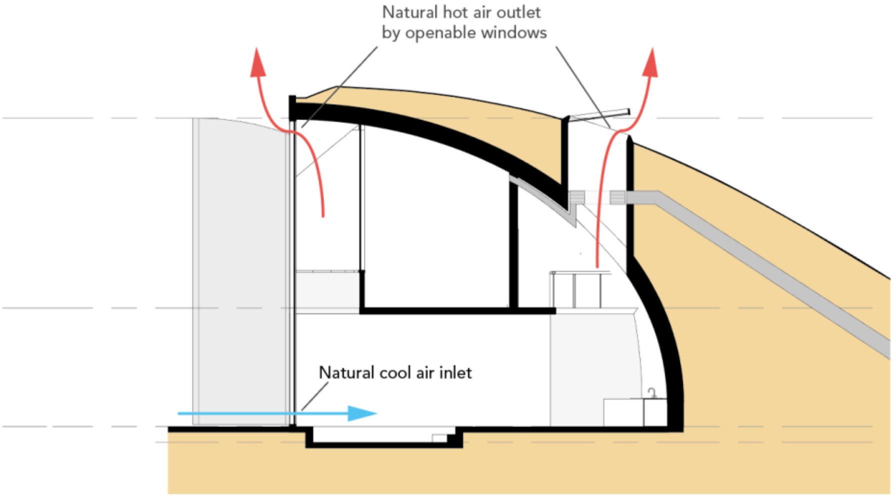


Figure 117: Schematic overview of the ventilation functionality for passive night cooling

Figure 117 shows the summer night situation in which the building is passively cooled by natural ventilation. The principle of hot air rising up is used, combined with pressure differences. The inlet is provided by grills in the bottom of the southern façade, which take in the cool air of the summer night. The outlet consists of two openings; one in the top of the southern façade, which is the highest point for the bedrooms, and another opening in the northern shaft, which is the highest point for the rest of the building. The latter opening is created by an openable roof window.

The principle of passive ventilation can be used any time that there is a cooling load and the outdoor temperature is lower than the indoor temperature, when there is no heating or cooling and the outdoor temperature is between the heating and cooling setpoints, or when there is a heating load and the outdoor temperature is higher than the indoor temperature. The latter probably won't occur.

In all other cases, the ventilation switches to the mechanical system, which is shown in Figure 118. The mechanical ventilation system is designed such, that it allows for heat exchange. The ventilation inlet crosses the ventilation outlet. This way, part of the thermal energy that is in the outlet ventilation, is transferred back to the inlet ventilation. The efficiency of a cross-flow heat exchange depends on the temperature differences between the inlet and the outlet air. Moreover, it depends on the air flow rate. Considering the fact that the heat-exchange system in the final design is non-regular, it is hard to state specific details about the efficiency. The set-up is similar to a cross flow heat exchanger, which has efficiencies of around 50-70%. To be safe, an efficiency of 50% could be used to adapt the ventilation losses.

$$Q_{ventilation;electrical} = Q_{ventilation} * 0.5$$

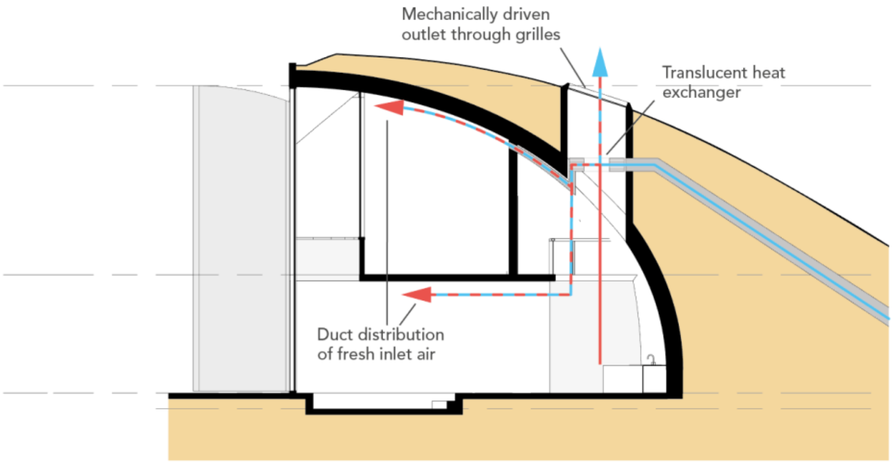


Figure 118: Schematic overview of the ventilation functionality for mechanical ventilation with heat exchange

7.4.5 Considerations for perfect energy-flatness

The energy-performance of the energy-flat design showed that perfect energy-flatness is not achieved. This section shortly describes how the remaining mismatch could be changed, effectively used or how a changing climate might affect it.

Turning off the supply

A very simple, though discussable, solution is to simply turn off the supply in times of supply surplus. By turning the supply off, the energy-grid will not have to handle the mismatch of the household. Using this solution would also allow for a slight increase of the supply, resulting in an even lower heating and cooling shortage.

Although this solution seems very effective, some aspects of it should be considered. First of all, this has a disadvantageous effect on the sustainability of the solar system. The production of the solar panel during its lifetime decreases, whilst the energy invested to produce the panel is constant. Second of all, in some cases the surplus of the building might compensate the shortage of another actor in the energy system.

Reduce supply surplus by other supply sources

The remaining surplus is the result of an increasing supply share in the run up to summer, with higher solar radiation. The design minimizes the mismatch by a ‘’happy medium’’; not too much shortage and not too much surplus. A higher supply would lower the shortages, but would increase the surplus. This main challenge, is the result of the difference in solar power in summer and winter.

Using other types of renewable energy can be beneficial for minimizing the mismatch. For a residential building, wind is the most obvious source of renewable energy. Wind is much stronger in winter, whilst solar radiation is much stronger in summer. Heide et al. (2010) show that the inversed seasonal performances of wind and solar can compensate each other.

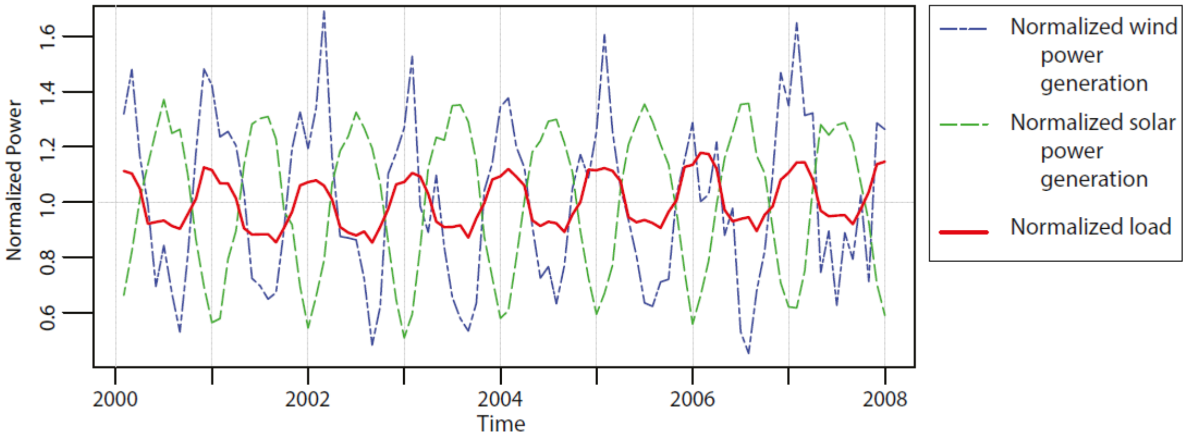


Figure 119: Normalized wind power generation (blue), solar power generation (green) and load (red) time series aggreggated over Europe. Each series is shown in a one-month resolution and is normalized to its 8 years average.(Heide et al., 2010)

Combining wind and solar as renewable energy source might mitigate one the biggest challenges of energy-flatness, and may thus result in an even lower mismatch.

Consider the demands of the energy system

Minimizing shortages and surpluses counteract each other. One way to reduce shortage is thus to increase the supply, resulting in a higher surplus. A way to reduce the total surplus is to lower the supply, resulting in larger shortages. One parameter study showed that having lesser supply results, to a certain extent, in a lower mismatch. Whether this is a favourable solution, depends on the requirements of the energy system. If, for example, returning supply surplus to the grid is not possible, a higher heat or cool demand is acceptable. On the other hand, if returning energy to the grid is economically more desirable than taking energy for heat or cool from the grid, the supply surplus should be accepted.

Using the centralized timing of the supply surplus

75% of the supply surplus occurs within a time range of three months, namely March, April and May. This centralized surplus ‘generation’ might be a potential solution. If the surplus could be linked to a certain activity that only occurs within this timeframe, it could be used effectively and is not disadvantageous to the energy system. Another option is that this centralized surplus is effective for creating storage as well. The principle of electrolysis, for instance, requires a certain constant amount of energy to generate hydrogen. If hydrogen is a save energy carrier to store inside a dwelling, it might be produced during these three months and used during the other months.

Climate change

A final thought for creating improved energy-flatness in the design, is the change of the climate. At this moment, it is almost certain that the average outdoor temperature will rise with at least 2 °C in the next decennia. More worst-case studies have shown that the temperature might even rise with more than 5°C. Although this is detrimental for numbers of societal and environmental aspects, it might positively influence energy-flat performance of buildings in the Dutch climate. Key challenge of energy-flatness is the high heating load in winter. The losses due to low outdoor temperatures highly decrease when the outdoor temperature rises, improving the ability to match the winter supply to the winter demand.

7.4.6 Reflection on the final design

As stated before, the final design that is presented is an example of an energy-flat design. It is not the only solution nor the best solution. Design is an iterative process and so, now the design is finished, some new insights are gained. A short reflection on the final design is provided below.

First of all, the spherical shape is beneficial in terms of area/volume ratio, but it may cause an inefficient space by the curved walls. Moreover, this shape does not allow for much urban repetition; it is ‘determined’ to be a unique, detached building. It would be interesting to research the precise effect of creating a more practical and conventional shape (e.g. cylinder, box).

The insulated blinds allow for some reflection as well. Currently, these are vertical panes. The benefit is that they can rotate with the azimuth of the sun. In summer, however, they do not provide shadow on the complete façade. Horizontal shades could cover the complete façade, hence creating more shadow. Moreover, horizontal shades make use of the sun’s high altitude in summer.

Another point is the thickness of the layer of earth and the location of the insulation in this layer. The energy-flatness simulation calculates up to 1 meter of thermal mass, but the effectivity of the extra thickness has not been calculated. This would require complex calculations. A thinner layer might result in different architecture. Also, the location of the insulation affects the performance. In the current design, the insulation layer is placed on top of the earth layer, meaning that all of the earth lies within thermal boundary of the building. It might be more effective to bring this layer closer to the zone boundary. This requires more detailed calculations as well.

The large window is focussed straight to the south, as was concluded to be the best for energy-flatness in the study. However, a slight extension of window surface to the east and west orientations was not studied, and a critical mindset would suggest that making partly use of these orientations could be beneficial. For example, to heat the building in the morning using the eastern sun and pre-heat it for the night using the western sun.

Finally, one might say that this building is too exceptional in too many ways; it is designed *tabula rasa,* without any context. It is covered by a big layer of earth, it’s spherical (N.B. how are we going to make that?) and it consists of large windows and large moving, insulating elements. Is it feasible at all? In my opinion, it is a pioneer-design for energy-flatness. It has to stand out, be somewhat strange and irregular. People should remember it, so they will be inspired to create energy-flat buildings themselves.

7.5 CONCLUSION

In this section, an answer was given to the question *‘’What does an energy-flat design look like?”.* This is done by describing the two preliminary designs, which focus on optimizing supply and demand separately. These optimizations are, combined with the knowledge of the parameter studies, translated into design solutions for energy-flatness which are summarized in a toolbox. Finally, the final design is described. This description consists of building design drawings, the energy performance and final considerations to energy-flatness in the design.

Both a demand-oriented and a supply-oriented design is made. For the demand-side, thermal mass, pre-heating and pre-cooling and shifting ventilation are, amongst others, effective solutions for energy-flatness. From the supply-oriented design, it is concluded that the east and west facades are essential for fulfilling the early morning and late afternoon demand, that the northern orientation is theoretically the most effective for a stable supply profile and that there is a certain mismatch that is unsolvable by supply. In general, the solutions for demand are effective for shifting the loads of the profile within shorter timesteps. The supply-oriented solutions mostly focus on increasing or decreasing the total profile, and focus more on shifting demands on larger timespans.

From the previously mentioned designs and the parameter study, a toolbox is made for energy-flat design. It consists of design solutions that improve the energy-flat performance of a residential building which may be used by designers. The design principles are linked to energy-flatness goals that were concluded from the quantitative research. Also, two sketch-level examples of energy-flat design are given to serve as inspiration for designers and to show the relation between energy-flat design principles.

The final design is a non-typical kind of architecture, which is almost energy-flat. The final design has the shape of a quarter elliptical sphere, with a flat façade oriented to the south. This façade is glazed for 80% and thereby optimized for passive radiative heating. The façade is covered with rotating, insulated blinds, which allow solar to enter in winter, block solar in summer and reduce transmission losses during the night. It is earth-sheltered for an increased amount of thermal mass. Moreover, solutions for optimal ventilation, a comfortable indoor climate, effective use of thermal mass and adaptive systems are integrated for optimal energy-flatness performance.

The overall energy-flatness performance of the final design is much better than the energy-flat performance of the reference design. The total annual mismatch has reduced from 9419 to 1608 kWh, a reduction of 83%. The total heating shortage, cooling shortage and supply surplus are respectively 356.4, 425.0 and 826.9 kWh. If the aim would be to make the building off grid, a battery sized of 610 kWh (determined by KPI3) would be required to suffice the demand at any time. The building is energy-neutral. It is noted that a higher supply would result in lower heating and cooling mismatches, but a higher surplus mismatch.

Considerations concerning building services and achieving perfect energy-flatness are described. Efficiencies of building services for heating and cooling result in a lower electricity load than the original heat and cool load, using a heat pump. Also, the supply can be optimized using amorphous photovoltaics, which are highly effective for using indirect solar radiation. Solutions to improve the energy-flatness even further, relate to the use of other renewable energy sources and curtailing supply in times of surplus. Also, the centralized timing of the surplus and finding demand-increasing activities in surplus-months. Also, climate change can have a positive effect on achieving energy-flatness.

Concluding, an example of an energy-flat design is made. The performance of this design in terms of energy-flatness is around 83% improved compared to the reference design. It is not perfectly energy-flat, and solutions for this should be found in a change of renewable supply source or in effective use of the supply surplus.

8 ENERGY-FLATNESS POSITIONED IN THE ENERGY SYSTEM

The way energy balancing should be approached in a system with an increased share of renewable energy allows for a scientific discussion. Several approaches are being researched as we speak, and energy-flat building design is just one of the many solutions. This section reflects on the potential role of residential energy-flatness in the challenge of solving the intermittency in the grid as a result of intermittent demand and supply and discusses its relevance in the transition to a sustainable energy system.

8.1 THE AGGREGATED MISMATCH BY DIFFERENT LEVELS OF THE ENERGY SYSTEM

The mismatch of supply and demand which starts at an individual building eventually affects aim for (inter)national balance in the energy system. All the mismatches of all individual actors in the energy system add up, and result in the final disbalance. In that extent, a mismatch can be both negative and positive, depending on the demands of the rest of the system. The energy mismatch is created by different levels, and on every point where multiple actors come together, their mismatches do as well.

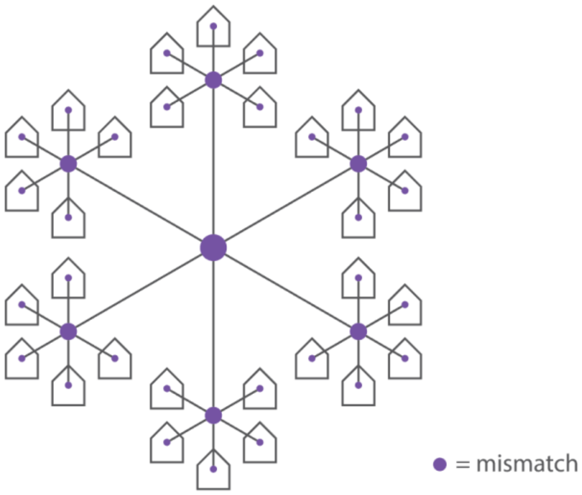


Figure 120: The energy system with a potential mismatch at every node

Figure 120 shows the built up of actors in the energy system. Imagine that every node has its own mismatch, then it is easy to see that a mismatch of an actor can be both beneficial or detrimental. An energy shortage of one actor, can be compensated by an energy surplus of another. If, however, both actors would have a shortage, these add up and are forwarded to the next level. If all mismatches are considered random and uncontrollable, this can lead to a highly fluctuating mismatch at the final ‘highest’ node. If, however, the mismatches can be (partly) controlled and adapted to each other, the size of the final mismatch can be limited. Hence, the solution to minimizing the final mismatch should be found at every node, at every level.

Every node in the energy system that has both a demand and a supply, might be able to minimize its mismatch if it is able to control this demand and supply. Chapter 2 already stated solutions for the international scale, where the mismatch is controlled by interconnection for example; an energy surplus is sold to another country, or a shortage is compensated by buying additional supply. On the a neighbourhood level, the smart use of waste flows of buildings and the interconnection of buildings provide possibilities to minimize the mismatch. This research showed the solution for the lowest level in the energy system; a single actor. In this case, a residential building.

Theoretically speaking, there would be no mismatch in the complete energy system if every single actor is able to become energy-flat. However, in all cases a general rule of effectivity applies which implies that the more detailed the fine-tuning of energy-flatness becomes the harder it is, as shown in Figure 121 . This research showed that making some first steps towards energy-flatness are easy, but achieving perfect energy-flatness is an almost impossible job.

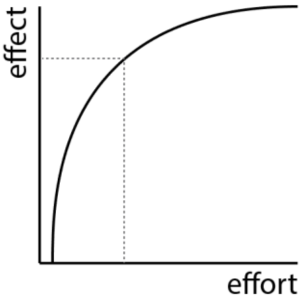


Figure 121: A general principle of effectivity, which implies more effort for significant effect as the goal becomes closer

The different levels of the energy system have different approaches for creating energy balance. In the extent of the figure above, one could argue that it would be most effective to apply the first steps of effort on all different levels. Considering that the type of solutions differs per level and so do their effects, the energy-flatness might be approached with relative low effort. In other words, overall energy-flatness in the energy system is approached most efficiently by implementing only the most effective solutions on every different level.

8.2 RELEVANCE OF ENERGY-FLATNESS IN THE TRANSITIONING ENERGY SYSTEM

The relevance of energy-flatness in the future depends on how the energy system will develop. Although it is widely accepted that fossil fuels are no sustainable solution, the development of energy supply and demand depends on a lot of factors, hence different scenarios are feasible. The development of energy storage, the share of renewable energy supply and the energy pricing affect the relevance of energy-flatness.

8.2.1 Storage

The development of storage is essential for the relevance of energy-flatness. The key aim of energy-flatness is to match supply and demand. The key functionality of energy storage is to shift a supply (i.e. by storing energy) or to shift demand (i.e. by draining the storage). In other words, if energy storage would be 100% efficient and wouldn't require any additional energy or materials, energy-flatness is unnecessary. However, energy storage will inevitably use some energy and some materials. In that case, more detailed properties of the effectivity of storage affect the relevance of energy-flatness.

First of all, the timespan capacity of storage is important. If, for instance, it will be possible to effectively store energy in a time span of 24 hours, then the challenge of energy-flatness would be reduced to achieving a daily match. If, on the other hand, bridging seasons will be effective, the energy-flatness challenges will focus more on the smaller timespans.

Second of all, the type of storage is important. Effective thermal energy storage allows the use of passive solar radiation even more. Effective electricity storage increases the applicability of the energy, but implies conversion losses from solar radiation or wind, to electricity.

Last of all, the scale of the storage is relevant. If energy storage becomes highly effective on small scales (i.e. residential), the mismatches could be solved at a residential level using this storage. In that case, energy-flatness principles will reduce the size of the storage. But when energy storage is only effective on large, centralized scales, energy-flatness will play an important role in minimizing the energy traffic.

8.2.2 Balance between fossil energy and renewable energy supply

In the conventional energy system, all electricity supply is centralized and produced by fossil fuels. This fossil supply is easily adaptable to the intermittent demand, resulting in a lower relevance for energy-flatness. However, it is to be accepted that the share of renewable energy will highly increase.

The bigger the share of renewable energy becomes, the higher the need for energy-flatness will be. A situation in which, for example, half of the energy supply is provided by renewables, the need for matching will rise. The biggest peaks and valleys of the renewable supply should then be compensated by the demand side, and the supply or renewables will have to focus on a match with demand rather than highest annual production. Small mismatches can, in this case, still be compensated by the fossil share of the supply system. Nevertheless, the smaller the share of fossil energy supply is, the lesser its ability to compensate for intermittencies.

In a situation where the energy supply consists of 100% renewable energy, all intermittencies should be compensated to each other. Energy-flat buildings will play an important role in using the renewable energy when it is available. This will happen partly on the level of the individual building, and partly on other levels, as discussed in previous section. Inherently to an energy system that has 100% renewable energy supply, is the decentralized energy supply. Some buildings will produce their own energy. The increased share of decentralized energy supply also demands for energy-flatness. After all, the uncontrolled decentralized creation of a mismatch can have big effects on the national mismatch. It is to be expected that these kind of mismatches, in a scenario with 100% renewable energy supply, are limited by utility grid managers.

8.2.3 Energy pricing

Another development is the one of energy pricing. As a result of the increased share of decentralized energy renewable energy supply and the increasing intelligence of energy management systems, it is to be expected that dynamic energy pricing will be introduced to the private market. With dynamic energy pricing, the price of energy is depending on the supply and demand of energy in the market.

In a situation with dynamic energy pricing, energy-flatness might become very cost-effective, especially the introduction of it. The main principle of energy-flat buildings is to use energy when it is easily available and to minimize energy use in times of low production. The general principle of energy pricing is a low price in times of high supply and a high price of times of little supply. Combining these principles results in the situation that energy-flat building use very little energy when it is expensive, and use more energy when the energy is cheap. This way, energy-flat buildings become economically effective.

8.3 CONCLUSION

Theoretically, making every building energy-flat is a solution for the energy-balancing challenge. However, a more effective way to achieve energy-balance is a synergy in terms of approach per level of the energy-system. Every level has its own, most-effective solutions to minimize the mismatch. Combining all the most effective solutions on all levels, may greatly decrease the final mismatch.

In the future, the energy system will change and so will the role of energy-flatness. The relevance of energy-flatness depends on developments of the energy system. Improved possibilities for energy storage reduce the relevance of energy-flatness, because storage is a solution to solving a demand and supply mismatch by nature. An increased share of renewable energy in the energy system, however, results in a larger relevance for energy-flatness, because of increased intermittencies and unpredictabilities. Finally, dynamic energy-pricing might make energy-flatness more relevant and cost-effective. Energy-flatness is a solution to use little energy in times of little supply (i.e. high price) and use more energy in times of sufficient supply (i.e. low price).

9 CONCLUSION

This research aimed to solve the residential energy mismatch by providing a definition for energy-flatness in the residential context, exploring design principles for energy-flat buildings and making an example design that is energy-flat. The research question that is answered in this thesis is: “*How can the residential mismatch of the supply and demand of energy be solved by architectural design?”*. To answer this question, six sub-questions are answered. For every sub-question a short summary is provided below.

9.1 SUMMARY OF THE RESEARCH AND RESULTS

What is energy-flatness and what are its key performance indicators?

Energy-flatness is the state of a buildings energy performance in which the mismatch between supply and demand is zero at any time. Eventually, energy-flatness considers the electrical demand and supply. However, the energy supply chain starts with the heating and cooling demand. Hence, matching the supply potential profile and the heating and cooling profiles is the first aim for energy-flatness. Energy-flatness can be quantified by three key-performance-indicators, each of which can be applied to the energy system as a whole and to the individual profiles of heating, cooling and supply.

How should the energy-flat performance of a design be evaluated?

The heating and cooling demand of a building are the direct result of the architecture and the building physics properties. Because energy-flatness considers a match at any time of the year, a dynamic energy simulation tool is required which provides hourly heating demand, cooling demand and supply potential values. Grasshopper Honeybee is concluded to be a software tool that matches the requirements to calculate energy-flatness and allow for design studies. A simulation tool is created with which all the calculations of this research are done.

What is the mismatch between supply and demand?

The current residential energy mismatch is represented by the simulated energy-performance of the NZEB reference design, as provided by DGMR (2016). The reference design is energy-neutral, all electric and is a large, detached house which allows for a variety of design solutions. The current residential energy mismatch is characterised by:

- An energy shortage in winter, a supply surplus in autumn and spring and an approximate match in the late summer
- A highly differing mismatch between successive days, as a result of changing outdoor temperatures and solar power
- A cooling load during daytime in summer, which matches the timing (but not the size) of the supply potential

- A heating load from the beginning of the evening to the early morning. This load should be shifted to achieve energy-flatness, because there is a lack of supply potential in the night.

From this is derived that there is a need to adapt all the three energy flows; heating, cooling and supply. The adaptations should be found in shifting, increasing, decreasing and flattening the profiles.

To what extent can supply and demand profiles be adapted by building parameters?

Nine parameters are researched by changing them individually and analysing the effect on energy-flatness;

- Geometry
- Insulation value
- Thermal mass
- Ventilation rate
- Temperature range
- Window share
- Window g-value
- Building orientation
- Supply potential share

Almost all parameter changes have a significant effect on the KPI’s. A change in one of the first four parameters mentioned, has a similar effect on all three energy flows, meaning that all KPI’s decrease or all KPI’s increases as the parameter changes. For the other five parameters, the surplus and shortage are affected oppositely, meaning that a decrease in surplus inherently means an increase in shortage and vice versa. For almost all parameters, a different approach in winter and summer is desired to minimize the total mismatch. In most cases, also a different approach in day and night is beneficial.

The conclusions of the parameter study are the input for a first design, which answers the next sub-question.

What could an energy-flat design look like?

A final design is made in three steps; a demand-oriented design, a supply-oriented design and a final design which is a mix of the former two. In these designs, the formerly researched parameter changes are combined and dynamic solutions are added. This results in improved insights on the effects of architectural design on the energy-flat performance of a building. These design solutions are summarized in a toolbox, which can be used by designers to improve the energy-flat performance of a building.

The overall energy-flatness performance of the final design is much better than the performance of the reference design. The total annual mismatch has reduced from 9419 to 1608 kWh, a reduction of 83%. The total heating shortage, cooling shortage and supply surplus are respectively 356.4, 425.0 and 826.9 kWh.

Finally, a translation of heat energy-flatness to electrical energy-flatness is made by describing the effects on the energy balance of fulfilling the heating and cooling demand and supply with certain building services. It is concluded that building services may have a positive effect on the energy-flatness, by needing relatively little energy to provide heat (i.e. by using a heat-pump) and by effectively using the diffuse solar potential by choosing the right photovoltaic panel (i.e. amorphous).

How do energy-flat buildings relate to solving the mismatch in the energy system that the building is part of?

Theoretically, making every building energy-flat is a solution for the energy-balancing challenge. However, a more effective way to achieve energy-balance is by implementing only the most effective energy-flatness solutions for every level of the energy-system. Combining all the effective solutions on all levels, may greatly decrease the final mismatch. The role of energy-flatness will change in the future as a result of changing technological possibilities. Improved efficiency of energy storage will reduce the relevance of energy-flatness, while an increased share of renewable energy will increase it. Eventually, energy-flatness for dwellings will become more cost-effective by private dynamic energy-pricing.

Summary

Energy-flatness is the state in which the supply and demand of energy are equal at any time. The heat balance and the electricity balance must be distinguished. Architectural design can almost completely result in residential heat balance energy-flatness. Electrical energy-flatness is influenced by the efficiencies of technology and perfect energy-flatness requires a small amount of long-term energy storage. The relevance of energy-flatness will change in the future, based on the developments of energy storage, renewable energy and energy pricing.

9.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The study was set out to explore the principle of energy-flatness and the possibilities to achieve this. Since the time was limited, not all questions that came across were answered. The following questions remained unanswered and are open for future studies:

- This research focussed on adapting the heat balance of a building, for it is the start of the energy supply-chain and this is the first research to energy-flatness in the residential context. The translation to electrical energy-flatness is essential and eventually is the most relevant. Therefore, the main follow-up study would be to research the possibilities of several building services in favour of energy-flatness.
- An energy mismatch in a dwelling as part of an energy system, can be both positive and negative. This research aimed for minimizing the mismatch, assuming a mismatch is negative. The next level of energy-flatness, would be a completely energy-flexible building; a building that can be perfectly energy-flat when desired, but which can also provide a shortage or surplus depending on the needs on the energy system that it is part of. Research on this topic, however, requires extensive knowledge on the (intermittent) demands of the energy system.
- Whereas the system boundary in this research was limited to one single household, it would be highly interesting to see the potentials and challenges of multiple actors in one energy system approaching energy-flatness together.
- In my opinion, there is a great economical potential in energy-flatness. Whereas this research explored the possibility of achieving energy-flatness by architectural

design, a look at the economical potential of energy-flatness as a concept could substantiate its relevance.

- It was concluded that for fine-tuning the energy-flat performance, improved predictability of the intermittencies of demand and supply is required. Moreover, dynamic solutions in the architecture (e.g. rotating sun-blinds and adaptive ventilation rates) are effective. In the extent of these two conclusions, it is interesting to research the possibilities of data- and sensor-driven solutions for adaptive buildings services.

10 Reflection

10.1 Academic

The graduation lab Sustainable Design Graduation, as part of the MSc Building Technology aims to emphasize on sustainability-related topics from a structural design, facade design and climate design point of view. Energy-flatness as a topic sheds a new light in the existing topic of sustainable buildings in terms of energy. It aims at making the current approach to sustainability more future-proof. The current approach is to reduce energy consumption, increase renewable energy production and thereby aiming for energy neutrality. This research explored the potential of energy-flat buildings, to reduce intermittent loads on the grid and thereby increase the effectivity of renewable energy production. Adapting the energy balance of a building, realizing energy-flatness in particular, considers the complete building as adaptation tool. Inherently, this research covers both facade design and climate design.

Strengths	**Weaknesses**
structured by sub-questions elaborately researched theme	sequential structure scope is limited due to time limitations
Opportunities	**Threats**
possibility of scaling research design by research approach	scope not completely clear due to new topic using tools that are unknown to me

Figure 122: SWOT analysis of the research approach

The topic of sustainable buildings and energy consumption of buildings is elaborately researched, making it easy to find decent literature to substantiate this topic. However, the scope is limited due to time limitations; one could easily fill a PhD with research to the boundaries and possibilities of energy-flat housing. Similarly, this results in the possibility of scaling the research. The opportunities for further research are broad. A SWOT analysis of the research approach is summarized in Figure 122.

The approach has mostly worked out effectively. The approach asked for a clear set of products for every sub-question, and because of this clear definition these products were provided. One remark, the potential delay of the sequential planning as was acknowledged during the P2, has become definite. Providing the parameter overview, the product of the fourth sub-question, took more time than expected. As a result, less time has been invested into the design of the individual energy-flat buildings. The elaboration on the parameter overview, however, is something I consider as a shift in design focus.

Design by research is the main method of creating an energy-flat design in this thesis. The project is characterized by a conceptual, abstract, but structured approach. The design tools are simplified to a set of building parameters that influence the energy demand and supply profiles. By analysing the effects of changing the parameters, the optimal energy-flat design is created. However, adjusting merely these parameters did not result in an optimal design. From that point, it became research by design. Several design solutions were implemented and analysed, eventually resulting in an almost optimal energy-flat design. Summarizing, the first stage of energy-flatness is achieved by design by research. The second stage, is achieved by fine-tuning the architecture by research by design.

10.2 PERSONAL

The first phase of the graduation project (until P2) focused strongly on the literature review and scoping of the subject. After the P2 I concluded, that this phase was characterized by the fluctuation between (the idea of) exactly knowing what you are doing, and founding yourself desperate between all the information and scoping decisions. The second phase (from P2 upon P3) had the main goals to finalize the literature research, set up the energy model and start with the early design. Once again, I have found that scoping the research seems the most challenging. At the P2 I was sure that I had a clear scope. Especially in the energy model and results processing however, I found that I was confronted with every little detail of the energy system of a building and had to make a logical decision whether or not to take it into account. Firstly, this is the result of using tools that were unknown to me upfront. Secondly, I assume this is the result of the introduced new definition of energy-flatness. The definition is new, and so is the scope of this definition. In the future, this might be prevented by brainstorming about the topic into detail. I assume that this way most relevant details will show up, and a choice of whether to account for them can be made.

My work approach is to define a clear structure, overview the complete approach and define clear goals, and then start the project. Within a graduation topic, this is not achievable. The project is too big and the field to explore is too unknown to overview the complete process at once. This inherently means that I must adapt my working method, and have to learn to work with the unknown in particular. Now, near the end of my graduation, I can state that this is a tough task for me. I found it hard to constantly work within uncertainties. Since P1 I have improved this though, by cutting up the project in smaller pieces and approach these in a structured way with clear goals. The only threat resulting from this; the goals and products per phase do not necessarily are one, coherent set of goals and products.

Nevertheless, I find the graduation process very interesting and it is education for sure. Although the process is tough, I am aware of this project making me a better designer, engineer and professional.

10.3 SOCIETAL

Sustainability is a hot topic. At the end of the 20th century, consciousness had to be created about the energy savings and climate problems. This task is still not finished, but the societal awareness around energy savings and global warming has driven immense. Sustainability itself, has already become a marketing word. Although sometimes misused, this term creates awareness after all.

As awareness on sustainability rises, it is the role of scientists to look ahead and create the foundation for further sustainable development. Energy-flatness is a concept that is not directly necessary, nor directly applicable in practice. However, the exploration of the concept contributes to the foundation of future sustainable developments by researching the potentials and risks of solutions to future problems.

In the built environment, there is a shift towards decentralization in energy production. Renewable energy production is increasingly present within the residential or neighbourhood boundaries. Awareness of private energy supply creates awareness on private energy demand, which eventually results in the increased desire of private consumers to adapt their demand and supply in ways that are economically most feasible. Energy-flatness contributes to this by exploring the role of architecture in this rising desire. It helps the planet, by giving more control to the people, so they can have a bigger profit of sustainable design.

So, should we build energy-flat housing? Creating perfect energy-flatness for every individual building is realistic nor efficient. The need for balancing energy on the highest level of the energy system, however, will rise with the increasing share of renewable energy supply. Therefore, dwellings should be '*as energy-flat as is efficiently possible*'. The factor 'efficiency' in this sentence, strongly depends on the state-of-the-art technologies. Hence, the efficient level of energy-flatness will change over time.

Whereas energy-flatness is considered the next stage of energy-neutrality, energy flexibility could be considered the next stage of energy-flatness. By that, I meant that it would be ideal if a building is so energy-flexible that it could be perfectly energy-flat if it is desired, but that it could also create a shortage or surplus depending on the needs of the energy system that it is part of. Thereby, it would not only solve its own mismatch, but also contribute to solving the energy mismatch of other actors in the system.

11 BIBLIOGRAPHY

Arasteh, D., Selkowitz, S., Apte, J., & LaFrance, M. (2006). Zero energy windows. *Lawrence Berkeley National Laboratory*.

Castleton, H. F., Stovin, V., Beck, S. B., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings, 42*(10), 1582-1591.

CBS. (2013). *Zonnestroomsystemen; handel in panelen, werkgelegenheid en omzet, 1991-2012*. http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=70949ned&LA=NL

CBS. (2016). Hernieuwbare energie in Nederland 2015. Den Haag: Centraal Bureau voor de Statistiek.

De Dear, R. J., Brager, G. S., Reardon, J., & Nicol, F. (1998). Developing an adaptive model of thermal comfort and preference/discussion. *ASHRAE transactions, 104*, 145.

DGMR. (2016). BENG referentiegebouwen. Den Haag: Rijksdienst voor Ondernemend Nederland.

Donker, J., Huygen, A., Westerga, R., & Weterings, R. (2015). Naar een toekomstbestendig energiesysteem: Flexibiliteit met waarde (pp. 89). Delft: TNO.

EnergyPlus. (2017). EnergyPlus™ building simulation software. Retrieved Jul 28, 2017, from https://www.energyplus.net/

Eurostat. (2017). Share of renewables in energy consumption in the EU still on the rise to almost 17% in 2015 [Press release]

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

Gellings, C. W., & Smith, W. M. (1989). Integrating demand-side management into utility planning. *Proceedings of the IEEE, 77*(6), 908-918.

GIW. (2008). GIW/ISSO-publicatie 2008 *Ontwerp- en montageadviezen nieuwbouw, eengezinswoningen en appartementen*. Rotterdam: Stichting GIW en Stichting ISSO.

Goorden, J. (2016). *Integration of seasonal thermal energy storage in refurbishment projects.* (Master of Science), TU Delft, Delft.

grasshopper3d.com. (2015, Dec 7, 2015). forumpost: "problem setting Energy plus fields in Honeybee". Retrieved Sep 26, 2017, from http://www.grasshopper3d.com/group/ladybug/forum/topics/problem-setting-energy-plus-fields-in-honeybee

Hafemeister, D. (2014). Physics of Societal Issues: Springer New York.

Hardin, G. (1968). The tragedy of the commons. *Science, 162*(3859), 1243-1248.

Hasnain, S. (1998). Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy conversion and management, 39*(11), 1127-1138.

Hegger, M., Fuchs, M., Stark, T., & Zeumer, M. (2008). *Energy manual-sustainable architecture*: Institut für Internationale Architekturdokumentation/Birkhäuser.

Heide, D., Von Bremen, L., Greiner, M., Hoffmann, C., Speckmann, M., & Bofinger, S. (2010). Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. *Renewable energy, 35*(11), 2483-2489.

IEA. (2011). Harnessing Variable Renewables: A guide to the Balancing Challenge. Paris, France: International Energy Agency.

IEA. (2016). International Energy Outlook 2016. Washington, DC 20585: Office of Energy Analysis, U.S. Department of Energy.

Indovance. (2016). Green roof. Retrieved 7 December 2017, from http://www.indovance.com/things-you-should-know-about-green-roofs-in-civil-engineering/

IPIN. (2015). Position paper kennis- en leertraject Thema visie

Utrecht: RVO.

ISSO. (1976). Publicatie 3 - Zonstralingstabellen. Rotterdam: ISSO.

Itard, L., & Meijer, F. (2008). *Towards a Sustainable Northern European Housing Stock: Figures, Facts, and Future* (Vol. 22): Ios Press.

Jaffal, I., Ouldboukhitine, S.-E., & Belarbi, R. (2012). A comprehensive study of the impact of green roofs on building energy performance. *Renewable energy, 43*, 157-164.

Jonker, M. (2017). Een jaar in een Tiny House. *www.marjoleininhetklein.com.* Retrieved 1 June 2017, from https://www.marjoleininhetklein.com/2017/05/23/een-jaar-in-een-tiny-house/

Juodis, E. (2006). Extracted ventilation air heat recovery efficiency as a function of a building's thermal properties. *Energy and Buildings, 38*(6), 568-573.

Kelly, N. (2012). *Future Energy Demand in the Domestic Sector* Retrieved from Glasgow:

Kingspan Insulation Ltd. (2017). Kooltherm K100 - Frequently Asked Questions. Retrieved Oct 1, 2017, from http://www.kingspaninsulation.co.uk/Knowledge-Base/Kooltherm-K100.aspx

Kok, K. (2013). The PowerMatcher: smart coordination for the smart electricity grid. *TNO: The Hague, The Netherlands*, 241-250.

Konstantinou, T. (2014). *Facade Refurbishment Toolbox; Supporting the Design of Residential Energy Upgrades.* Delft University of Technology, Delft.

Ladybug Tools. (2017). Honeybee/Ladybug Tools. Retrieved Jul 28, 2017, from http://www.grasshopper3d.com/group/ladybug

Langen, S. v., Tol, P. v., Quak, T., & Bruggen, M. v. (2017). *Profielen elektriciteit 2017*. http://www.nedu.nl/portfolio/verbruiksprofielen/

Laverge, J., Van Den Bossche, N., Heijmans, N., & Janssens, A. (2011). Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. *Building and Environment, 46*(7), 1497-1503.

LenteAkkoord. (2017). Woningbouw volgens BENG; Do's en dont's voor bijna energieneutraal bouwen. In LenteAkkoord (Ed.), *www.lente-akkoord.nl*. Voorburg: Lente-akkoord.

Lund, H., Marszal, A., & Heiselberg, P. (2011). Zero energy buildings and mismatch compensation factors. *Energy and Buildings, 43*(7), 1646-1654.

Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy, 137*, 511-536.

Maréchal, K. (2009). An evolutionary perspective on the economics of energy consumption: the crucial role of habits. *Journal of Economic Issues, 43*(1), 69-88.

Meggers, F., Ritter, V., Goffin, P., Baetschmann, M., & Leibundgut, H. (2012). Low exergy building systems implementation. *Energy, 41*(1), 48-55.

Palmero-Marrero, A. I., & Oliveira, A. C. (2010). Effect of louver shading devices on building energy requirements. *Applied Energy, 87*(6), 2040-2049.

Peeters, L., De Dear, R., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy, 86*(5), 772-780.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings, 40*(3), 394-398.

ReVolt House. (2011). ReVolt House, Deliverable #3 - Press Release [Press release]. Retrieved from http://www.sdeurope.org/wp-content/uploads/downloads/2011/10/TUD_PR3_2011-09-14.pdf

ReVolt House. (2012). ReVolt House, Deliverable #4 - Project Manual. Delft: TU Delft.

Robinson, P., & Hutchins, M. (1994). Advanced glazing technology for low energy buildings in the UK. *Renewable energy, 5*(1-4), 298-309.

RVO. (2015). Cloud Power Texel *Smart Grid Pilot Projects*. Utrecht: RVO.

S. Klijn Velderman, D. Hughes, M. Witkamp, & Verduijn, S. (2016). Handboek NOM Keur (Versie 1.04 ed.). Den Haag: Vereniging De BredeStroomversnelling.

Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews, 15*(8), 3617-3631.

Salom, J., Widén, J., Candanedo, J., Sartori, I., Voss, K., & Marszal, A. (2011). *Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators.* Paper presented at the proceedings of building simulation.

Salpakari, J., & Lund, P. (2016). Optimal and rule-based control strategies for energy flexibility in buildings with PV. *Applied Energy, 161*, 425-436.

Santamouris, M., & Asimakopoulos, D. (1996). *Passive cooling of buildings* (Vol. 1): James & James London;.

Santamouris, M., Sfakianaki, A., & Pavlou, K. (2010). On the efficiency of night ventilation techniques applied to residential buildings. *Energy and Buildings, 42*(8), 1309-1313.

Sartori, I., Napolitano, A., & Voss, K. (2012). Net zero energy buildings: A consistent definition framework. *Energy and Buildings, 48*, 220-232.

Schellen, L., van Marken Lichtenbelt, W., Loomans, M., Toftum, J., & De Wit, M. (2010). Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition. *Indoor air, 20*(4), 273-283.

Shameri, M., Alghoul, M., Sopian, K., Zain, M. F. M., & Elayeb, O. (2011). Perspectives of double skin façade systems in buildings and energy saving. *Renewable and Sustainable Energy Reviews, 15*(3), 1468-1475.

Shaviv, E., Yezioro, A., & Capeluto, I. G. (2001). Thermal mass and night ventilation as passive cooling design strategy. *Renewable energy, 24*(3), 445-452.

Stichting Schoonschip. (2018). Schoonschip Amsterdam. Retrieved Jan 14, 2018, from

Tillie, N., Van Den Dobbelsteen, A., Doepel, D., Joubert, M., De Jager, W., & Mayenburg, D. (2009). Towards CO2 neutral urban planning: presenting the Rotterdam Energy Approach and Planning (REAP). *Journal of Green Building, 4*(3), 103-112.

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). Zero energy buildings: a critical look at the definition. *National Renewable Energy Laboratory and Department of Energy, US*.

TRNSYS. (2017). TRNSYS Transient System Simulation Tool. Retrieved Jul 28, 2017, from http://www.trnsys.com/

Van den Dobbelsteen, A. (2008). *655: Towards closed cycles-New strategy steps inspired by the Cradle to Cradle approach.* Paper presented at the PLEA2008, UCD, Dublin.

Van der Linden, A. (2005). Zonnestraling en zonstralingsgegevens. Retrieved from

Van der Linden, A., Boerstra, A. C., Raue, A. K., Kurvers, S. R., & De Dear, R. (2006). Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate. *Energy and Buildings, 38*(1), 8-17.

van Sark, W., Segaar, P., Gerrissen, P., Esmeijer, K., Moraitis, P., van den Donker, M., . . . Bosselaar, L. (2014). Opbrengst van zonnestroomsystemen in Nederland: Utrecht: Universiteit Utrecht.

Wang, R., Yu, X., Ge, T., & Li, T. (2013). The present and future of residential refrigeration, power generation and energy storage. *Applied Thermal Engineering, 53*(2), 256-270.

Widén, J., Wäckelgård, E., & Lund, P. D. (2009). Options for improving the load matching capability of distributed photovoltaics: Methodology and application to high-latitude data. *Solar Energy, 83*(11), 1953-1966.

Xu, L., & Ojima, T. (2007). Field experiments on natural energy utilization in a residential house with a double skin façade system. *Building and Environment, 42*(5), 2014-2023.

12 APPENDIX

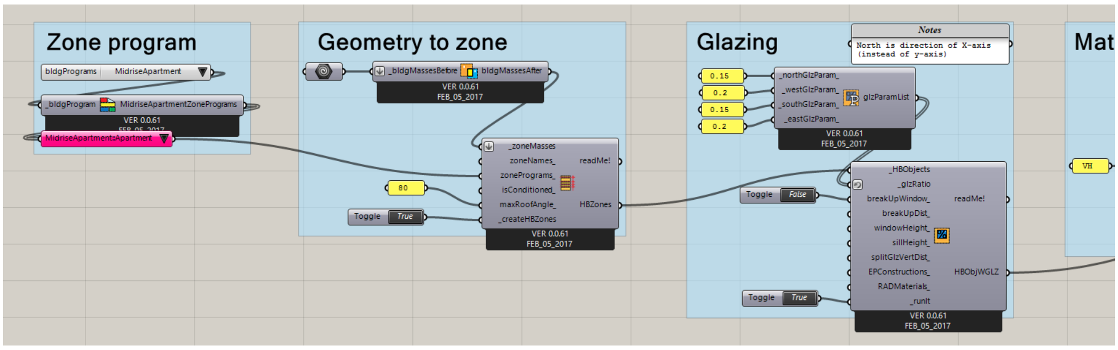
12.1 APPENDIX 1: FUNCTIONALITY OF THE ENERGY SIMULATION MODEL

12.1.1 Geometry

The groups *Zone program*, *Geometry to zone* and *Glazing* represent the geometry set-up, in which the surfaces are translated to Honeybee zones that can be used for calculation.

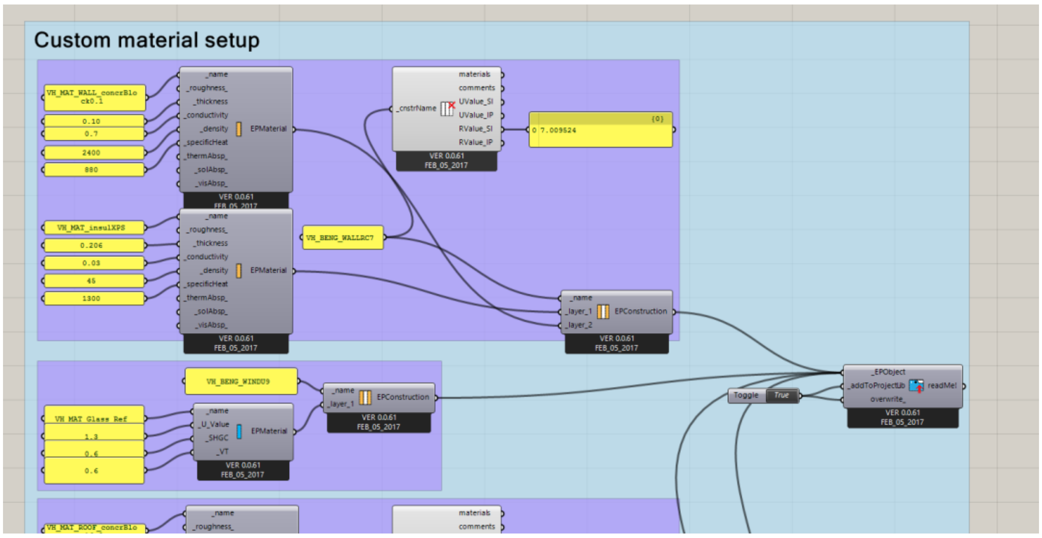
Zone program provides the required default starting values for all parameters, which are changed later in the data-flow. *Geometry to zone* translates the Rhino geometry to Honeybee zones. The geometry is built in Rhino using a closed Brep.

Glazing assigns window surfaces to the facade. The windows in the facade are simplified to one or two windows per facade in favour of calculation speed (see figure on the right). Since the radiation calculation is based on orientation and area, the effect of the simplification of windows on the results is negligible.



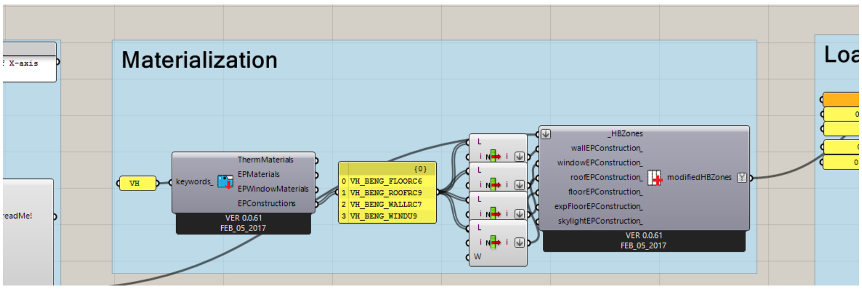
12.1.2 Materialization

The *Materialization* group assigns construction properties to all external surfaces, like insulation value, g-value and thermal mass. EnergyPlus provides a library with pre-set materials, but instead custom materialization is used to achieve the exact same U-values as prescribed by the reference design.



The group *Custom material setup* creates material layers and constructions and writes them to the construction library.

The *Materialization* group assigns the (custom) constructions from the library to the surfaces of the zone. Assigning of construction is per surface type, which means all walls have similar properties, all roof surfaces have similar properties et cetera.



The zones, that now contain data on geometry and materialization, flow on to the loads and schedules groups.

12.1.3 Loads & schedules

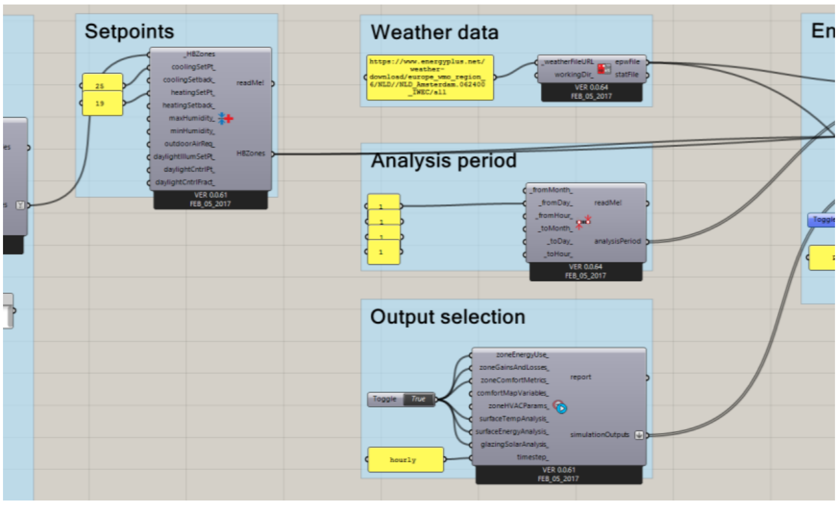
In the loads module, the ventilation rates and internal loads are assigned. In Honeybee, one has the possibility to assign a fractional schedule to a load which multiplies the load by a set fraction for any hour of the year. The loads to be assigned are

- Infiltration rate
- Ventilation rate
- Equipment load
- Lighting density
- Number of people

These loads were elaborately described in 4.4 Model set-up & input

12.1.4 Weather data and simulation parameters

This group sets indoor temperature setpoints, links a weather file to the data-flow and sets all the simulation parameters.



The heating and cooling *setpoints* determine the boundaries of accepted indoor air temperature. In other words, a cooling setpoint of 24°C turns on the cooling demand when the temperature is about to exceed this temperature.

Weather data files contain information on temperature, humidity, radiation, wind etcetera. Weather files are openly available for many locations in the world. Honeybee makes use of the -.epw-type of weather file and the ladybug community provides the epw-map to find the correct weather file by searching for it on a world map (see Figure 123).

For this research an -.epw file of Amsterdam, The Netherlands, is used. It can be openly downloaded from:

https://www.energyplus.net/weather-download/europe_wmo_region_6/NLD//NLD_Amsterdam.062400_IWEC/all.

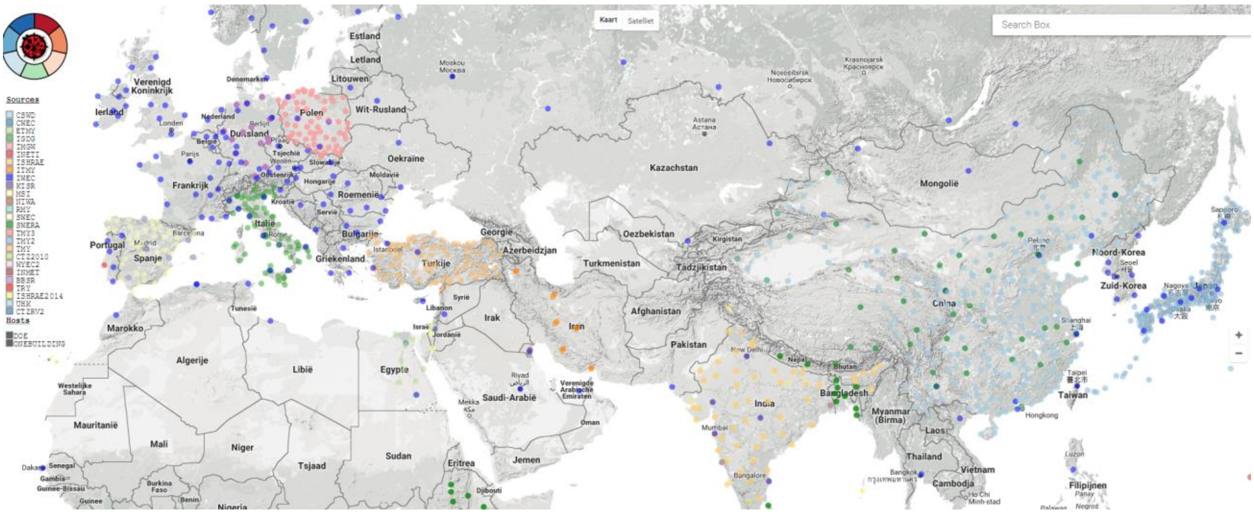


Figure 123: a preview of the epw-map initiated by the Ladybug Tools community (http://www.ladybug.tools/epwmap/)

The *Analysis period* group allows for selecting a specific period of the year to be simulated. Since the data-processing of the simulation is done in excel, all simulations are executed for a complete year so that every dataset contains all data of a full year. Desired smaller analysis periods are selected separately from the dataset in Excel.

In the *Output selection* module, one can choose which outputs are desired. This module saves calculation time; unneeded outputs are skipped in the calculation. HVAC parameters are skipped because of the usage of ideal air loads. Comfort mapping and surface temperature are skipped because they do not provide direct information for the energy balance. Lastly, the output selector sets the timestep. An hourly timestep is chosen; smaller timesteps are not representative in thermal calculations of a complete building and larger timesteps would be too undetailed.

12.1.5 Solar radiation analysis

The solar radiation analysis group relates to the supply side of the heat balance and its goal is to return the total solar radiation on every surface of the building. This radiation potential can then be translated to the actual energy supply by taking into account PV and thermal collector efficiencies.

The module takes the weather file, the geometry, and the orientation of the building as input. It returns the total solar potential in kWh/m^2 for every hour for every surface with a unique orientation. This value is multiplied by each surface’s area to result in the total solar potential in kWh per surface. Also, the total solar radiation potential is calculated, which is of more use than area-specific results when comparing total demand versus total potential.

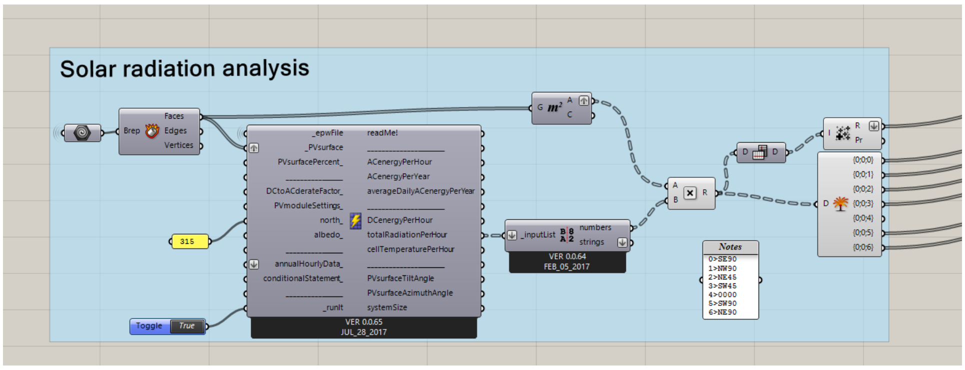


Figure 124: the solar radiation group in which the geometry is related to the weather file to result in the total solar potential

12.1.6 EnergyPlus simulation module

The EnergyPlus simulation component takes all the previous described inputs, runs it through the EnergyPlus simulation software, and then returns outputs to be used by Grasshopper. In fact, it is the bridge between the input and the output. Though this component performs the most complex task, in Honeybee it is relatively simple. The weather file, the north angle and the total data-flow are used as input. Moreover, it has a “runIt’’-toggle to make sure the module only runs when desired (N.B. this module takes a long time to run due to the complex simulation calculations). The output is the ‘resultFileAdress’, in which all the hourly data is stored, to be used in further data-processing of the output. Another output is the report, which provides a summarized error-report if errors occurred during the simulation.

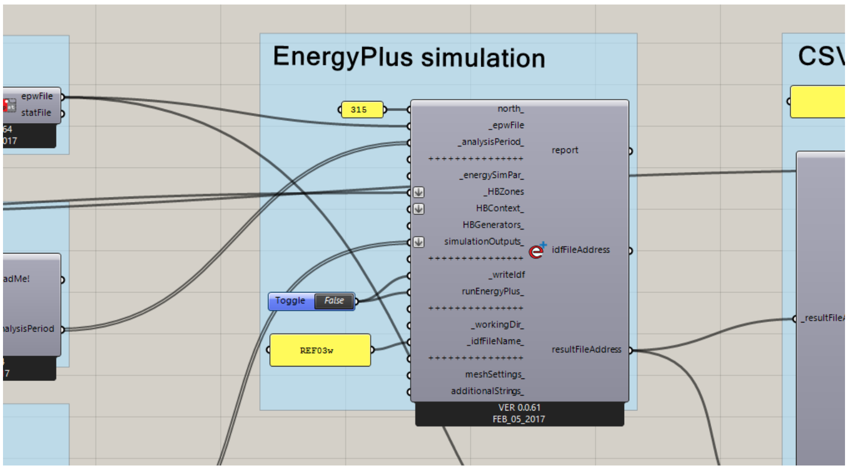


Figure 125: the EnergyPlus component that defines the bridge between input and output

The output is used for visualization of results in Grasshopper/Rhino and for the -.CSV creation that is used by Excel. The handling of outputs is described in the next section.

12.1.7 Other settings

During the building of the model, some more specific settings were implemented to improve the validity of the model. These settings are not included in the model description in the section above and therefore are described in this section.

Ventilation

The model consists only of mechanical ventilation, not of natural ventilation. The mechanical ventilation has a constant rate of 150 m^3/h, meaning that for every hour of the year this rate is exactly equal.

This value is not completely realistic. Firstly, because most houses have natural ventilation; users open their windows when they find their indoor climate uncomfortable or wish to refresh the air in the building. Secondly, some mechanical ventilation systems (as is the case in this reference design) have the so-called airside economizer. Which increases the ventilation rate when the following two boundary conditions are met:

1. there must be a heating demand
2. the outside temperature is lower than the indoor temperature

Preliminary versions of the model showed that the airside economizer resulted in unclear and ‘biased’ results. In models that have the airside economizer included, the total ventilation volume is unpredictable. For the parameter study, this is not desired, because all parameters should be constant in every study, apart from the parameter that is studied. Natural ventilation is skipped in the first model for similar reasons.

Ground temperature

In the model, the default ground temperature of the weather file is overwritten by a list of values. The reason is that the default ground temperature results in an extremely high energy loss through the buildings ground floor. The cause and solution to this problem are discussed in a forum-post by Honeybee developer Chris Mackey himself (grasshopper3d.com, 2015).

The solution is to overwrite the default ground temperature with a list of 12 values, representing the ground temperature for every month of the year. The overwriting values are the average outdoor temperature of the corresponding month, minus two. This is a representative value to compensate for the fault in ground temperature calculation (grasshopper3d.com, 2015).

12.1.8 Not included in the simulation set-up

Beside the settings as explained above, Honeybee contains a lot of features regarding installations, costs and others. In fact, only a small set of functions is used for this simulation. Two functionalities that might seem relevant in the simulation, but are not included, are explained.

HVAC systems

Using the HVAC components, one can set the type of HVAC system, air details, heating and cooling of air details. Included in this is the option of Heat Recovery. The documentation of the *Reference Design* states that the design has a CO2 controlled mechanical in- and outlet of air and a heat recovery unit (DGMR, 2016). Since this simulation makes use of an Ideal Air Loads system and the desired output is the energy demand rather than the final energy (see *3.1* Energy definitions). When the results of the simulation are analysed and solutions are to be found, the solution of heat exchange will eventually come in.

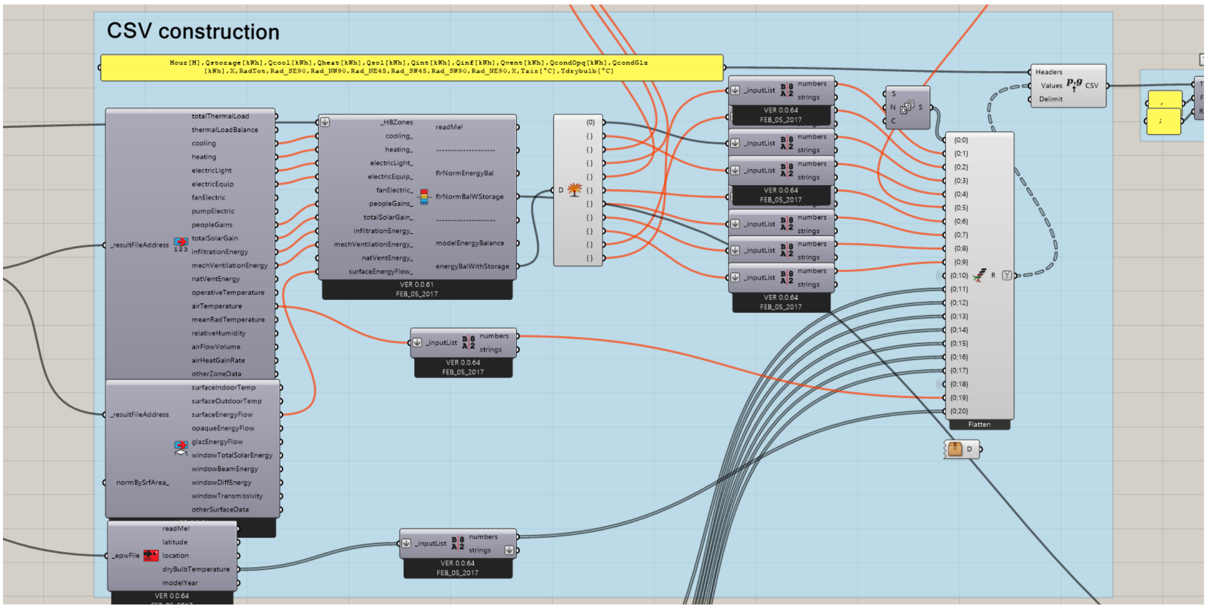
PV system

Honeybee also grants components to set-up the properties of a PV and solar collecting system. In the same line as the HVAC component, the goal in the initial simulation is to derive the solar potential (energy supply) rather than the final energy supply, including PV-system efficiencies. Therefore, the potential is simulated using just the incident solar power on each surface. When the results are analysed and solutions are to be found, the efficiencies of PV-systems and solar collecting units will be considered.

12.1.9 Output processing

Translating the EnergyPlus simulation result to a -.csv

From the 'EnergyPlus simulation module'', as described in *12.1.6 EnergyPlus simulation module*, a result-file is created. This result file can be processed directly by Grasshopper for preliminar result studies, but cannot be used for analysis in other software. Using the set-up as shown in Figure 126, a -.csv is created. This -.csv containts the 19 headers as described in the previous section and links the corresponding values to them. Moreover, it merges the energy-balance values that focus on the demand side, with the solar radiation potential values that focus on the supply side. The resulting -.csv contains all values for all categories for all hours of the year. While for most analyses not all these values will be used, documenting the result sets with all values allows for future changes in method and research.



CSV construction

```
Hour[H],Qstorage[kWh],Qcool[kWh],Qheat[kWh],Qsol[kWh],Qint[kWh],Qinf[kWh],Qvent[kWh],QcondOpq[kWh],QcondGls
[kWh],X,RadTot,Rad_SE90,Rad_NW90,Rad_NE45,Rad_SW45,Rad_SW90,Rad_NE90,X,Tair[°C],Tdrybulb[°C]
```

Figure 126: translating the EnergyPlus simulation output to a processable -.csv

Importing the -.csv into excel and creating graphs and data summaries

The data is loaded into an excel file. The excel file has three main functions; it calculates the values for the key-performance indicators, it summarizes hourly values into hourly, daily and monthly values, and it plots graphs from this data. The excel file takes a dynamic data source, meaning that every -.csv file with the same formatting can be linked to it and can be used to process. This way, time to process is reduced and the chances of mistakes in the processing are limited.

All the summaries and key-performance indicators are always linked directly to the data-source, also to limit chances of mistakes. When aggregated data is shown in graphs for a certain time frame, it always represents the sum of hourly values within that timeframe. For example, if a graph shows that the 21st of February has a heating load of 20 kWh, it means that the sum of the 1224th hour till the 1248th hour is 20 kWh. The analysis of the key-performance indicators works similarly. The value for a key-performance indicator is first calculated per hour, and then these hourly KPI values are combined to define the yearly KPI.

12.1.10 Explanation of outputs

The simulation generates hourly results for 19 different categories. One category is the hours of the year to order all other values, ten categories describe the energy balance (i.e. demand), seven categories describe the supply results and the two remaining categories describe the indoor temperature and the outdoor temperature for every timestep. The simulation is done for a time interval of a full year with a timestep of one hour, resulting in a total of 8760 timesteps per simulation. The -.csv that is created thus results in 19 columns, with 8760 values resulting in 166.440 values plus 19 headers.

The categories are shortly described below:

Header	Unit	Description
Hour	H	The hour of the year, counting from 1 to 8760. The first hour is 00:00-01:00, January 1st. February counts 28 days or 672 hours (i.e. not an intercalary year)
Qstorage	kWh	The energy stored in thermal mass of the building. This value is not used in the analysis, because it also teks into account air as thermal mass.
Qcool	kWh	The energy needed for cooling to keep the indoor temperature on or below the cooling setpoint
Qheat	kWh	The energy needed for heating to keep the indoor temperature on or above the heating setpoint.
Qsol	kWh	The energy gained by solar radiation through glazed surfaces
Qint	kWh	The energy gained by internal heat gains, like people, appliances, and light
Qinf	kWh	The heat loss (negative) or gain (positive) resulting from infiltration
Qvent	kWh	The heat loss (negative) or gain (positive) resulting from the outdoor air that enters the building by ventilation
QcondOpq	kWh	The heat loss (negative) or gain (positive) through all opague surfaces, i.e. all surfaces that are not glazed surfaces
QcondGlz	kWh	The heat loss (negative) or gain (positive) through all glazed surfaces, except the solar radiation gain

RadTot	kWh	The sum of the total incident radiation of each surface
Rad_SE90	kWh	The total incident solar radiation on the south-east facade
Rad_NW90	kWh	The total incident solar radiation on the north-west facade
Rad_NE45	kWh	The total incident solar radiation on the north-east facade
Rad_SW45	kWh	The total incident solar radiation on the south-west roof surface
Rad_SW90	kWh	The total incident solar radiation on the south-west facade
Rad_NE90	kWh	The total incident solar radiation on the north-east facade
Tair	°C	The indoor air temperature in the corresponding hour
Tdrybulb	°C	The outdoor dry bulb temperature in the corresponding hour

The names of the headers are used in all graphs and visuals to refer to the corresponding flows.

12.2 Appendix 2: Internal heat gain calculation according to GIW/ISSO 2008

	Uur van de dag	6	8	10	12	14	16	18	20	22	24	2	4
Woonkamer	Apparatuur (W.)	90	125	100	150	100	150	100	150	105	0	0	0
	Verlichting (%)	50	15	0	0	0	0	35	100	50	0	0	0
	Personen (%)	15	30	30	30	30	30	30	30	30	15	0	0
	Rekentijd	x	x	x	x	x	x	x	x	x	x		
Slaapkamer	Apparatuur (W.)	125	25	25	25	25	25	125	25	25	25	25	25
	Verlichting (%)	25	10	0	0	0	0	25	0	0	12,5	0	0
	Personen (%)	50	50	50	50	25	0	35	0	25	50	50	50
		x	x	x	x	x					x	x	x
Badkamer	Apparatuur (W.)	87,5	55	25	55	25	25	150	25	40	25	25	25
	Verlichting (%)	40	50	0	50	0	0	80	0	25	0	0	0
	Personen (%)	27,5	40	0	40	0	0	55	0	20	0	0	0
		x	x	x	x	x	x	x	x	x			
Werkkamer	Apparatuur (W.)	57,5	90	90	90	90	90	90	90	57,5	25	25	25
	Verlichting (%)	25	50	50	25	50	25	50	50	25	0	0	0
	Personen (%)	17,5	35	35	35	35	35	35	35	17,5	0	0	0
		x	x	x	x	x	x	x	x	x			
SUBTOTAAL	Apparatuur (W)	360	295	240	320	240	265	340	265	202,5	25	25	25
	Verlichting (%)	35,0	31,3	12,5	18,8	12,5	6,3	41,3	37,5	25,0	3,1	0,0	0,0
	Personen (%)	27,5	38,8	28,8	38,8	22,5	16,3	30,0	16,3	16,9	16,3	12,5	12,5
Gebouw-gegevens	Verlichting	12	W/m^2		vermenigvuldigd met bovenstaand totaal percentage								
	Personen	10,2	W/m^2		vermenigvuldigd met bovenstaand totaal percentage								
	Ag	181	m^2		totale gebruiksoppervlakte								
TOTAAL	Apparatuur (W)	360	295	240	320	240	265	340	265	202,5	25	25	25
	Verlichting (W)	760	679	272	407	272	136	896	815	543	68	0	0
	Personen (W)	508	715	531	715	415	300	554	300	312	300	231	231
	TOTAAL (W/m^2)	**9,0**	**9,3**	**5,8**	**8,0**	**5,1**	**3,9**	**9,9**	**7,6**	**5,8**	**2,2**	**1,4**	**1,4**

12.3 APPENDIX 3: PROPERTIES CONSTRUCTION ELEMENTS OF THE REFERENCE DESIGN

Construction	**VH_BENG_WALLRC7**		
		INSIDE	
Layer 1	*Name*	VH_MAT_WALL_concrBlock0,1	
	Description	Inner leaf, structural concrete	
	Thickness	0,1	m
	Conductivity	0,7	W/mK
	Density	2400	kg/m^3
	Specific Heat	880	J/kgK
Layer 2	*Name*	VH_MAT_insulXPS	
	Description	Insulation layer	
	Thickness	0,206	m
	Conductivity	0,03	W/mK
	Density	45	kg/m^3
	Specific Heat	1300	J/kgK
		OUTSIDE	

Construction	**VH_BENG_WINDU9**		
	[constructed with Honeybee Glass module]		
	Name	VH_MAT_Glass_ref	
	Description	Double glazing	
	U-value	1,3	W/m^{2}K
	SolarHeatGainCoeff	0,6	
	VisualTransm.	0,6	

Construction	**VH_BENG_ROOFRC9**		
	INSIDE		
Layer 1	*Name*	VH_MAT_ROOF_concr0,15	
	Description	Roof construction	
	Thickness	0,15	m
	Conductivity	0,7	W/mK
	Density	2400	kg/m³
	Specific Heat	880	J/kgK
Layer 2	*Name*	VH_MAT_ROOF_insulXPS	
	Description	Insulation layer	
	Thickness	0,2637	m
	Conductivity	0,03	W/mK
	Density	45	kg/m³
	Specific Heat	1300	J/kgK
	OUTSIDE		

Construction	**VH_BENG_FLOORC9**		
	INSIDE		
Layer 1	*Name*	VH_MAT_FLOOR_concr0,2	
	Description	Roof construction	
	Thickness	0,15	m
	Conductivity	0,7	W/mK
	Density	2400	kg/m³
	Specific Heat	880	J/kgK
Layer 2	*Name*	VH_MAT_ROOF_insulXPS	
	Description	Insulation layer	
	Thickness	0,1738	m
	Conductivity	0,03	W/mK
	Density	45	kg/m³
	Specific Heat	1300	J/kgK
	OUTSIDE		

12.4 APPENDIX 4: INPUT & OUTPUT OVERVIEW OF THE PARAMETER STUDY

			Image	**REF05d**	GeoSrf_A	GeoSrf_C	GeoSrf_D	GeoSrf_E	SrfIns_A	SrfIns_B	SrfIns_D	SrfIns_E
Demand	**Geomet**	**Floor Area**	**m2**	176	176	176	176	176	176	176	176	176
		Volume	**m3**	674,1	512,6	831,6	771,7	1146,6	674,1	674,1	674,1	674,1
		Facade surface area	**m2**	367,9	306,6	441,5	529,8	652,7	367,9	367,9	367,9	367,9
	Surface	**Insulation (windows)**	**m2K/W**	0,77	0,77	0,77	0,77	0,77	0,31	0,54	1,00	1,23
		Insulation (walls)	**m2K/W**	7,00	7,00	7,00	7,00	7,00	2,80	4,90	9,10	11,20
		Insulation (roof)	**m2K/W**	9,00	9,00	9,00	9,00	9,00	3,60	6,30	11,70	14,40
		Average U-value	**W/m2K**	0,15	0,15	0,15	0,15	0,15	0,06	0,10	0,19	0,23
		Thermal mass constr	**J/K**	1,1E+08	9,4E+06	1,2E+08	1,3E+07	1,6E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08
	Comfor	**Ventilation**	**m3/h**	150	150	150	150	150	150	150	150	150
		Air tightness (infilration)	**dm3/sm2**									
		Temperature range	**°C - °C**	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25
	Orientation depended	**NE - share of window surface**	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		SE - share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		SW - share of window surface	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		NW -share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		NE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		NW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		Rotation from North	**°**	45,00	45,00	45,00	45,00	45,00	0,00	0,00	0,00	0,00
Supply		**NE / N**	**m2**	68,20	51,04	96,32	44,41	129,07	68,20	68,20	68,20	68,20
		SE / E	**m2**	61,30	58,25	69,93	184,17	156,35	61,30	61,30	61,30	61,30
		SW / S	**m2**	68,20	51,04	96,32	44,41	129,07	68,20	68,20	68,20	68,20
		NW / W	**m2**	61,30	58,25	69,93	184,17	156,35	61,30	61,30	61,30	61,30
		Roof SW	**m2**	54,50	44,00	54,48	36,31	40,91	54,50	54,50	54,50	54,50
		Roof NE	**m2**	54,50	44,00	54,48	36,31	40,91	54,50	54,50	54,50	54,50
KPI - absolute performance		**Absolute loads**	**Heat**	3732,5	3400,5	4178,2	4713,0	5572,0	9864,9	5549,3	2765,2	2171,6
			Cool	3675,1	3827,0	3491,1	3326,0	2928,0	1625,7	2755,3	4380,9	4901,3
			Supply	7793,6	6827,0	9044,1	9980,5	12076,9	7793,6	7793,6	7793,6	7793,6
		KPI 1 - total mismatch	**Heat**	-3223,6	-2975,9	-3559,2	-3967,2	-4612,4	-8601,9	-4795,4	-2396,8	-1886,6
			Cool	-1292,8	-1422,1	-1168,2	-1095,2	-906,4	-503,5	-923,9	-1580,8	-1800,9
			Supply	4902,3	3997,5	6102,1	7003,8	9095,6	5408,3	5208,2	4625,0	4408,3
		KPI 2 - maximum peak	**Heat**	-3,3	-3,1	-3,5	-3,7	-4,1	-5,5	-4,0	-2,9	-2,6
			Cool	-4,6	-4,7	-4,6	-4,7	-4,7	-4,7	-4,6	-4,6	-4,6
			Supply	5,0	4,5	5,7	6,5	7,2	5,0	5,0	4,9	4,9
		KPI 3 - max. cumulative mism.	**CumMis**	2766,3	1849,9	3950,6	4754,8	6755,2	3911,8	3232,0	2285,8	1941,9
KPI - performance relative to reference design		**Absolute loads**	**Heat**	0%	-9%	12%	26%	49%	164%	49%	-26%	-42%
			Cool	0%	4%	-5%	-10%	-20%	-56%	-25%	19%	33%
			Supply	0%	-12%	16%	28%	55%	0%	0%	0%	0%
		KPI 1 - total mismatch	**Heat**	0%	-8%	10%	23%	43%	167%	49%	-26%	-41%
			Cool	0%	10%	-10%	-15%	-30%	-61%	-29%	22%	39%
			Supply	0%	-18%	24%	43%	86%	10%	6%	-6%	-10%
		KPI 2 - maximum peak	**Heat**	0%	-5%	6%	14%	24%	69%	21%	-12%	-20%
			Cool	0%	2%	0%	3%	3%	2%	0%	0%	0%
			Supply	0%	-9%	14%	31%	45%	0%	0%	0%	-2%
		KPI 3 - max. cumulative mism.	**CumMis**	0%	-33%	43%	72%	144%	41%	17%	-17%	-30%

			Image	REF05d	SrfThm_A	SrfThm_B	SrfThm_D	SrfThm_E	CmfVen_A	CmfVen_B	CmfVen_D	CmfVen_E
Demand	Geomet	**Floor Area**	**m2**	176	176	176	176	176	176	176	176	176
		Volume	**m3**	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1
		Facade surface area	**m2**	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9
	Surface	**Insulation (windows)**	**m2K/W**	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77
		Insulation (walls)	**m2K/W**	7,00	6,90	6,95	7,07	7,12	7,00	7,00	7,00	7,00
		Insulation (roof)	**m2K/W**	9,00	8,83	8,92	9,09	9,18	9,00	9,00	9,00	9,00
		Average U-value	**W/m2K**	0,15					0,15	0,15	0,15	0,15
		Thermal mass constr	**J/K**	1,1E+08	2,1E+07	6,4E+07	1,5E+08	1,9E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08
	Comfor	**Ventilation**	**m3/h**	150	150	150	150	150	37,5	75	300	600
		Air tightness (infilration)	**dm3/sm2**									
		Temperature range	**°C - °C**	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25
	Orientation depended	**NE - share of window surface**	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		SE - share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		SW - share of window surface	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		NW -share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		NE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		NW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
Supply		**Rotation from North**	**°**	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00
		NE / N	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		SE / E	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		SW / S	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		NW / W	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		Roof SW	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
		Roof NE	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
KPI - absolute performance		**Absolute loads**	**Heat**	3732,5	3964,3	3778,6	3696,6	3659,5	1874,0	2457,9	6632,5	13238,7
			Cool	3675,1	4042,2	3718,4	3662,5	3649,0	5118,3	4577,1	2455,6	1121,3
			Supply	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6
		KPI 1 - total mismatch	**Heat**	-3223,6	-3442,3	-3249,8	-3200,7	-3169,5	-1635,5	-2135,6	-5741,2	-11625,2
			Cool	-1292,8	-1681,1	-1419,7	-1230,5	-1200,5	-1953,0	-1693,0	-805,8	-354,7
			Supply	4902,3	4910,5	4966,0	4865,7	4855,1	4389,8	4587,2	5252,4	5413,5
		KPI 2 - maximum peak	**Heat**	-3,3	-3,6	-3,3	-3,2	-3,2	-2,5	-2,7	-4,4	-6,9
			Cool	-4,6	-6,1	-5,0	-4,4	-4,2	-4,2	-4,3	-5,1	-5,9
			Supply	5,0	5,0	5,0	5,0	5,0	4,8	4,9	5,0	5,0
		KPI 3 - max. cumulative mism.	**CumMis**	2766,3	2239,0	2698,9	2791,5	2814,9	1825,5	2173,2	3396,4	6562,1
KPI - performance relative to reference design		**Absolute loads**	**Heat**	0%	6%	1%	-1%	-2%	-50%	-34%	78%	255%
			Cool	0%	10%	1%	0%	-1%	39%	25%	-33%	-69%
			Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
		KPI 1 - total mismatch	**Heat**	0%	7%	1%	-1%	-2%	-49%	-34%	78%	261%
			Cool	0%	30%	10%	-5%	-7%	51%	31%	-38%	-73%
			Supply	0%	0%	1%	-1%	-1%	-10%	-6%	7%	10%
		KPI 2 - maximum peak	**Heat**	0%	11%	2%	-2%	-2%	-24%	-16%	34%	110%
			Cool	0%	33%	10%	-5%	-7%	-8%	-6%	11%	28%
			Supply	0%	0%	0%	0%	0%	-4%	-2%	0%	0%
		KPI 3 - max. cumulative mism.	**CumMis**	0%	-19%	-2%	1%	2%	-34%	-21%	23%	137%

			Image	REF05d	CmfTmp_A	CmfTmp_B	CmfTmp_D	CmfTmp_E	ShrNE01	ShrNE90	ShrSE01	ShrSE90
Demand	Geomet	**Floor Area**	**m2**	176	176	176	176	176	176	176	176	176
		Volume	**m3**	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1
		Facade surface area	**m2**	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9
	Surface	**Insulation (windows)**	**m2K/W**	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77
		Insulation (walls)	**m2K/W**	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00
		Insulation (roof)	**m2K/W**	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00
		Average U-value	**W/m2K**	0,15	0,15	0,15	0,15	0,15	0,14	0,17	0,14	0,17
		Thermal mass constr	**J/K**	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	9,7E+07	1,1E+08	9,8E+07
	Comfor	**Ventilation**	**m3/h**	150	150	150	150	150	150	150	150	150
		Air tightness (infilration)	**dm3/sm2**									
		Temperature range	**°C - °C**	19-25	17-27	18-26	20-24	21-23	19-25	19-25	19-25	19-25
	Orientation depended	**NE - share of window surface**	**m2**	13,64	13,64	13,64	13,64	13,64	0,68	61,38	13,64	13,64
		SE - share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	0,61	55,15
		SW - share of window surface	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		NW -share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		NE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		NW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
Supply		**Rotation from North**	**°**	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00
		NE / N	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		SE / E	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		SW / S	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		NW / W	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		Roof SW	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
		Roof NE	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
KPI - absolute performance		**Absolute loads**	**Heat**	3732,5	2394,1	3034,2	4494,7	5344,0	3302,6	5320,3	3955,4	3245,7
			Cool	3675,1	2401,9	2998,8	4423,1	5249,9	3003,0	5894,7	2713,2	9134,3
			Supply	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6
		KPI 1 - total mismatch	**Heat**	-3223,6	-2089,3	-2632,6	-3872,0	-4599,7	-2837,7	-4675,7	-3337,6	-2960,8
			Cool	-1292,8	-747,4	-993,2	-1640,1	-2047,1	-1040,2	-2334,0	-934,3	-4301,1
			Supply	4902,3	5834,2	5386,5	4387,9	3846,5	5365,8	3588,4	5396,8	2675,6
		KPI 2 - maximum peak	**Heat**	-3,3	-2,9	-3,1	-3,5	-3,7	-3,0	-4,2	-3,2	-3,8
			Cool	-4,6	-4,1	-4,4	-4,8	-5,0	-4,1	-6,2	-4,0	-7,2
			Supply	5,0	5,0	5,0	4,9	4,8	5,0	4,9	5,0	4,6
		KPI 3 - max. cumulative mism.	**CumMis**	2766,3	4376,2	3619,6	1784,8	2797,8	3491,9	3418,6	3565,3	4690,0
KPI - performance relative to reference design		**Absolute loads**	**Heat**	0%	-36%	-19%	20%	43%	-12%	43%	6%	-13%
			Cool	0%	-35%	-18%	20%	43%	-18%	60%	-26%	149%
			Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
		KPI 1 - total mismatch	**Heat**	0%	-35%	-18%	20%	43%	-12%	45%	4%	-8%
			Cool	0%	-42%	-23%	27%	58%	-20%	81%	-28%	233%
			Supply	0%	19%	10%	-10%	-22%	9%	-27%	10%	-45%
		KPI 2 - maximum peak	**Heat**	0%	-12%	-6%	6%	12%	-7%	28%	-3%	18%
			Cool	0%	-10%	-5%	5%	9%	-11%	36%	-12%	58%
			Supply	0%	0%	0%	0%	-4%	0%	-2%	0%	-8%
		KPI 3 - max. cumulative mism.	**CumMis**	0%	58%	31%	-35%	1%	26%	24%	29%	70%

			Image	REF05d	ShrSW01	ShrSW90	ShrNW01	ShrNW90	GvlNE05	GvlNE95	GvlSE05	GvlSE95
Demand	Geomet	**Floor Area**	**m2**	176	176	176	176	176	176	176	176	176
		Volume	**m3**	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1
		Facade surface area	**m2**	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9
	Surface	**Insulation (windows)**	**m2K/W**	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77
		Insulation (walls)	**m2K/W**	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00
		Insulation (roof)	**m2K/W**	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00
		Average U-value	**W/m2K**	0,15	0,14	0,17	0,14	0,17	0,15	0,15	0,15	0,15
		Thermal mass constr	**J/K**	1,1E+08	1,1E+08	9,7E+07	1,1E+08	9,8E+07	1,1E+08	1,1E+08	1,1E+08	1,1E+08
	Comfor	**Ventilation**	**m3/h**	150	150	150	150	150	150	150	150	150
		Air tightness (infilration)	**dm3/sm2**									
		Temperature range	**°C - °C**	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25
	Orientation depended	**NE - share of window surface**	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		SE - share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		SW - share of window surface	**m2**	13,64	0,68	61,38	13,64	13,64	13,64	13,64	13,64	13,64
		NW -share of window surface	**m2**	9,20	9,20	9,20	0,61	55,15	9,20	9,20	9,20	9,20
		NE - g-value		0,60	0,60	0,60	0,60	0,60	0,05	0,95	0,60	0,60
		SE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,05	0,95
		SW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		NW - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
Supply		**Rotation from North**	**°**	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00
		NE / N	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		SE / E	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		SW / S	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		NW / W	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		Roof SW	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
		Roof NE	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
KPI - absolute performance		**Absolute loads**	**Heat**	3732,5	4121,9	3267,3	3455,5	5205,9	4008,0	3512,9	4443,6	3242,2
			Cool	3675,1	2104,5	9978,0	3204,3	5992,6	2547,7	4815,2	2414,0	4936,2
			Supply	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6	7793,6
		KPI 1 - total mismatch	**Heat**	-3223,6	-3460,3	-2937,9	-2974,3	-4570,2	-3440,4	-3055,9	-3759,3	-2842,9
			Cool	-1292,8	-658,4	-5304,3	-1082,6	-2568,6	-842,1	-1777,9	-802,2	-1812,7
			Supply	4902,3	5685,8	2790,5	5190,7	3733,8	5520,3	4299,3	5497,5	4270,8
		KPI 2 - maximum peak	**Heat**	-3,3	-3,2	-3,9	-3,1	-4,1	-3,3	-3,2	-3,4	-3,2
			Cool	-4,6	-3,6	-8,1	-4,2	-6,9	-4,0	-5,1	-3,9	-5,1
			Supply	5,0	5,0	4,7	5,0	4,9	5,0	4,9	5,0	4,9
		KPI 3 - max. cumulative mism.	**CumMis**	2766,3	4019,3	5449,2	3268,8	3402,2	3743,9	1731,1	3708,4	1694,2
KPI - performance relative to reference design		**Absolute loads**	**Heat**	0%	10%	-12%	-7%	39%	7%	-6%	19%	-13%
			Cool	0%	-43%	172%	-13%	63%	-31%	31%	-34%	34%
			Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
		KPI 1 - total mismatch	**Heat**	0%	7%	-9%	-8%	42%	7%	-5%	17%	-12%
			Cool	0%	-49%	310%	-16%	99%	-35%	38%	-38%	40%
			Supply	0%	16%	-43%	6%	-24%	13%	-12%	12%	-13%
		KPI 2 - maximum peak	**Heat**	0%	-3%	19%	-5%	26%	1%	-1%	3%	-2%
			Cool	0%	-22%	77%	-9%	51%	-13%	11%	-14%	12%
			Supply	0%	0%	-6%	0%	-1%	0%	0%	0%	-2%
		KPI 3 - max. cumulative mism.	**CumMis**	0%	45%	97%	18%	23%	35%	-37%	34%	-39%

			Image	REF05d	GvlSW05	GvlSW95	GvlNW05	GvlNW95	ChNrth90	ChNrth135	ChNrth180	SupNE90
Demand	Geomet	**Floor Area**	**m2**	176	176	176	176	176	176	176	176	176
		Volume	**m3**	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1	674,1
		Facade surface area	**m2**	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9	367,9
	Surface	**Insulation (windows)**	**m2K/W**	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77
		Insulation (walls)	**m2K/W**	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00	7,00
		Insulation (roof)	**m2K/W**	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00	9,00
		Average U-value	**W/m2K**	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
		Thermal mass constr	**J/K**	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08
	Comfor	**Ventilation**	**m3/h**	150	150	150	150	150	150	150	150	150
		Air tightness (infilration)	**dm3/sm2**									
		Temperature range	**°C - °C**	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25	19-25
	Orientation depended	**NE - share of window surface**	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		SE - share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		SW - share of window surface	**m2**	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64	13,64
		NW -share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20	9,20
		NE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SE - g-value		0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60
		SW - g-value		0,60	0,05	0,95	0,60	0,60	0,60	0,60	0,60	0,60
		NW - g-value		0,60	0,60	0,60	0,05	0,95	0,60	0,60	0,60	0,60
		Rotation from North	**°**	45,00	45,00	45,00	45,00	45,00	90,00	135,00	180,00	45,00
Supply		**NE / N**	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		SE / E	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		SW / S	**m2**	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20	68,20
		NW / W	**m2**	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30	61,30
		Roof SW	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
		Roof NE	**m2**	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50	54,50
KPI - absolute performance		**Absolute loads**	**Heat**	3732,5	4861,8	3024,7	3924,2	3572,4	3819,1	3733,5	3598,2	3732,5
			Cool	3675,1	1750,2	5692,6	2874,3	4473,5	3676,1	3644,8	3446,4	3675,1
			Supply	7793,6	7793,6	7793,6	7793,6	7793,6	7792,0	7788,7	7791,0	13391,3
		KPI 1 - total mismatch	**Heat**	-3223,6	-4096,8	-2660,0	-3375,5	-3100,3	-3289,5	-3229,7	-3121,0	-3075,2
			Cool	-1292,8	-520,7	-2243,8	-938,9	-1654,1	-1292,7	-1266,3	-1194,0	-1021,7
			Supply	4902,3	5799,0	3980,0	5309,4	4502,1	4878,9	4906,5	5061,3	10080,7
		KPI 2 - maximum peak	**Heat**	-3,3	-3,5	-3,2	-3,3	-3,3	-3,3	-3,3	-3,3	-3,3
			Cool	-4,6	-3,5	-5,5	-4,1	-5,0	-4,5	-4,5	-4,3	-4,4
			Supply	5,0	5,0	4,8	5,0	4,9	4,8	5,0	4,9	9,4
		KPI 3 - max. cumulative mism.	**CumMis**	2766,3	4180,3	1684,3	3465,5	2046,3	2781,6	2780,7	3005,4	7873,7
KPI - performance relative to reference design		**Absolute loads**	**Heat**	0%	30%	-19%	5%	-4%	2,3%	0,0%	-3,6%	0%
			Cool	0%	-52%	55%	-22%	22%	0,0%	-0,8%	-6,2%	0%
			Supply	0%	0%	0%	0%	0%	0,0%	-0,1%	0,0%	72%
		KPI 1 - total mismatch	**Heat**	0%	27%	-17%	5%	-4%	2,0%	0,2%	-3,2%	-5%
			Cool	0%	-60%	74%	-27%	28%	0,0%	-2,0%	-7,6%	-21%
			Supply	0%	18%	-19%	8%	-8%	-0,5%	0,1%	3,2%	106%
		KPI 2 - maximum peak	**Heat**	0%	6%	-2%	1%	0%	0,6%	-0,1%	-0,3%	0%
			Cool	0%	-24%	21%	-11%	9%	-0,9%	-1,1%	-6,1%	-3%
			Supply	0%	0%	-4%	0%	0%	-3,4%	0,2%	-1,7%	89%
		KPI 3 - max. cumulative mism.	**CumMis**	0%	51%	-39%	25%	-26%	0,6%	0,5%	8,6%	185%

			Image	REF05d	SupSE90	SupSW90	SupNW90	SupSW45	SupNE45
Demand	Geomet	**Floor Area**	**m2**	176	176	176	176	176	176
		Volume	**m3**	674,1	674,1	674,1	674,1	674,1	674,1
		Facade surface area	**m2**	367,9	367,9	367,9	367,9	367,9	367,9
	Surface	**Insulation (windows)**	**m2K/W**	0,77	0,77	0,77	0,77	0,77	0,77
		Insulation (walls)	**m2K/W**	7,00	7,00	7,00	7,00	7,00	7,00
		Insulation (roof)	**m2K/W**	9,00	9,00	9,00	9,00	9,00	9,00
		Average U-value	**W/m2K**	0,15	0,15	0,15	0,15	0,15	0,15
		Thermal mass constr	**J/K**	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08	1,1E+08
	Comfor	**Ventilation**	**m3/h**	150	150	150	150	150	150
		Air tightness (infilration)	**dm3/sm2**						
		Temperature range	**°C - °C**	19-25	19-25	19-25	19-25	19-25	19-25
	Orientation depended	**NE - share of window surface**	**m2**	13,64	13,64	13,64	13,64	13,64	13,64
		SE - share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20
		SW - share of window surface	**m2**	13,64	13,64	13,64	13,64	13,64	13,64
		NW -share of window surface	**m2**	9,20	9,20	9,20	9,20	9,20	9,20
		NE - g-value		0,60	0,60	0,60	0,60	0,60	0,60
		SE - g-value		0,60	0,60	0,60	0,60	0,60	0,60
		SW - g-value		0,60	0,60	0,60	0,60	0,60	0,60
		NW - g-value		0,60	0,60	0,60	0,60	0,60	0,60
Supply		**Rotation from North**	**°**	45,00	45,00	45,00	45,00	45,00	45,00
		NE / N	**m2**	68,20	68,20	68,20	68,20	68,20	68,20
		SE / E	**m2**	61,30	61,30	61,30	61,30	61,30	61,30
		SW / S	**m2**	68,20	68,20	68,20	68,20	68,20	68,20
		NW / W	**m2**	61,30	61,30	61,30	61,30	61,30	61,30
		Roof SW	**m2**	54,50	54,50	54,50	54,50	54,50	54,50
		Roof NE	**m2**	54,50	54,50	54,50	54,50	54,50	54,50
KPI - absolute performance		**Absolute loads**	**Heat**	3732,5	3732,5	3732,5	3732,5	3732,5	3732,5
			Cool	3675,1	3675,1	3675,1	3675,1	3675,1	3675,1
			Supply	7793,6	17039,8	18482,4	12976,8	20052,0	15646,0
		KPI 1 - total mismatch	**Heat**	-3223,6	-3071,6	-3066,2	-3086,4	-3050,8	-3056,5
			Cool	-1292,8	-1038,6	-988,1	-985,5	-969,5	-997,7
			Supply	4902,3	13742,4	15129,1	9641,2	16664,7	12292,7
		KPI 2 - maximum peak	**Heat**	-3,3	-3,3	-3,3	-3,3	-3,3	-3,3
			Cool	-4,6	-4,4	-4,4	-4,4	-4,4	-4,4
			Supply	5,0	14,1	15,4	8,7	15,8	11,2
		KPI 3 - max. cumulative mism.	**CumMis**	2766,3	10903,2	12279,2	7500,8	13988,8	10075,6
KPI - performance relative to reference design		**Absolute loads**	**Heat**	0%	0%	0%	0%	0%	0%
			Cool	0%	0%	0%	0%	0%	0%
			Supply	0%	119%	137%	67%	157%	101%
		KPI 1 - total mismatch	**Heat**	0%	-5%	-5%	-4%	-5%	-5%
			Cool	0%	-20%	-24%	-24%	-25%	-23%
			Supply	0%	180%	209%	97%	240%	151%
		KPI 2 - maximum peak	**Heat**	0%	0%	0%	0%	0%	0%
			Cool	0%	-3%	-3%	-3%	-4%	-4%
			Supply	0%	184%	211%	75%	218%	126%
		KPI 3 - max. cumulative mism.	**CumMis**	0%	294%	344%	171%	406%	264%

12.5 APPENDIX 5: DESIGN 1A: DEMAND ADAPTED TO SUPPLY - OPTIMIZATION PROCESS

The content in this section describes the optimization iteration of the demand-oriented design. It substantiates the conclusions drawn in *7.1 Design 1A - Demand adapted to* supply. Per variant, the input and the results are described. All results are produced using the energy-flatness simulation tool as described in *4 Simulation of energy-flatness; the energy model*.

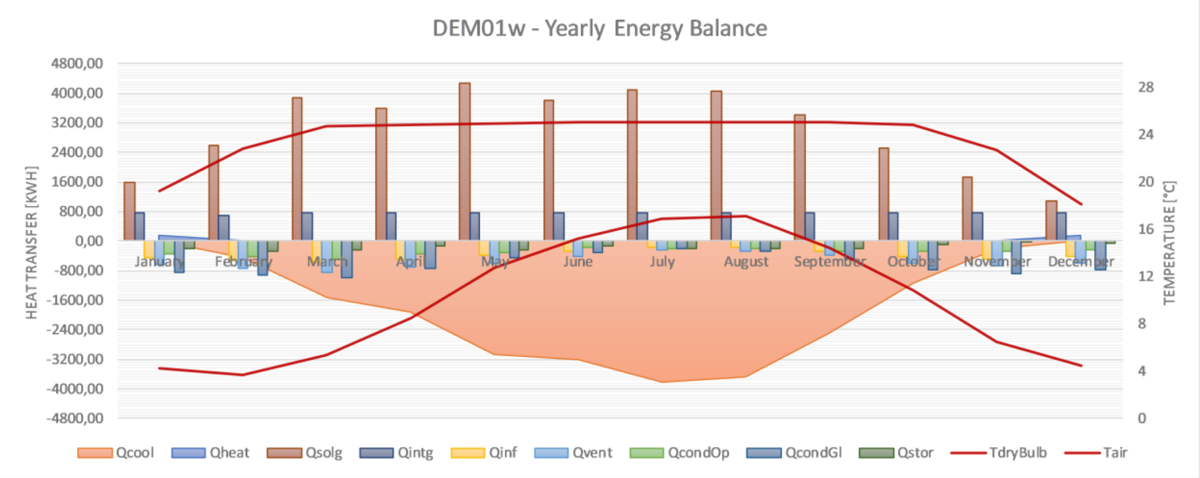
12.5.1 1A_DEM_v1

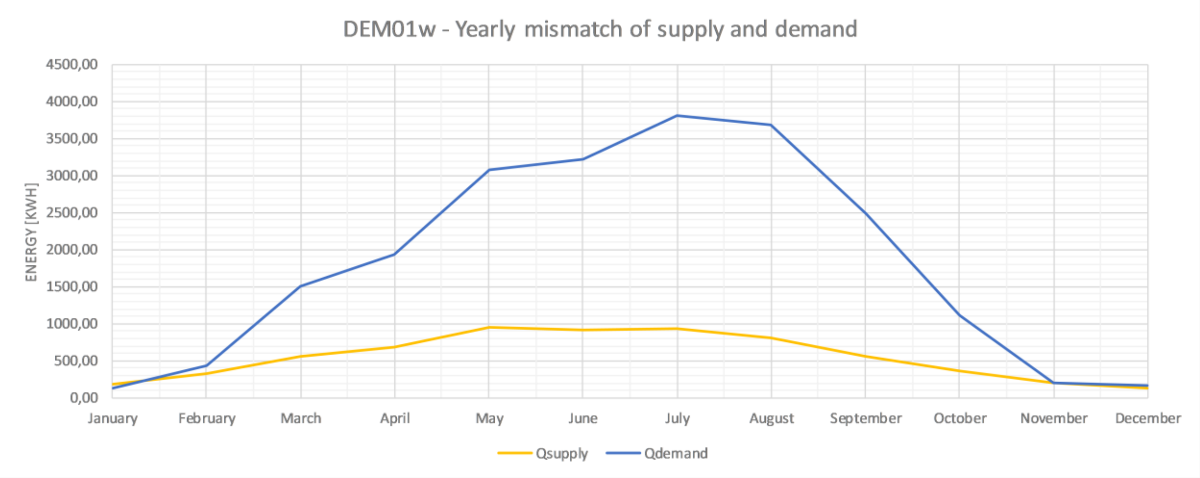
Input

	Input	**Remarks**
Geometry; energy losing surface	Conclusion of parameterstudy GeoSrf_A	Smallest surface
Surface; insulation	Conclusion of parameterstudy SrfIns_E	Highest insulation
Surface; thermal mass	Added superficial thermal mass; thermal mass amount of SrfThm_D, but now superficial	Surface area of 126 m^2 of a wall similar to the construction wall (dens = 2400 kg/m^3, 880 J/kgK, dikte = 0.15m). 1. 40.000.000 / (0.15*2400*880) = 126 m^2 2. this results in 40.000.000 J/K extra thermal mass, which is similar to variant D, but now all superficial. 3. Having a larger surface of indoor walls might not be realistic
Comfort; ventilation rate	Dynamic ventilation per season	i. September-February; minimize night (50-200) ii. March-May; 100 day, 200 night iii. Jun-Aug; 150 m^3/constant (original) iv. Model; set to CmfVen_D Summer; maximize when Tout < Tin
Comfort; temperature range	Heatinng setpoint is lowered CmfTmp_A = 17°C	Lowering cooling setpoint would be beneficial for energy-flatness, but would create strange temperatures
Windows; share per orientation	a. decrease north facades to 1% b. increase south facades to 90% c. keep East and West the same (15%)	In a first iteration, dynamic solutions for day/night are desired
Windows; g-value per orientation	Conclusion of parameterstudy Gval Maximize g-value	Winter; maximize g-value on solar oriented windows Summer; minimize g-value on solar oriented windows to prevent excessive cooling
Geometry; orientation	Orientation set to 0, straight north-south	That is equal to 180 (according to parameterstudy), but is easier modelling
Supply; share of energy surface	no changes	is changed in design variant 1B

Results

Below, the annual demand graph and the annual mismatch graph are shown.



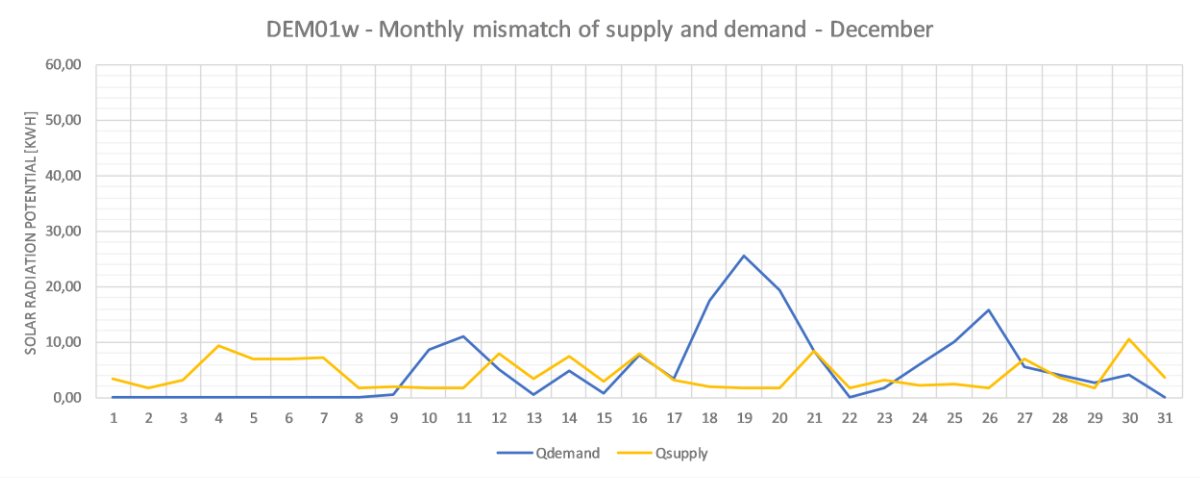


Analysis annual profiles

- this variant results in excessive cooling loads

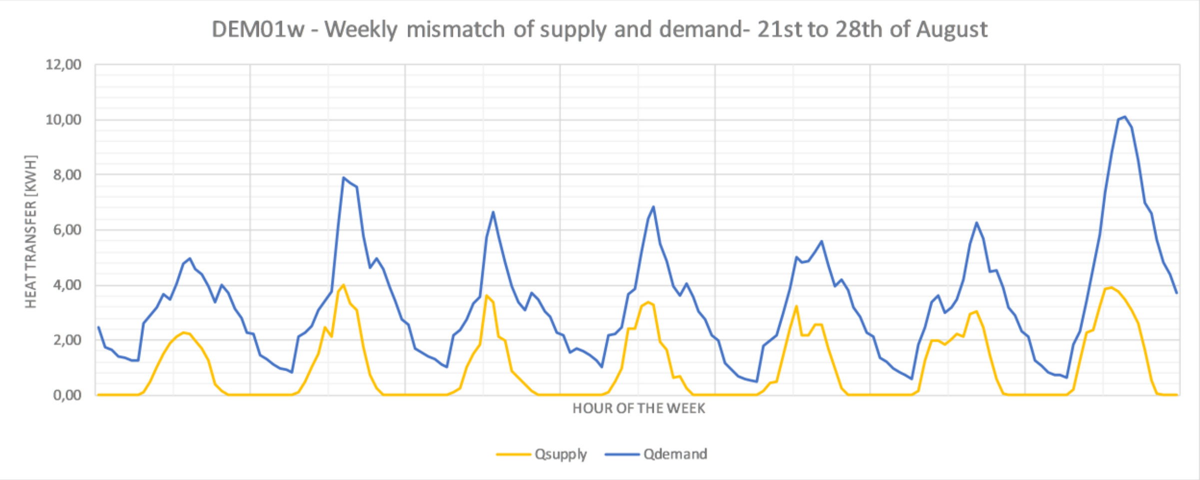
- Explanation
    - these loads are the logical result of two parameters that are combined; increasing the window surface on the south facade and increasing the g-value.
    - The parameter study already showed that increasing the g-value results in higher cooling loads.
    - Also increasing the window share on the south-facade increase the cooling loads.
    - Now that these two parameters are combined, the cooling loads become so high that the decreased heat demand in winter does not compensate for the increased cooling load
- Interesting conclusions
    - although this design results in excessive cooling loads, which are by far not energy-flat, it does provide some useful insights to be used in other studies.
    - This design is nearly energy-flat in the months of November, December and January. In the reference design, these are the months with a big shortage. This

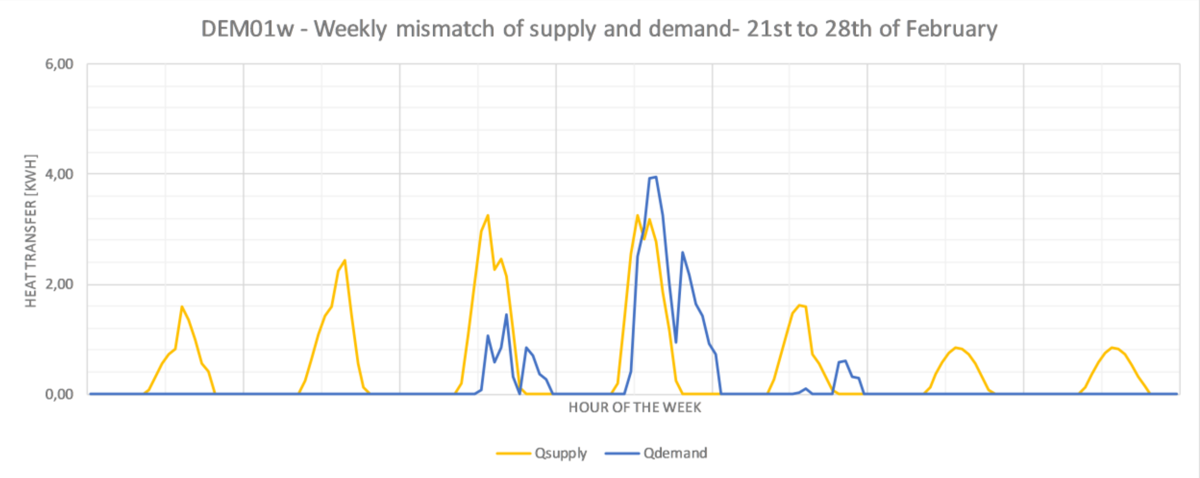
design proves that energy-flatness can be reached, also in winter months with high thermal demand.



- The monthly mismatch shows that for most days the demand is close to the supply. By exception, the demand is much higher than the supply, e.g. 19th of December.

Analysis weekly profiles





- The weekly graphs of supply and demand show that in winter, most demand is vanished. there is a high peak in demand just after sunset.

    - in summer, the profiles for supply and demand are more or less equal, but the demand is much higher.

- **Suggestions for next iteration**
    - Decrease the g-value of the southern window or decrease the window share from March till October.
        - the supply increases with the power of the sun, so solar power should be blocked accordingly.
    - Decrease the southern window share slightly, because the amount of heat is not needed and it saves the
    - Dynamic insulated blinds --> they are the solution for dynamic window size changing.

12.5.2 1A_DEM_v2

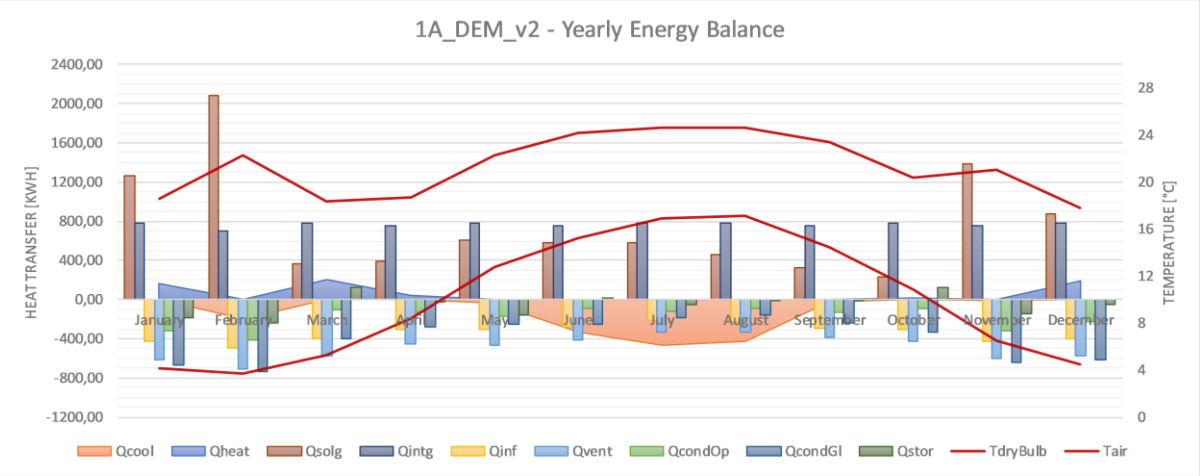
Input

Only the changes compared to the previous model are described.

- Window insulation set to U = 0.2 W/m^{2}K during winter nights (Nov-Feb, 18h-7h)
- Window share is set to 0.7 for the south facade
- G-value of all windows is set to 0.2 in summer days (Mar-Oct, 8-18h)

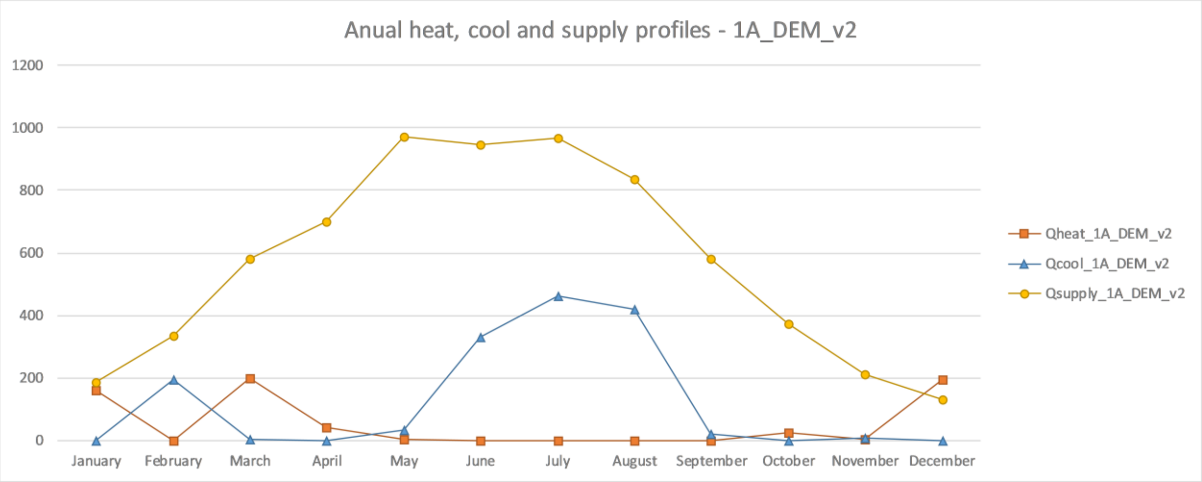
Results

Below, the graph of the annual demand is shown.



Analysis & explanation

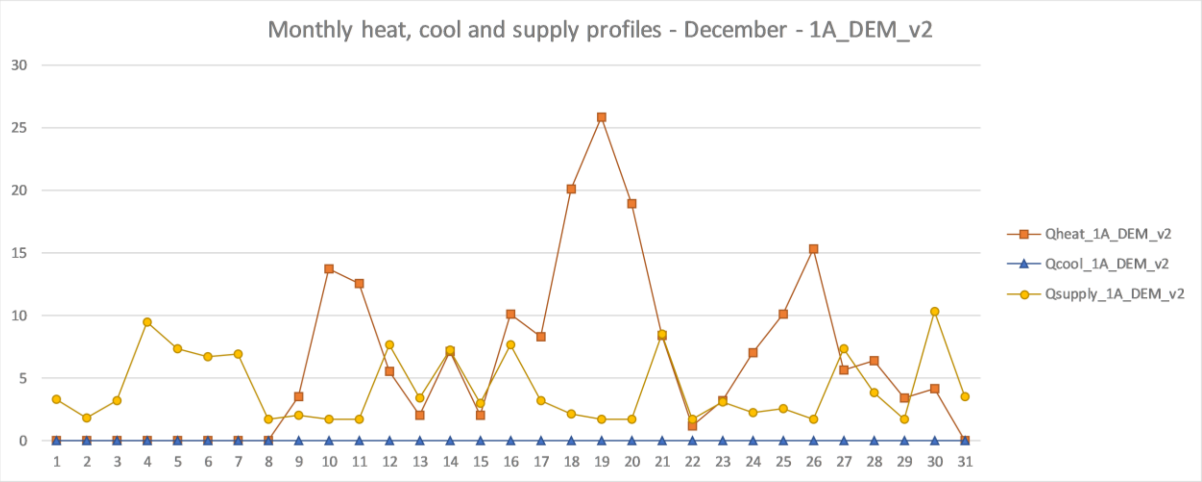
- the graph above shows how cooling demand and heating demand are highly diminished
- remarkable is the radiation gain in February
    - this is the result of the solar shading that are set on after February
    - <u>for next design: high solar radiation should be blocked in February as well</u>



- the graph above shows that both heating and cooling demand are almost always below the surplus. In this research by design, it is assumed that having an energy surplus is not something that should be solved;
  - first, because using more energy will never be the problem
  - second, because the way the supply is used to fulfill the demand is not perfectly clear yet.

Analysis of the winter situation

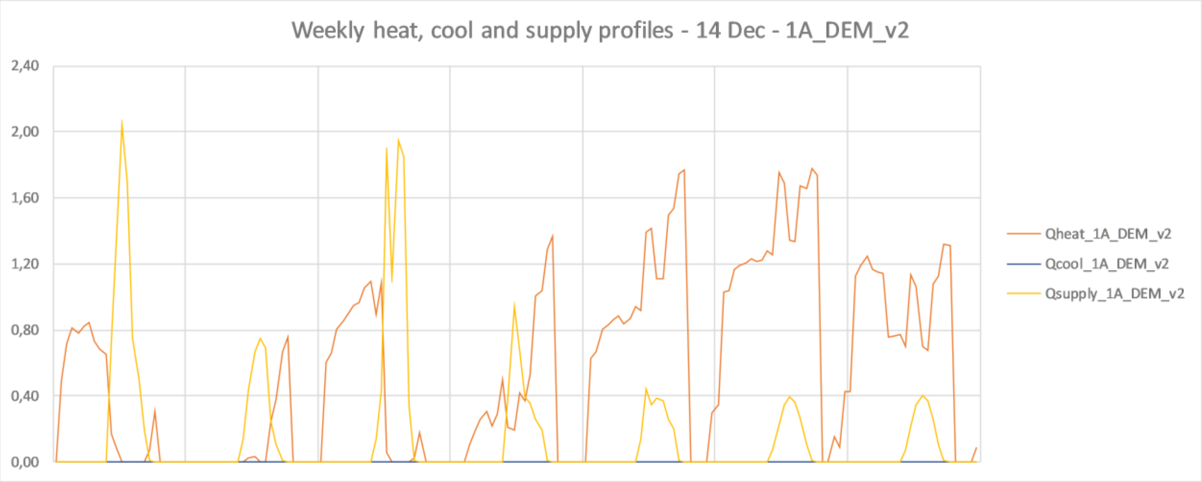
- the graph above shows the month of December, which from the annual overview resulted to be the month with a heating load slightly higher than supply.



- Supply and heating demand do not match in most cases. In some cases, the demand nicely follows supply (11-16 dec, 21-23 dec and 27-29 dec)
- In the week from 14 December till 20 December, both a matching and mismatching occur.

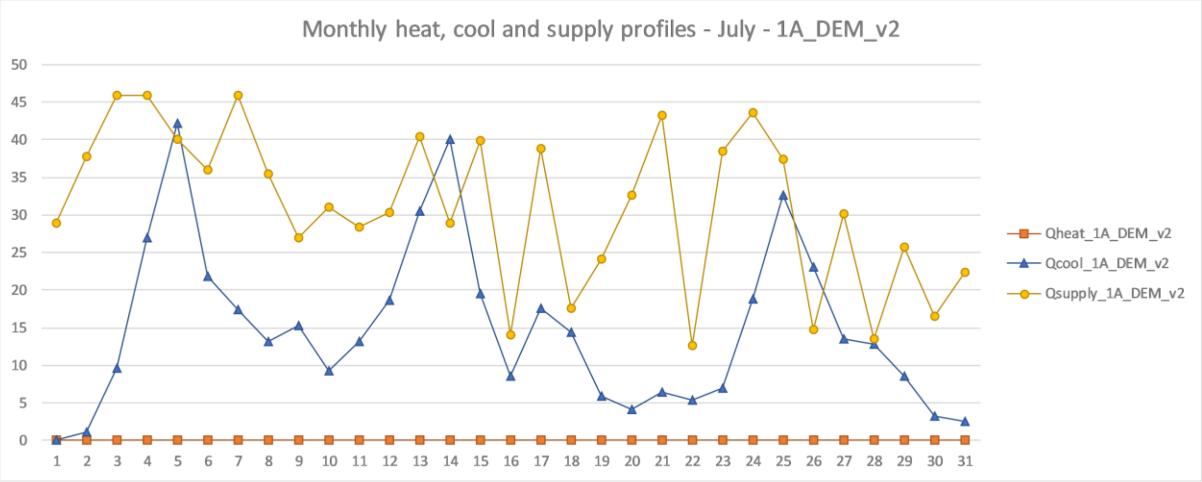
Analysis of a winter week situation

- The graph below shows that even during the ‘’matching’’ days, the heating peak is before the supply peak. Moreover, in some days, the heating load is much higher than supply.
- It is thus necessary to increase the supply, and it might be useful to shift some more heat peaks, by adding thermal mass.



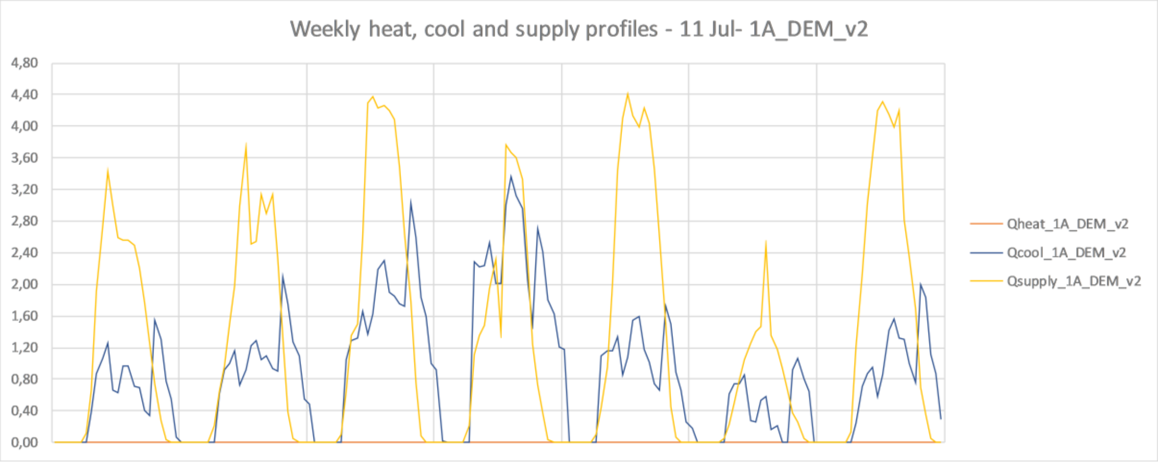
Analysis of the summer situation

- The month of July (below) has a few days in which the cooling demand exceeds the supply. Some other days, have excessive supply surplus.
    - <u>Loads may be increased in summer, if that is beneficial for other parameters.</u>



Analysis of a summer week

- the cooling loads match with the supply, although the supply is most often higher during the day.
- Moreover, the cooling load occurs somewhat longer than the supply, <u>which means that the shades should be closed a little longer.</u>



12.5.3 1A_DEM_v3 – adding thermal mass

Input

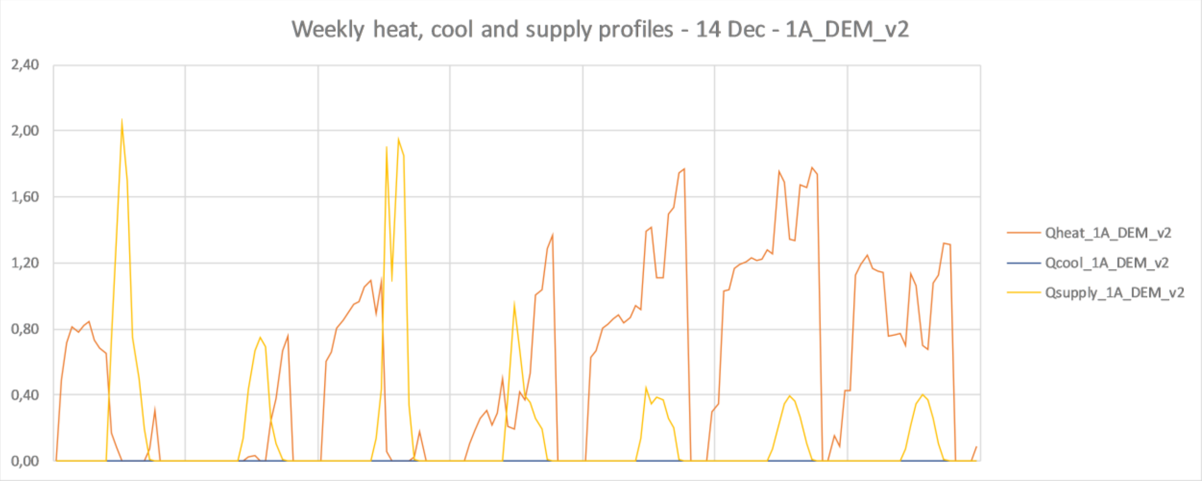
Only the changes compared to the previous model are described.

- The thermal mass of the construction elements is doubled in thickness; d = 0.3m
- The thermal mass is doubled in surface; A= 252m^2

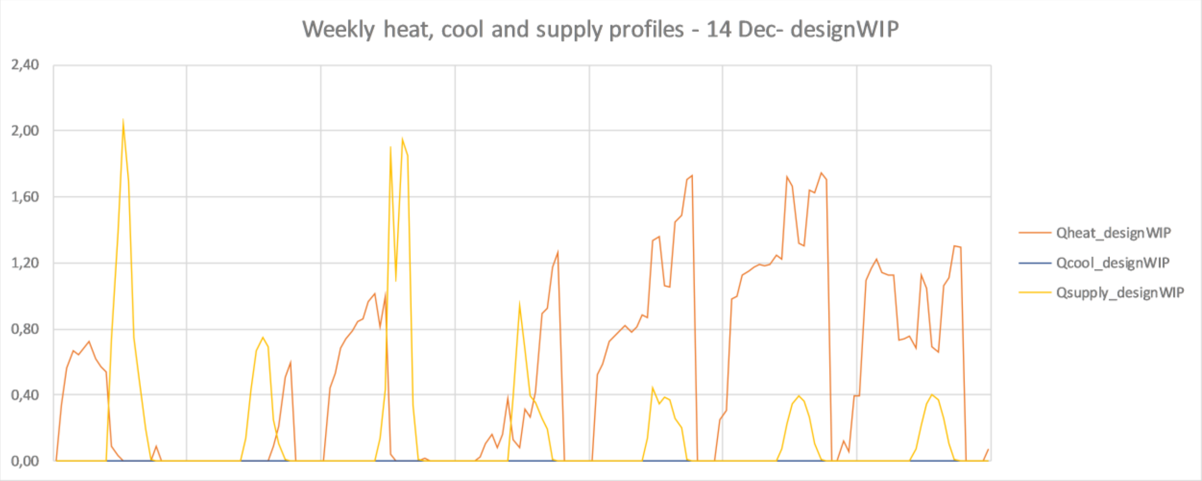
Results

Analysis of the weekly differences for three thermal mass situations

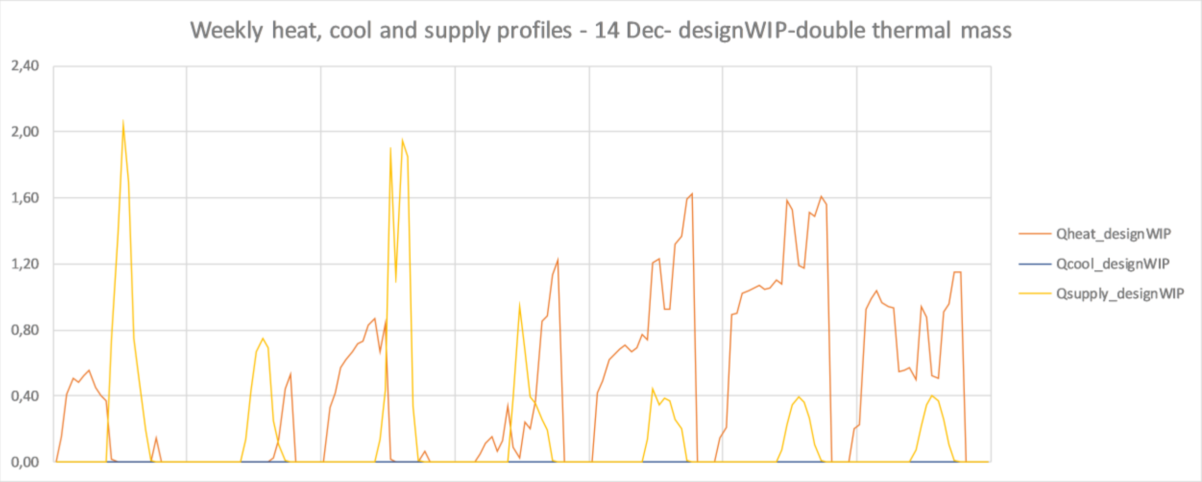
- The figures below show demand and supply profiles for a winter week.



- The graph above is the original situation (previous variant)



- The graph above is the situation with the thermal mass only doubled (to d=0.3m)
  - the effect on the demand profile is small
    - the effect is significant in days with high supply (day 1, day 3)
    - the effect is very small in days with low supply (day 5,6,7)



- The graph above shows the final situation for this variant; doubled thickness and doubled surface area for thermal mass.
    - The thick thermal mass is especially effective for bridging multiple days. The heating load is much lower on the days with low external supply.

12.5.4 1A_DEM_v4 – change g-value and adapt ventilation schedule

Input

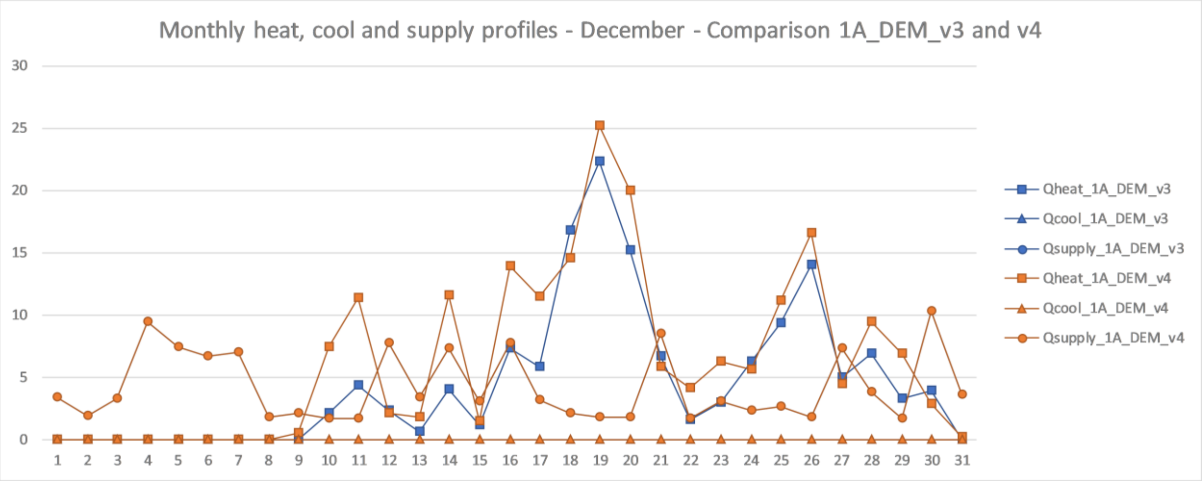
Only the changes compared to the previous model are described.

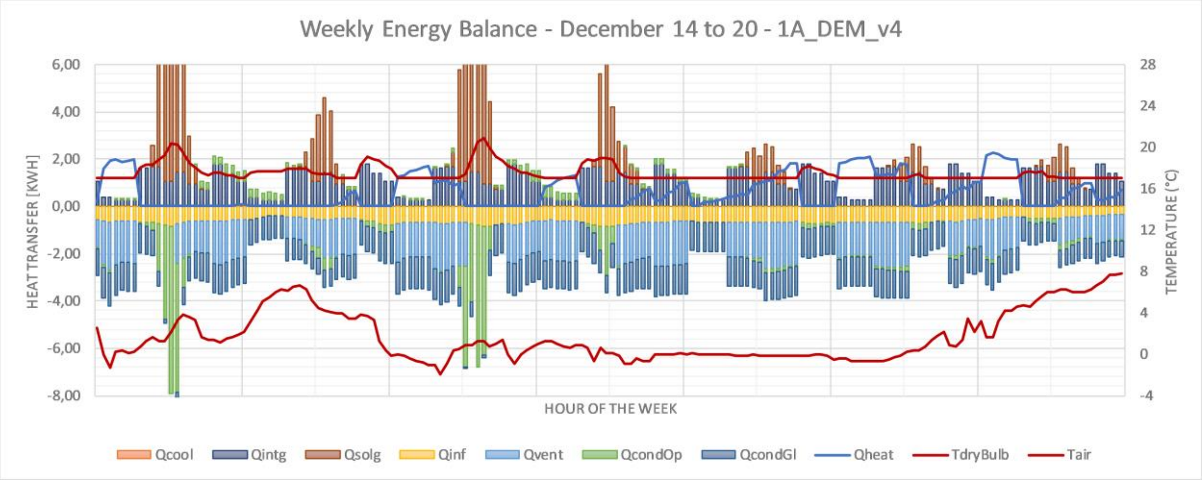
- Winter ventilation schedule is implemented, which minimizes ventilation rates in times of low outside temperature. The schedule is as follows and results in an average ventilation rate of 150 m^3/h (similar to the reference):
    - 00h to 06h = 0 m^3/h
    - 06h to 12h = 225 m^3/h
    - 12h to 18h = 300 m^3/h
    - 18h to 24h = 75 m^3/h
- The window share is increased to 0.8
- The sun shading system is on for three hours longer (till 21h)

Results

This variant results in a higher heating load. The cooling loads decrease, which is beneficial. The higher heating load results in a bigger heating shortage, shortage peak and cumulative mismatch.
This heating load is mainly higher in the month of December (37%). In March and April, it is slightly bigger and in the other months is either equal or smaller.

- the graph of the monthly heat, cool and supply profiles in December (next page) shows that on most days the heating load is much higher. This is probably the result of the ventilation at a wrong timing.
- The Weekly energy balance of December shows that there is a problem with the ventilation schedule. The daily schedule contains only 18 numbers, meaning that it starts three times per day. Some days, this results in excessive ventilation loads during the night.
- Analysis showed that there was a problem with setting the ventilation schedule. Further analysis is skipped, variant 1A_DEM_v5 changes this value





12.5.5 1A_DEM_v5 – correct ventilation schedule

Input

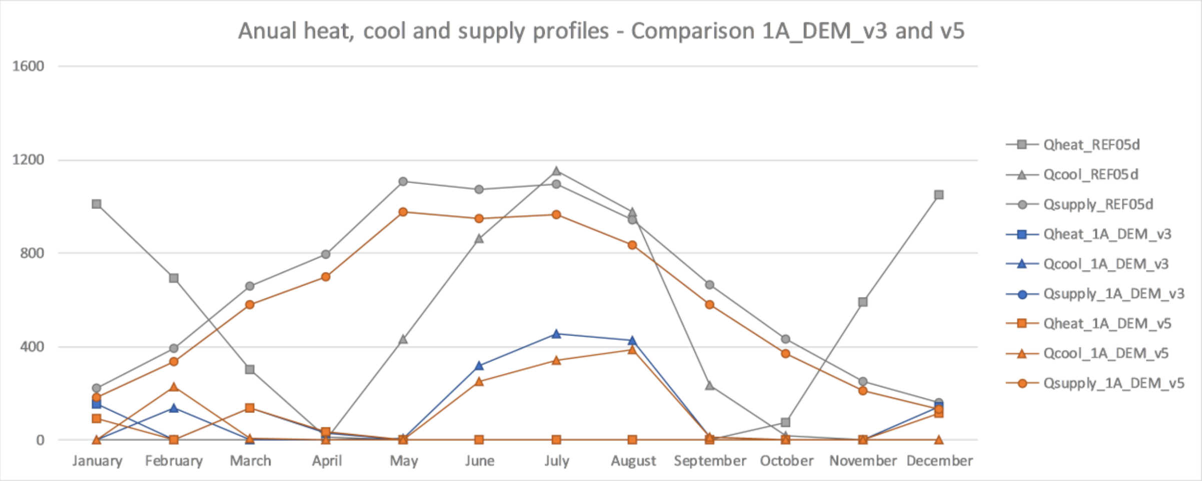
The comparison in this piece is compared to 1A_DEM_v3, because 1A_DEM_v4 contained a mistake. The input of this variant is equal to variant _v4, but is now input correctly in the simulation.

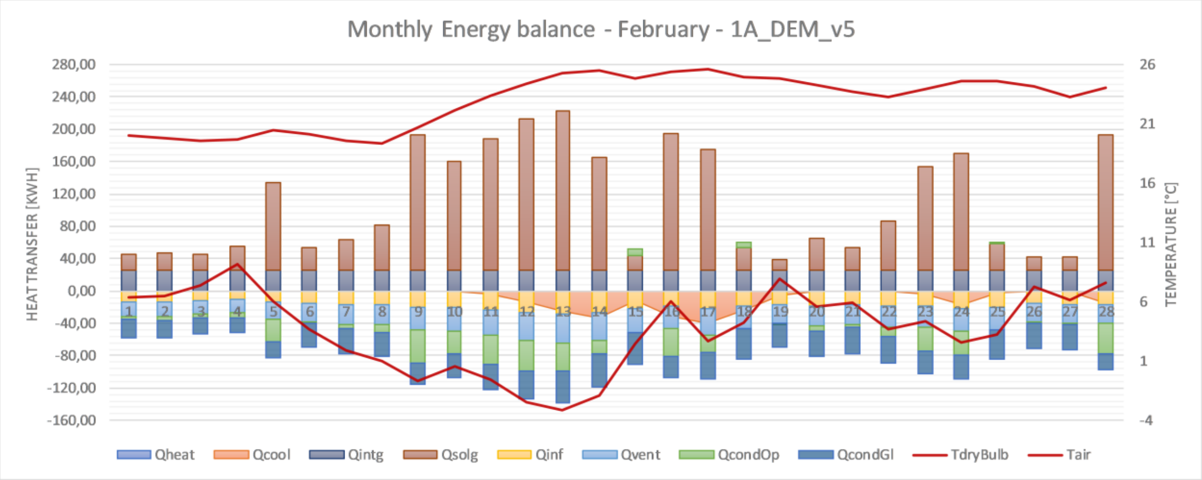
Results

- the total heating load is lower, meaning that the g-value and ventilation are effective.
- the cooling load is lower as well, as a result of the extended time of the shading.

Analysis of the annual demands

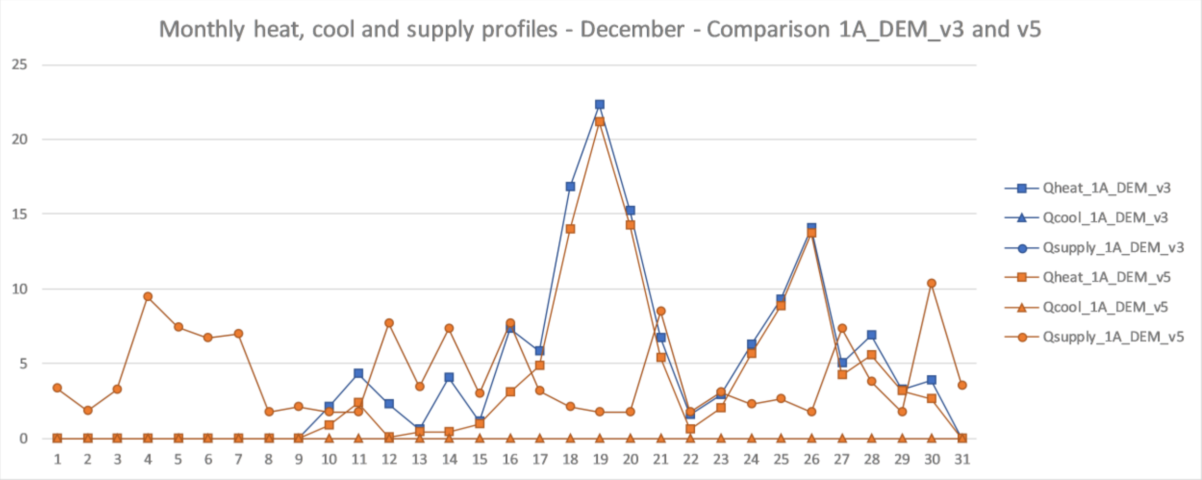
- February has a strange, high cooling load. The figure below, the monthly energy balance of February, shows that this is the cause of multiple successive days of high solar radiation, in which the indoor air temperature gradually increases.
- The outdoor temperature is very low in these days, so additional cooling should not be necessary. An increased ventilation could resolve this. Ventilation schedules should adapt to outdoor temperatures; if there is a cooling load inside and the outdoor temperature is lower, the ventilation rate should be increased.





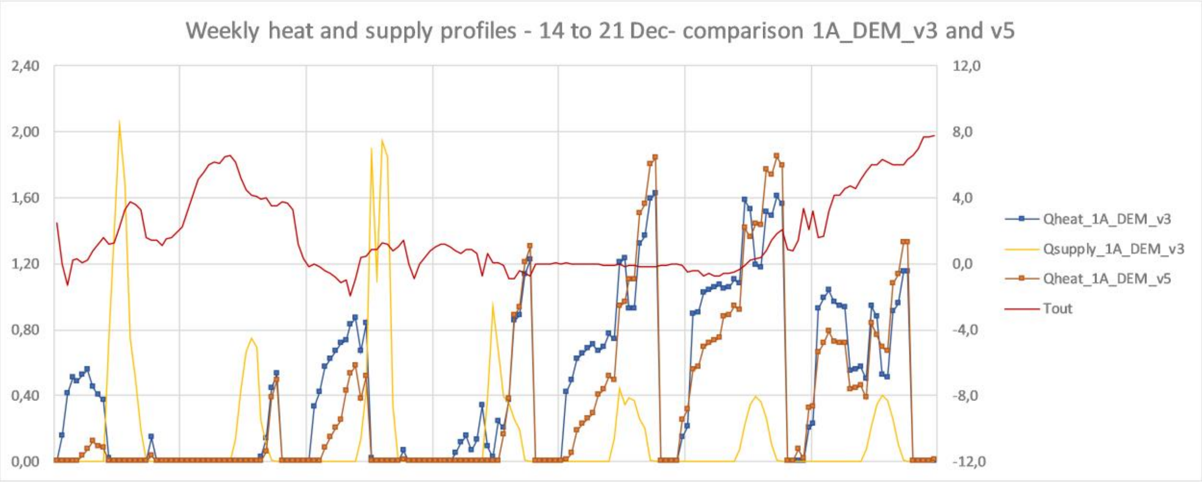
Analysis of December

- the month of December, graph below, shows that heating loads are lower for v5. However, especially in times of high heating loads (Dec 18,19,20 and Dec 25,26) the decrease in heating load by variant 5 is low.
- <u>The graph shows that, although much days have acceptable heating loads compared to the supply, there are still days where big mismatches occur. However, there also still is a big surplus. This might be used to pre-heat the building, to diminish heating loads in times of lack of supply.</u>

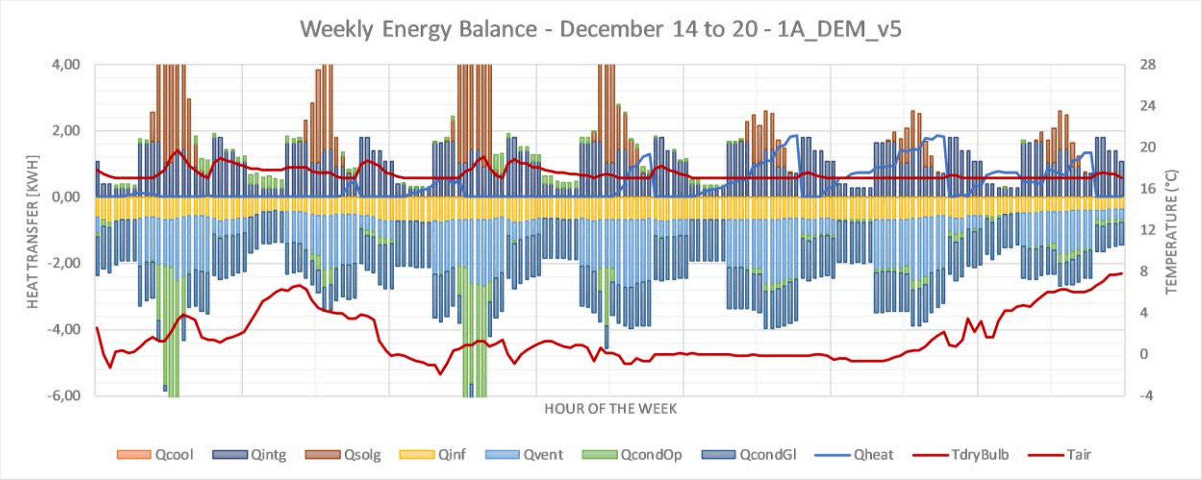


Analysis of a winter week

- The weekly graph below shows the effect of the reduced ventilation. The effect on high heating load days is beneficial, because a part of the heating load is shifted from midnight to midday. However, it also shows that even without ventilation, there is still a heating load. Especially on days when there is a low outdoor temperature and no supply (i.e. solar radiation), there still is a high heating load.

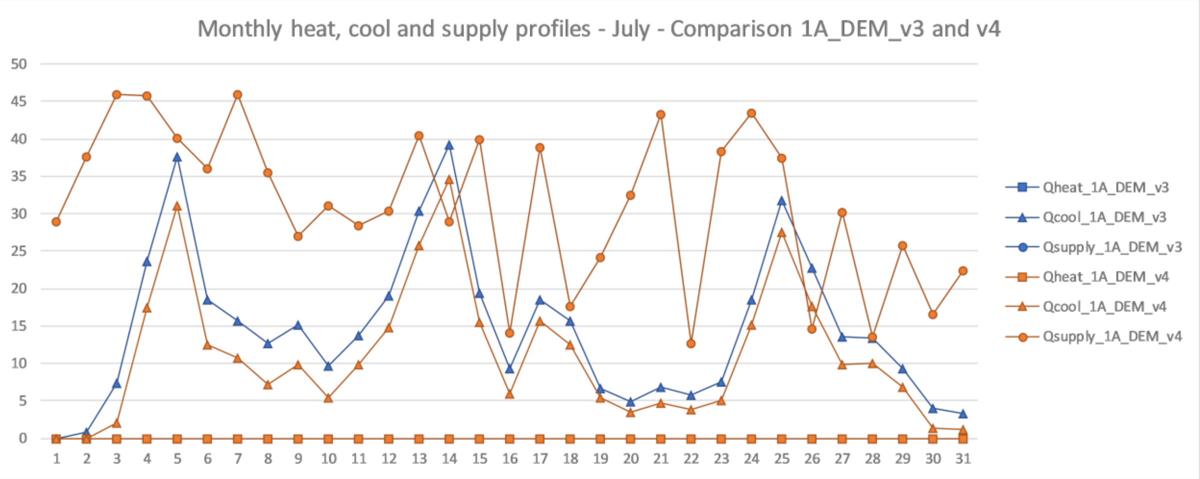


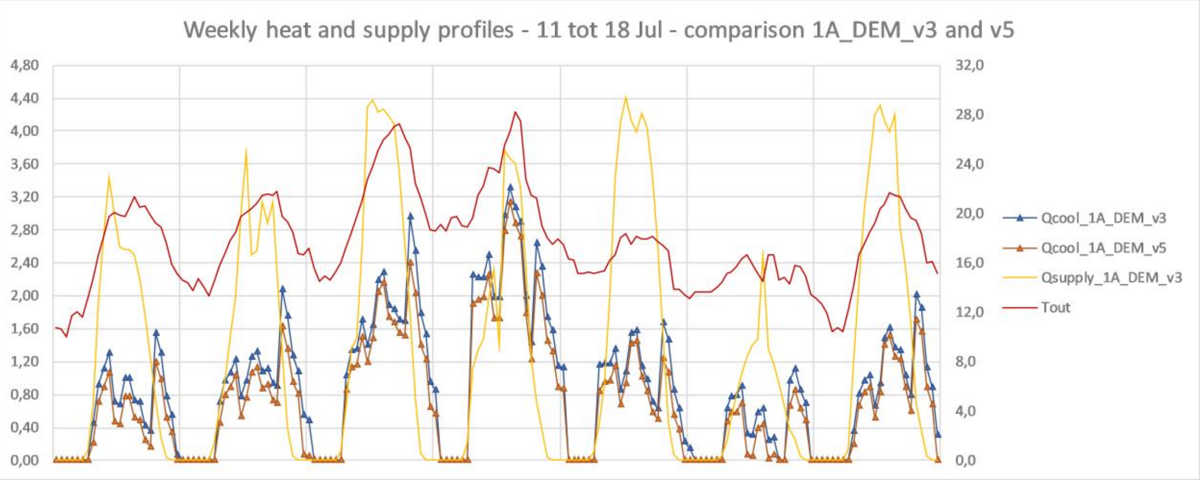
- the heat balance of the same week (graph below) shows
  - that when the ventilation is shut off at night, infiltration and transmission through glazing are the only two heat flows
  - that transmission through glazing does not differ between night and day, even if the outdoor temperature is equal. This means that the night insulation on glazing does not function correctly.



Analysis of the cooling situation

- The graph of the monthly heat, cool and supply of July (next page, top image) clearly shows that the cooling load is constantly lower than the cooling load in a previous variant
- The weekly graph for July (next page, lower image) shows that the cooling load in the morning starts equally with the supply, which is beneficial for energy-flatness. However, there still is a cooling load peak after the supply reduces to zero. The peak that is visible here, is the result of the internal gains. At this time, the outdoor temperature most often already below the indoor temperature. The cooling load can be diminished by introducing extra ventilation.





Conclusions for improvements

- Cooling loads occur during days with a low outdoor temperature.
  - By improving ventilation in these times, cooling loads can be prevented.
- Heating loads occur during midnight, and right before the morning
  - part of these loads might be solved by pre-heating the building; increasing the indoor air temperature above the heating setpoint in times of supply surplus. The challenge with this is that it is hard to predict the outdoor climate conditions.
  - the other part can only be solved by reducing the glazing transmission and losses through transmission
- Cooling loads occur after supply reduction to zero as a result of internal gains
  - this might be reduced by introducing extra ventilation, to prevent cooling loads.

12.5.6 1A_DEM_v6 – increasing heating and cooling in times of energy surplus to shift loads

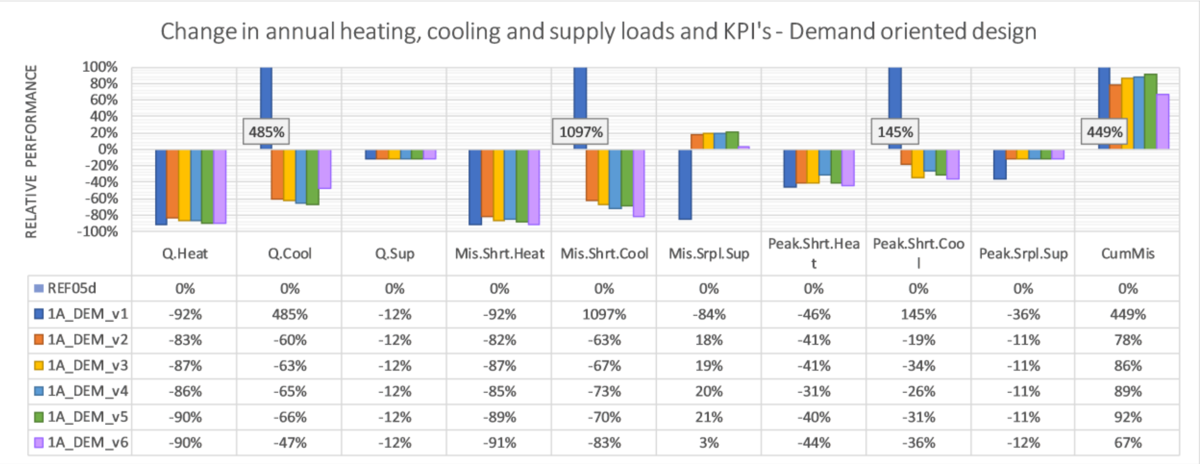
Input

Only the changes compared to the previous model are described.

- Set ventilation conditions that adjust depending on outdoor and indoor temperature
- Set heating loads when there is a supply surplus --> heat to 21°C
- Set cooling loads when there is supply surplus --> cool to 20°C
- Check the adaptive insulated shades

Result

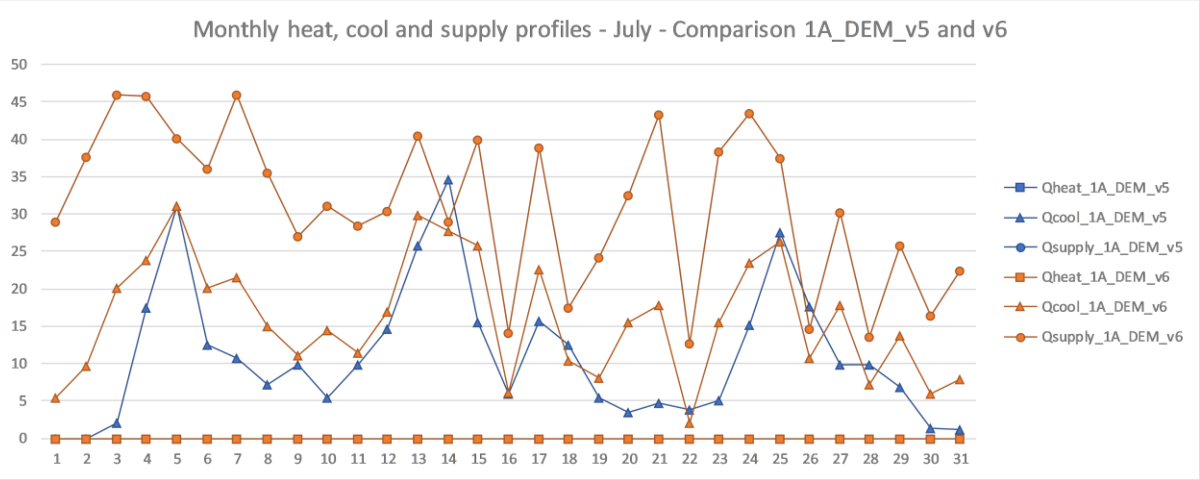
The effect is very effective. It results in a higher cooling load, but in a much lower cooling mismatch, heating mismatch and surplus mismatch. Also the peaks for heating and cooling and the cumulative mismatch are reduced.



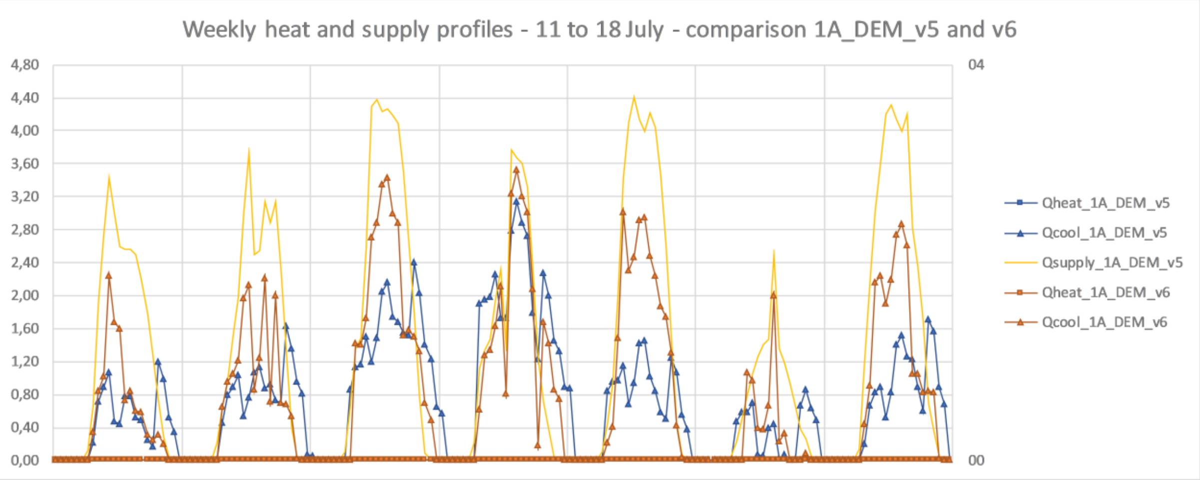
	Q.Heat	Q.Cool	Q.Sup	Mis.Shrt.Heat	Mis.Shrt.Cool	Mis.Srpl.Sup	Peak.Shrt.Heat	Peak.Shrt.Cool	Peak.Srpl.Sup	CumMis
REF05d	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1A_DEM_v1	-92%	485%	-12%	-92%	1097%	-84%	-46%	145%	-36%	449%
1A_DEM_v2	-83%	-60%	-12%	-82%	-63%	18%	-41%	-19%	-11%	78%
1A_DEM_v3	-87%	-63%	-12%	-87%	-67%	19%	-41%	-34%	-11%	86%
1A_DEM_v4	-86%	-65%	-12%	-85%	-73%	20%	-31%	-26%	-11%	89%
1A_DEM_v5	-90%	-66%	-12%	-89%	-70%	21%	-40%	-31%	-11%	92%
1A_DEM_v6	-90%	-47%	-12%	-91%	-83%	3%	-44%	-36%	-12%	67%

Analysis of the summer situation

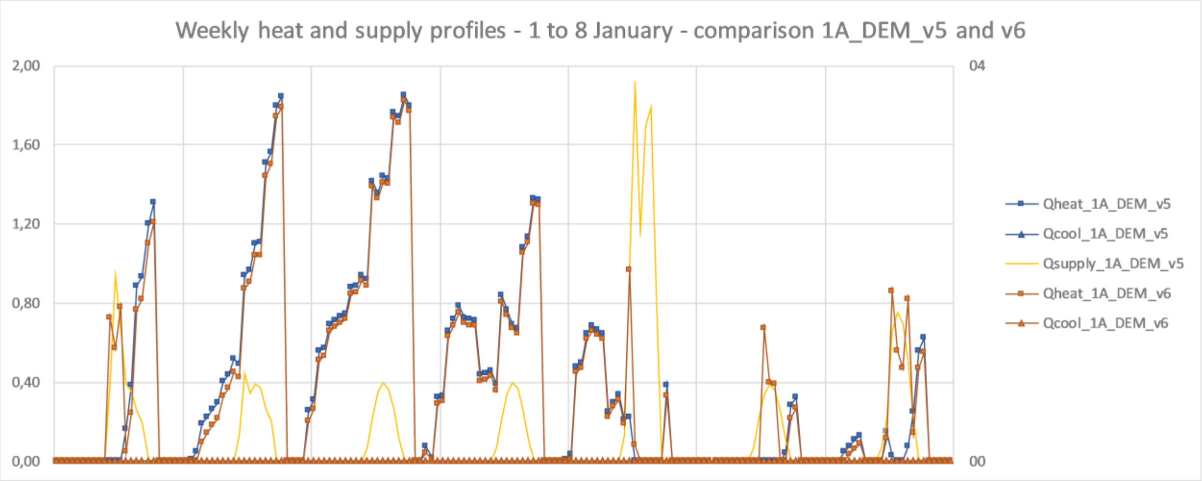
- the graph below shows that the overall cooling loads are higher, but the peaks are flattened out perfectly (look at the 14th and the 26th of July)



- The figure below shows the increased cooling load in times of sufficient supply compared to the previous variant. It results in a lower cooling in times of lower supply.



- The figure below shows the same principle, but then for heating. The effect is slightly lower, but still visible.



12.5.7 Final conclusions of the demand oriented design

The final conclusions are summarized in *7.1 Design 1A - Demand adapted to* supply

12.6 Appendix 6: Design 1B: Supply adapted to demand - optimization process

The content in this section describes the optimization iteration of the supply-oriented design. It substantiates the conclusions drawn in *7.2 Design 1B - Supply adapted to* demand. Per variant, the input and the results are described. All results are produced using the energy-flatness simulation tool as described in *4 Simulation of energy-flatness; the energy model*.

12.6.1 1B_SUP_v1 – Parameter study input as starting point

The parameter studied concluded that the supply surface should be maximized in winter, should be lowered from March till October, and should not be changed in July and August.

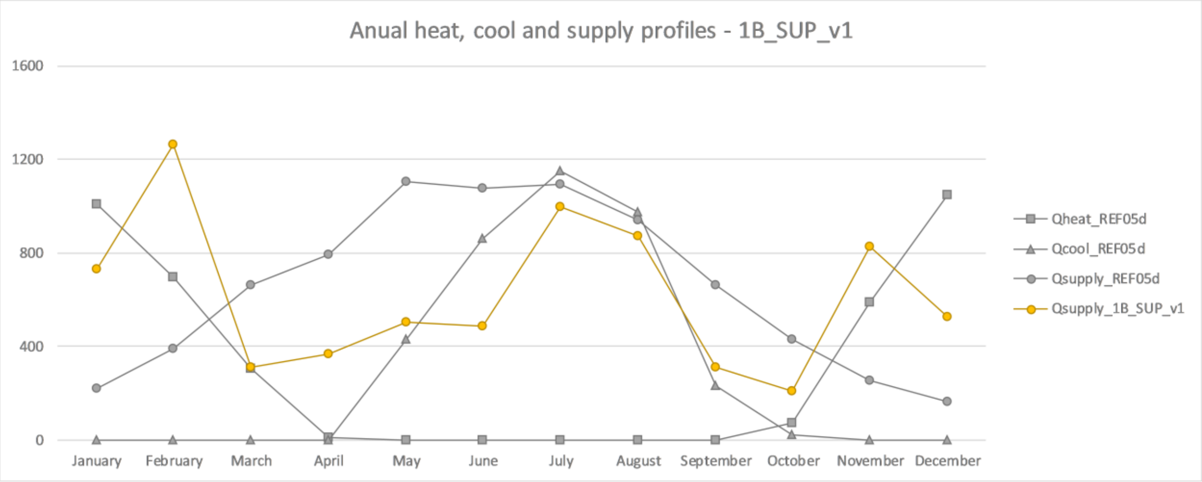
Input

In the table below, the supply shares per orientation per month are provided. In this variant, the same pattern is used for all surfaces.

Surface	**Input**
North	0.1 in Nov,Dec,Jan,Feb // 0.015 in Mar,Apr,May,Jun,Sep,Oct // 0.03 in Jul,Aug
East	0.1 in Nov,Dec,Jan,Feb // 0.015 in Mar,Apr,May,Jun,Sep,Oct // 0.03 in Jul,Aug
South	0.1 in Nov,Dec,Jan,Feb // 0.015 in Mar,Apr,May,Jun,Sep,Oct // 0.03 in Jul,Aug
West	0.1 in Nov,Dec,Jan,Feb // 0.015 in Mar,Apr,May,Jun,Sep,Oct // 0.03 in Jul,Aug
North roof	0.1 in Nov,Dec,Jan,Feb // 0.015 in Mar,Apr,May,Jun,Sep,Oct // 0.03 in Jul,Aug
South roof	0.1 in Nov,Dec,Jan,Feb // 0.015 in Mar,Apr,May,Jun,Sep,Oct // 0.03 in Jul,Aug

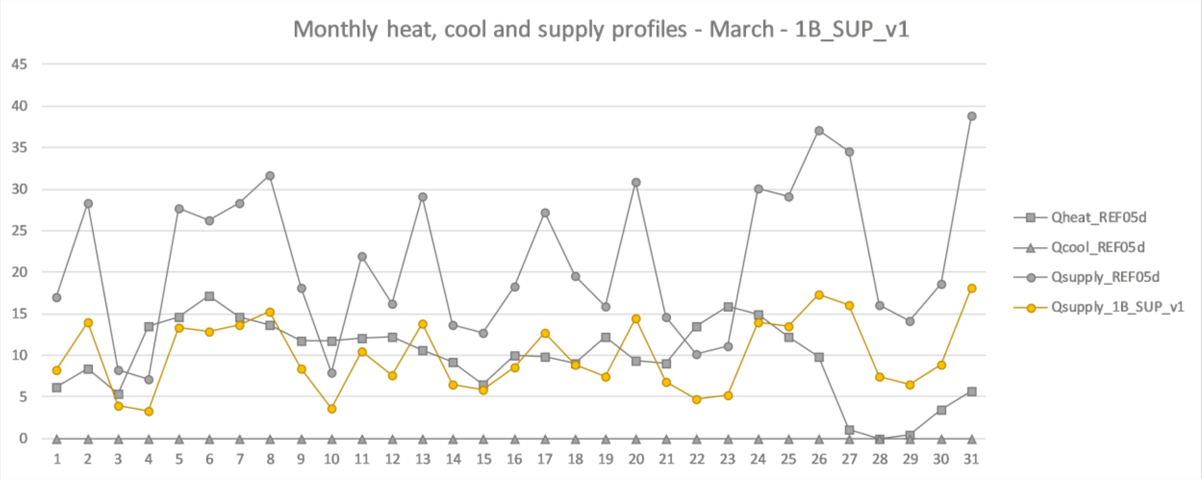
Results

Compared to the reference design, a few changes are significant. First of all, the total supply has decreased. Second of all, the shortage for heating has decreased whilst the shortage for cooling has increased. The supply surplus has slightly decreased. The supply surplus peak is much bigger.

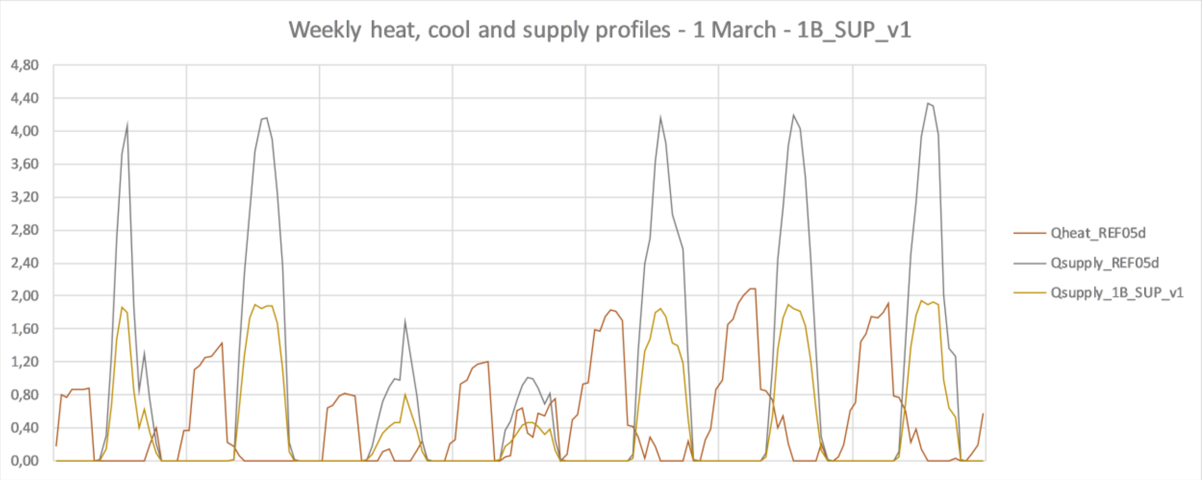


The graph above shows the new supply profile. The following can be concluded:

- There is a strange big surplus in February. <u>This should be adopted in the next variant.</u>
- The match in March, April and May is better than in the reference design
- The supply matches the demand rather accurate from July to November



The figure above shows the match in March. For the average day, the match is pretty good. The supply line sort of seems to follow the supply line. Zooming in to the hourly values of the first week of march shows the following graph:

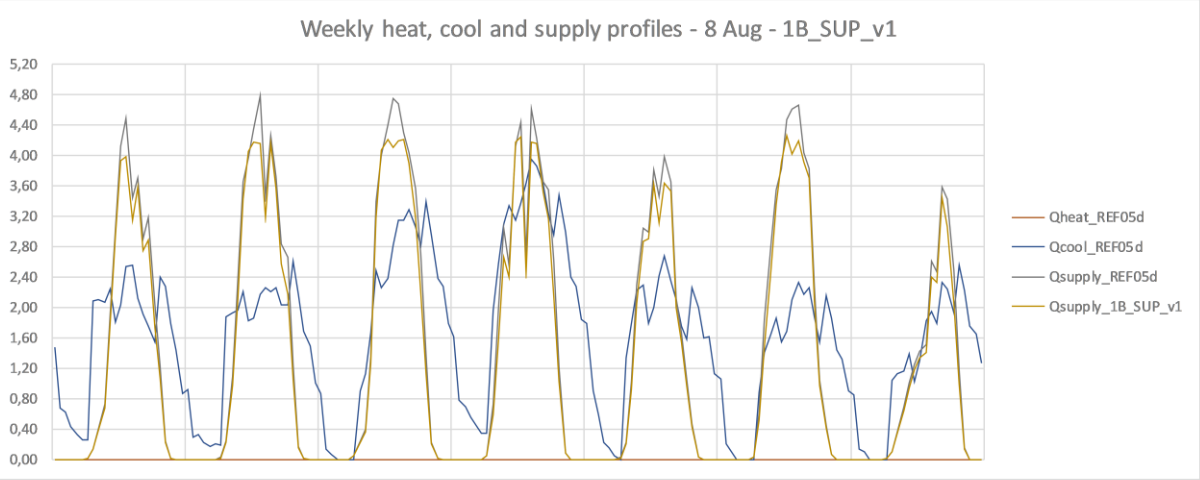


This weekly graph above clearly shows that for the supply match, it is very important to focus on the weekly graphs;

- Although no compensation is possible when supply is zero, there are some moments in the early morning where there is little supply and a heating load which is higher. Increasing the small amount of supply available at that time decreases the mismatch
- <u>The supply potential in the morning should be used more effectively to fulfil the heating and cooling demand by increasing the eastern supply share. This then should be compensated by a lower southern share</u>
- <u>Nevertheless, the drop of supply to zero shows that there is no chance to solve the mismatch.</u>

Another matching week is August, shown by the graph below. This week has accurate daily matches, but the hourly match provides more info:

- there is a cooling load in times of supply, but the supply is too low, both in the morning and in the afternoon
- this effect occurs from June till October (in March, April and May the cooling load matches in the morning)
  - <u>In a next design; increase the late evening supply (all year) and increase the morning supply from June</u>



12.6.2 1B_SUP_v2 – increasing east and west, making south zero

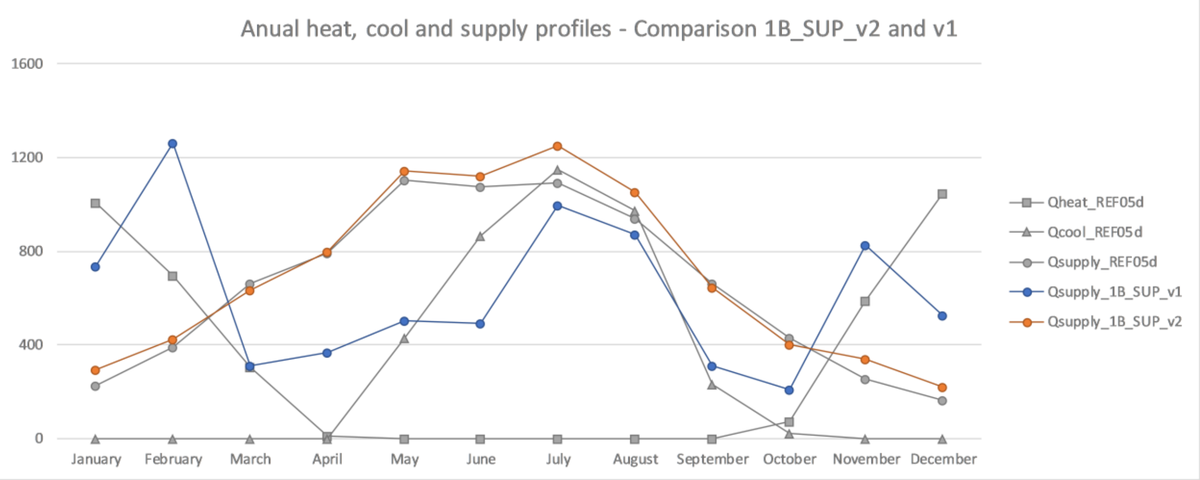
Input

In the table below, the supply shares per orientation per month are provided. Only the changes compared to the previous design are shown.

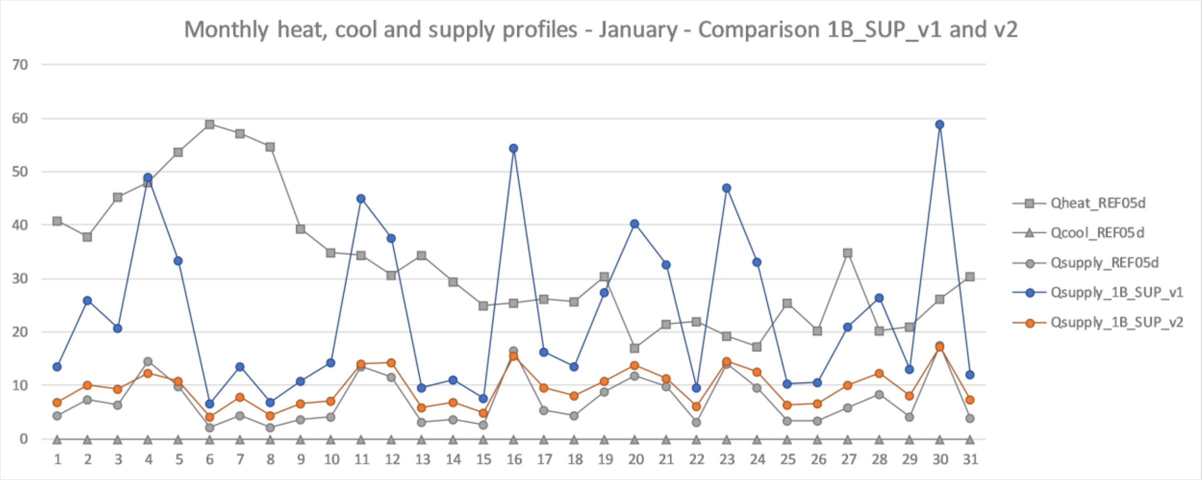
Surface	**Input**
North	
East	0.1 all year
South	0
West	0.1 all year
North roof	
South roof	0

Results

The graph below shows the annual changes in supply profile.

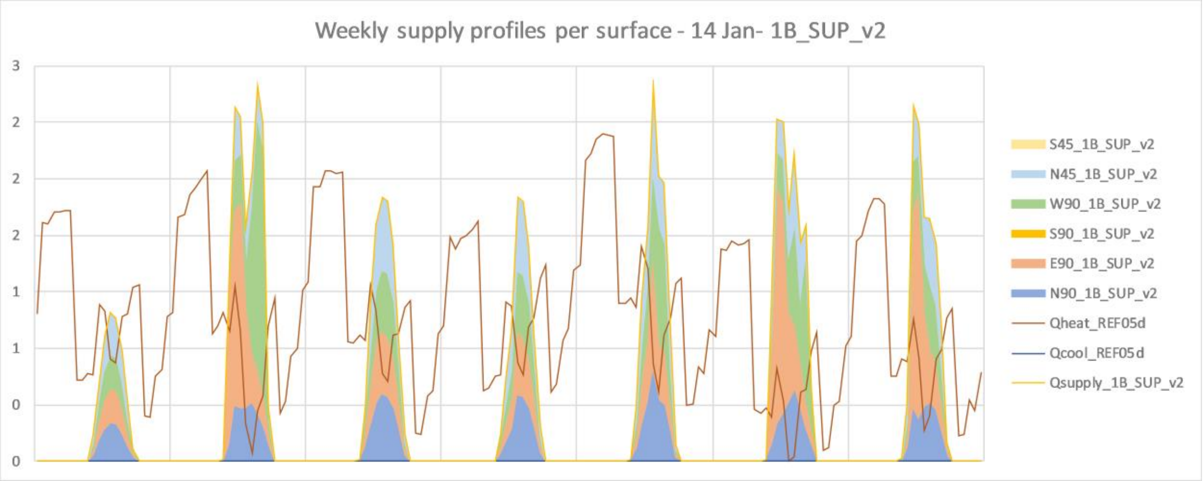


- the supply shape looks much more like the original shape; four surfaces have returned to an all year consistent state
    - the heating shortage mismatch is worse compared to the previous variant; the south surfaces do play an important role in reducing the heating shortage
    - the cooling mismatch is reduced with 15% compared to the reference, which shows the positive effect of increasing supply on east/west facades.
    - the overall supply surplus is increased, which shows that the overall match is worse, except for the cooling



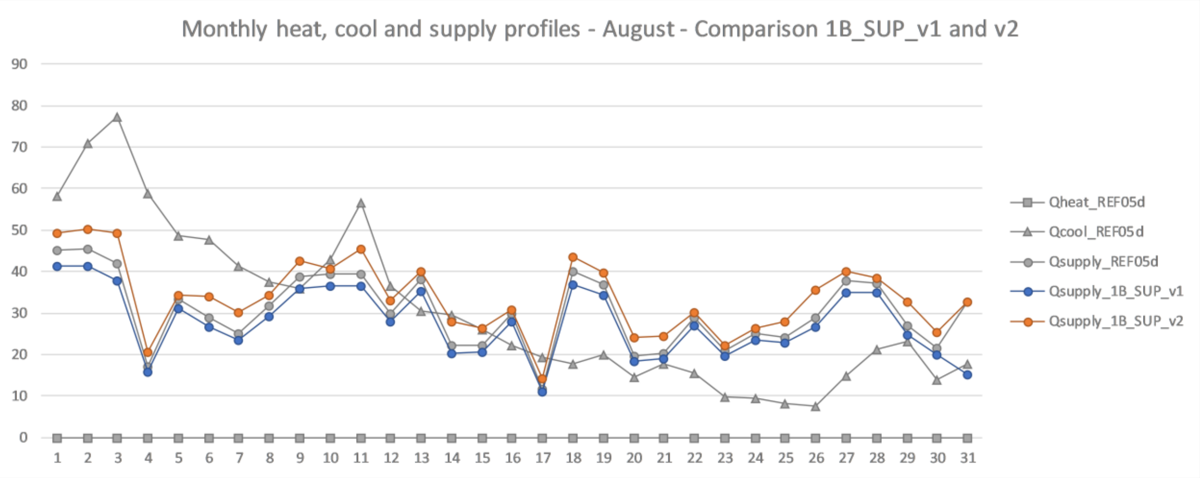
- The graph above shows the energy profiles in January. It shows the origin of the increased heating shortage; the total supply potential is much lower.
    - this is probably the result from the reduced supply on the southern areas; the sun is highest and strongest on the south orientation. Especially in winter, there is little solar power on the east and west sides (in the early morning and early evening)

- The weekly graph below elaborates on where the mismatch occurs. Using this supply technique, there is supply peak in most days, but the overall shortage mismatch still occurs. The effect of high supply on east and west does match the heat profile; the peak occurs at the same time

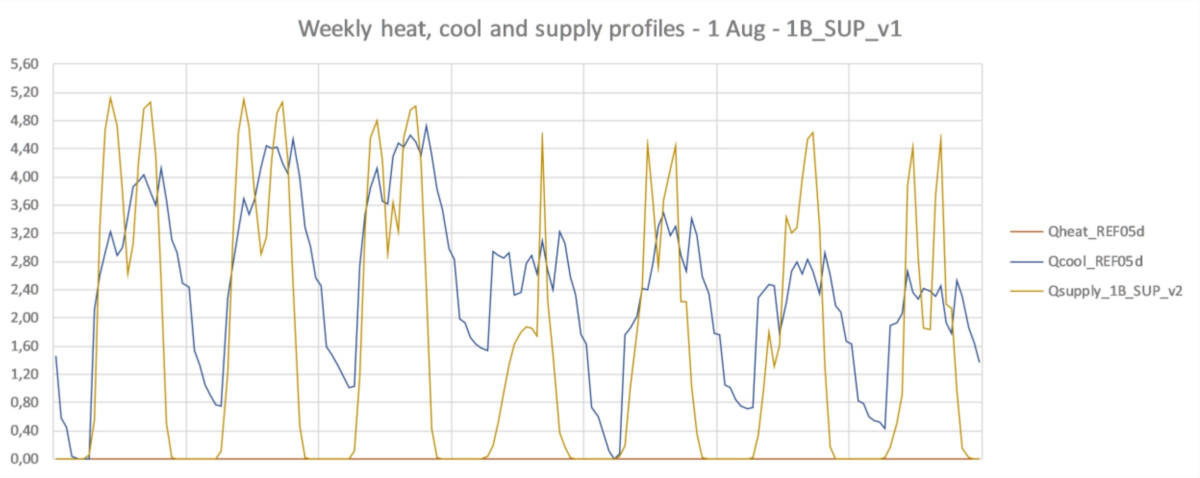


- The 16th and 17th of January show that a peak is inevitable; these are two days with just the base load, resulting in a peak. The 15th of January shows that the peak drop of the south matches the drop in the load.

- The heating shortage increases when moving the supply from the south to the east/west. However, the resulting supply pattern is more similar to the heating demand pattern. In other words, the southern orientation is very effective for high solar radiation per m^2 in winter, but the east and west result in a matching pattern. Solar elements on east and west improve the match, but only if they are also compensated for the lowered individual gain.



- this graph (above) shows that the supply potential is very equal to the supply potential of the previous variant. Considering the changes in supply surface (higher east and west in summer and zero south and south-roof). The supply potential surface is more than doubled, and the supply is approximately equal. The solar power on east and west is thus remarkably lower. Nevertheless, the pattern is similar to the previous variant, meaning that the south orientation in particular is not necessary to achieve high supply loads.



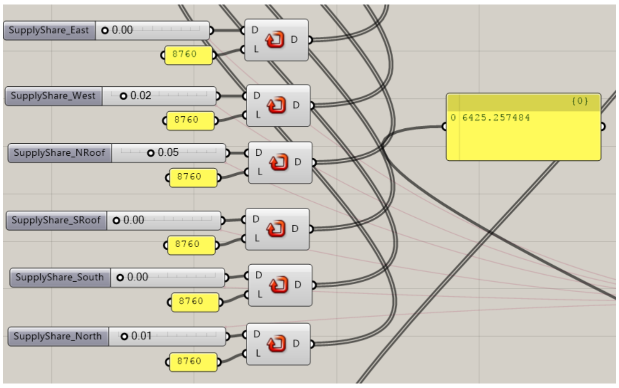
- the graph shows that the supply drop in the middle of the day due to the reduced southern facade is undesired for the cooling load. The cooling load profile is a consistent peak pattern, and the sudden drop of supply is fatal for the mismatch.
    - In the next design, the southern facade needs some supply area.

12.6.3 1B_SUP_v3 – evolutionary solver for share per orientation

Because the previous design variants showed that is very hard to adapt the supply load, one test is done in which an evolutionary solver is used. The goal of the evolutionary solver is to minimize the mismatch. Since it can only have one goal, the mismatch is summarized in one number.

mismatch = supply surplus + heating shortage + cooling shortage

The solver considers one annual constant 'share' value per orientation. This way, there are only 6 parameters to change (one share value per orientation). This is more representative; if supply potential would be created, it would probably be done by implementing a solar panel. The size of this element will not change over the year. Moreover, it makes the calculation much quicker. The evolutionary solver resulted in the following shares per orientation:

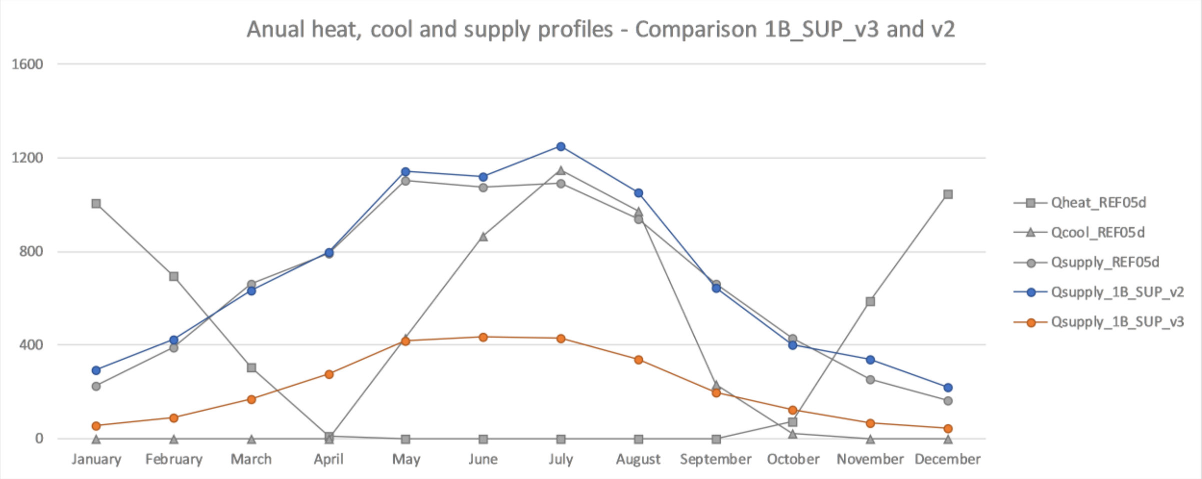


SupplyShare_East 0.00
SupplyShare_West 0.02
SupplyShare_NRoof 0.05
SupplyShare_SRoof 0.00
SupplyShare_South 0.00
SupplyShare_North 0.01

{0}
0 6425.257484

Results

This variant shows that the focus of the solver lies in the supply side; both heating mismatch and cooling mismatch have increased (resp. 5 and 58%). The supply surplus has decreased with 79%. This shows why the solver founds this the most reasonable solution.



Conclusion

When supply surplus, heating shortage and cooling shortage are valued equally and only supply adaptations are considered, the lowest total mismatch is achieved by reducing the supply. It results in an annual energy shortage (not energy-neutral).

- This is probably the result of the high mismatch in terms of patterns; a slightly higher share of supply result in peak surpluses in summer.

12.6.4 1B_SUP_v4 – Supply surplus is less of a problem and energy-neutrality is a condition

Input

Based on the previous results, the following considerations are made:

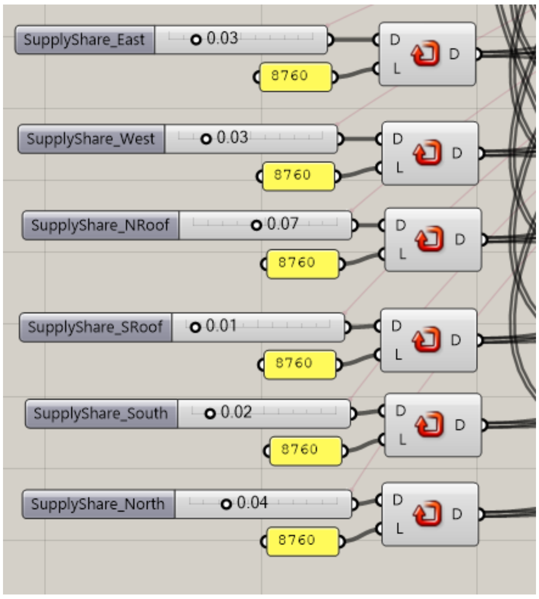
- the value of the supply surplus is reduced to 20%. This represents the situation in which a building would be able to deliver energy to the grid and would benefit slightly from that.
- Also the boundary condition of having at least the same amount of energy supply as heating or shortage (so energy-neutral or energy positive) is implemented.

For the evolutionary solver, this results in the following goal:

min[0.2*supply surplus + heating shortage + cooling shortage]

Results

It results in the following share per orientations:



SupplyShare_East 0.03

SupplyShare_West 0.03

SupplyShare_NRoof 0.07

SupplyShare_SRoof 0.01

SupplyShare_South 0.02

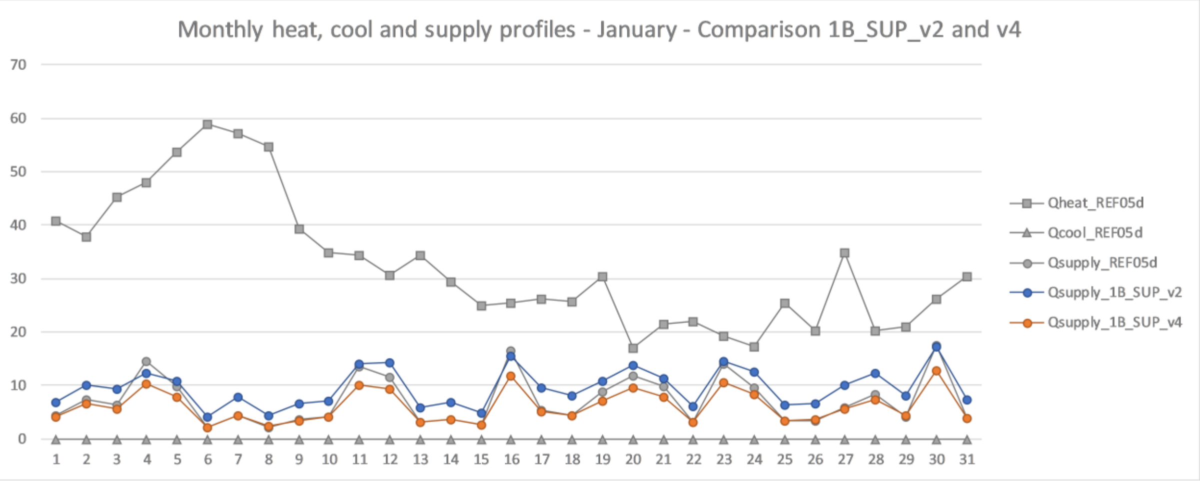
SupplyShare_North 0.04

The shares are remarkable. The north surfaces have relative high shares. This is probably the result from them providing a stable amount of supply (diffuse) and do not result in a high supply surplus.

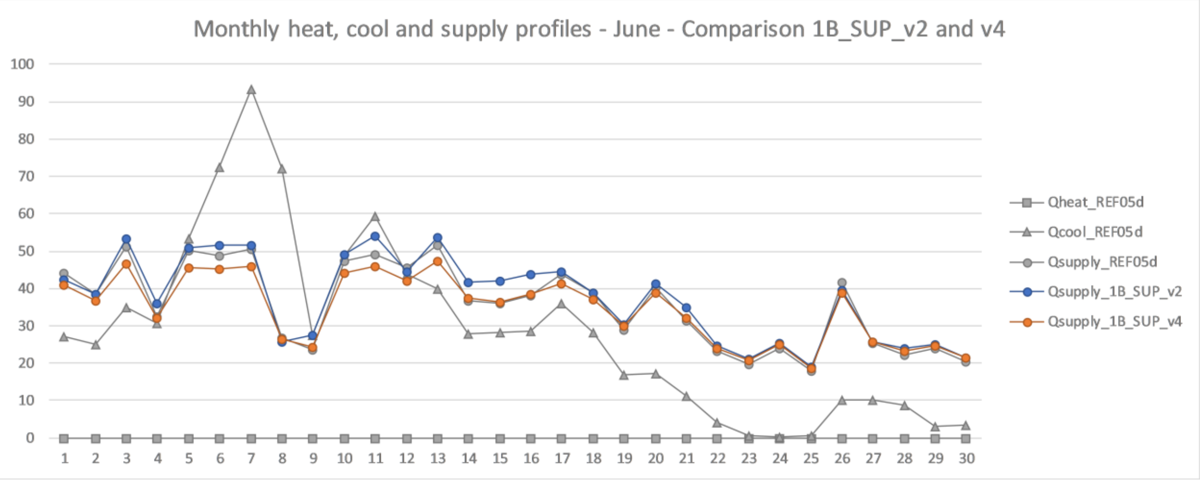
In practice, this would not be a preferred solution. After all, the north surfaces provide a relative low supply, whilst a high amount of supply units is needed. Nevertheless, for energy-flatness the relevance is shown. N.B. the results will depend on the ability of the solar collectors or photovoltaics to use diffuse light to generate supply.

- **Energetic results**
  - the total supply is much higher than the previous variant, but still 6% lower than the reference.
  - the heating shortage and cooling shortage are lower compared to the previous variant, now respectively resulting in -3% and -9% compared to the reference.

- the supply surplus has reduced with 12% compared to the reference.



- the graph above shows a lower supply in winter. Also, the effect of peaks is highly mitigated. This is probably the result of a higher dependency on indirect supply potential (i.e. higher northern supply share)



- the graph above shows that in times of lower supply, the supply levels for variant 4 are relatively higher. In times of high supply, it is the other way around. Once again, this is probably the result of the higher dependency on indirect supply.

Conclusions

A relative high share of supply potential on the north surfaces results in a lower mismatch. This is probably the result of the bigger share of diffuse supply potential on these surfaces.

12.6.5 1B_SUP_v5 – Defining the inevitable mismatch by neglecting supply surplus

Input

For design optimizations, it is useful to know the inevitable mismatch. In other words, the mismatch that cannot be solved even if all the solar supply potential is used effectively. In this variant an evolutionary solver is used to achieve the following goal:

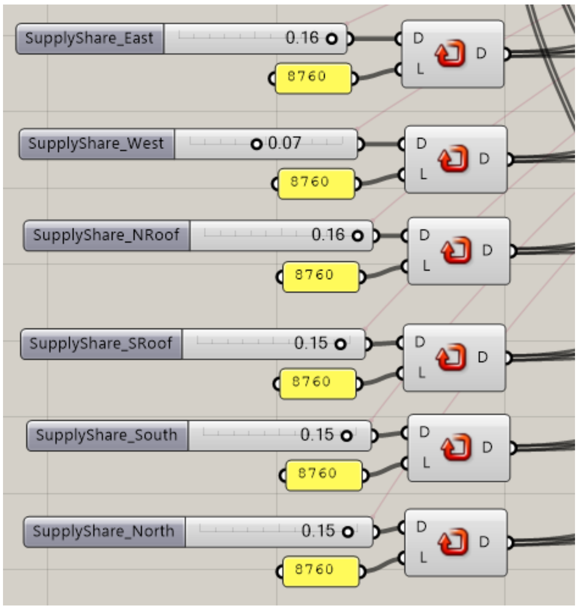
min[heating shortage + cooling shortage]

This means that a supply surplus is not considered a problem. The supply is only limited by the size of the surface that it is part of. Similar to the parameter study, the maximum supply is thus:

$$\textbf{Supply} = \textbf{Psolar} * \textbf{Asurface} * \textbf{0.2} * \textbf{0.8}$$

Results

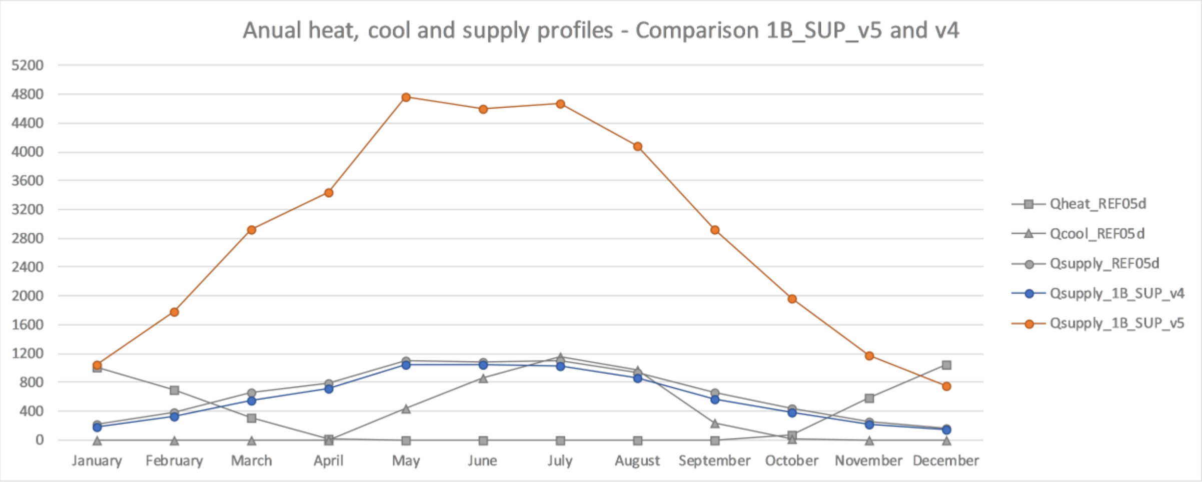
It results in the following shares per orientation:



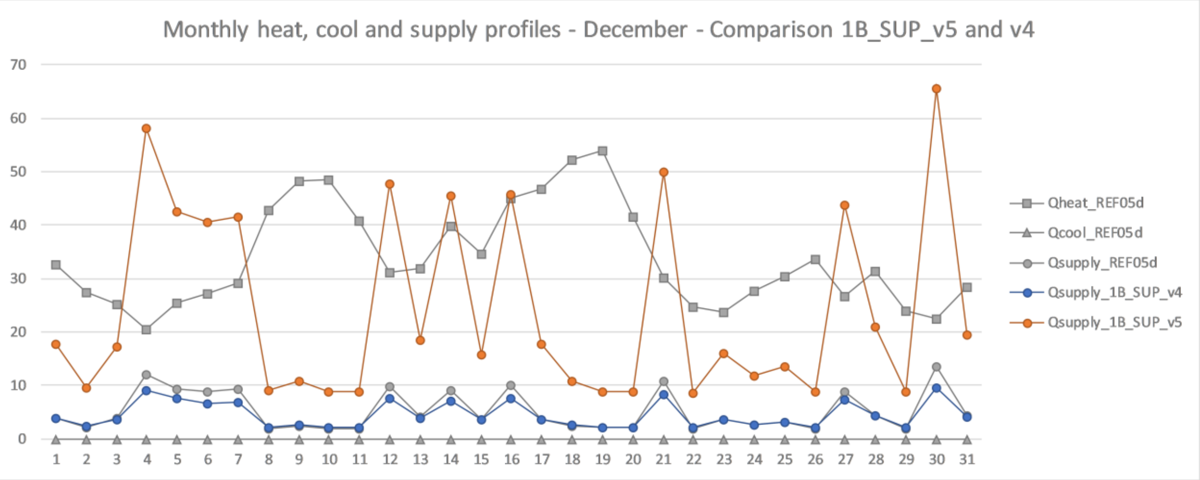
SupplyShare_East 0.16
8760
SupplyShare_West 0.07
8760
SupplyShare_NRoof 0.16
8760
SupplyShare_SRoof 0.15
8760
SupplyShare_South 0.15
8760
SupplyShare_North 0.15
8760

Resulting in the following values for loads and KPI’s:

Q_Heat	3598,1	kWh
Q_Cool	3446,7	kWh
Q_Sup	34153,6	kWh
Mis_Shrt_Heat	-2843,3	kWh
Mis_Shrt_Cool	-763,8	kWh
Mis_Srpl_Sup	30716,0	kWh
Peak_Shrt_Heat	-3,3	kWh
Peak_Shrt_Cool	-4,0	kWh
Peak_Srpl_Sup	22,2	kWh
CumMis	27652,6	kWh



Obviously, the total supply becomes much higher. The surplus is not considered a problem, and thus the supply is maximized in times it is needed. It is seen that in December the demand is still larger than the supply.

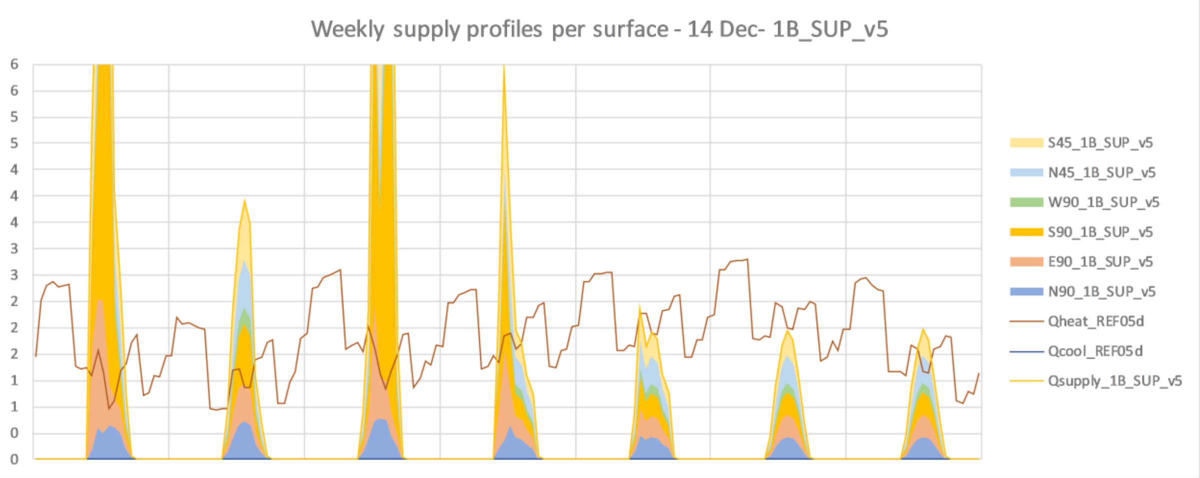


The graph above shows the month of December. It clearly shows the effect of increasing the supply surface for cloudy days and not so cloudy days; as soon as the sun starts shining, the supply is very high. On cloudy days, however, the supply does not match the demand by far.

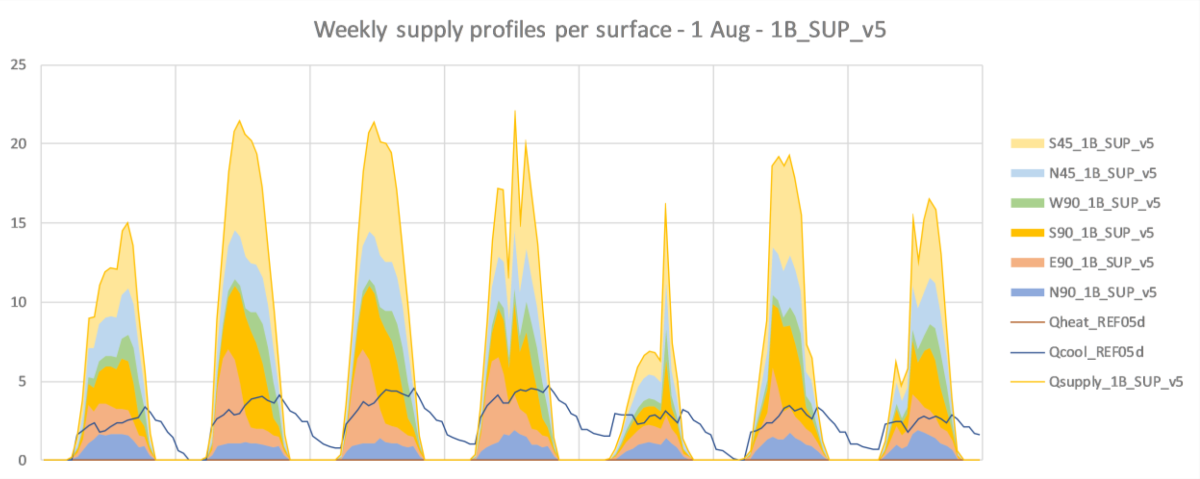
This study has not resulted in a maximum supply on all sides, even though the supply does not cover the demand in the worst month December and there practically is no disadvantage in increasing the supply. It shows that the heating demand does not occur at a time the supply can be increased more.

The graph below shows a week profile for a week in December. It shows a few things

- that the heating shortage is determined by the nights
- that on cloudy days, with just diffuse supply potential, the surface of the building is not sufficient to match the demand.
- that on cloudy days, the contribution of the surfaces is not dependent on the orientation (e.g. the west surfaces provide supply all day)



The graph below shows a summer week for this variant. It shows where the cooling mismatch occurs, namely in the evening. High supply load can diminish this, because solar is gone in times of this demand.



12.6.6 Final conclusions of the supply oriented design

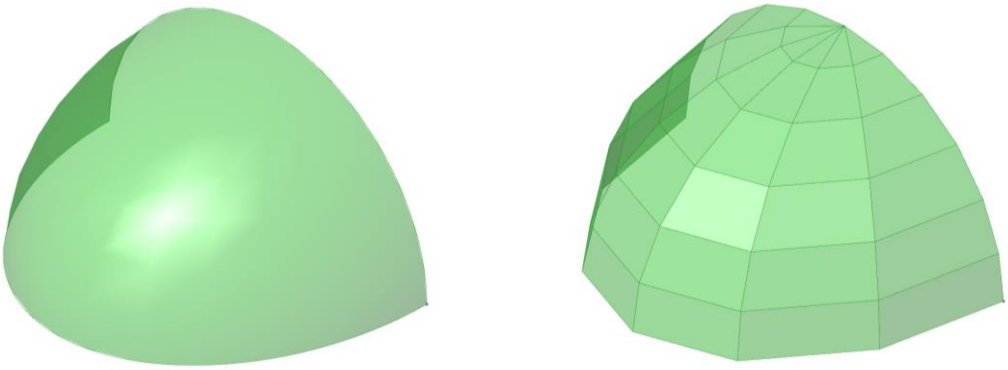
The final conclusions are summarized in *7.2 Design 1B - Supply adapted to* demand*.*

12.7 APPENDIX 7: ADJUSTMENTS TO THE ENERGY-FLATNESS SIMULATION TOOL

The energy performance of the final design is calculated using the same simulation as is used for all the parameter studies, as described in *4 Simulation of energy-flatness; the energy model*. However, the final design is so significantly different and more complex than the reference design that some adjustments and additions to the simulation tool are required. This appendix exaggerates on the adjustments, additions and the impossibilities in terms of modelling the design.

12.7.1 Meshed geometry

The final design considers a quarter of an elliptical sphere. EnergyPlus, the kernel of the Honeybee tool, is only able to calculated with planar surfaces. The geometry therefore is meshed into planar surfaces.



The adaptation of the geometry from the design elliptical sphere (left) to the meshed elliptical sphere (right)

When meshing curved surfaces, more mesh surfaces means accurate representation. However, more mesh surfaces also induces a longer calculation time for the energy simulation. The elliptical surfaces is split up in 36 mesh surface, which is assumed to be a representative meshing. The meshing using points on the original geometry to create the outlines for new geometry, resulting in an incircular mesh with a slightly smaller surface area. The original geometry has a surface area of 200.1 m^2, the meshed geometry has a total surface area of 193.6 m^2.

12.7.2 Thermal massing

The thermal massing is added in two ways:

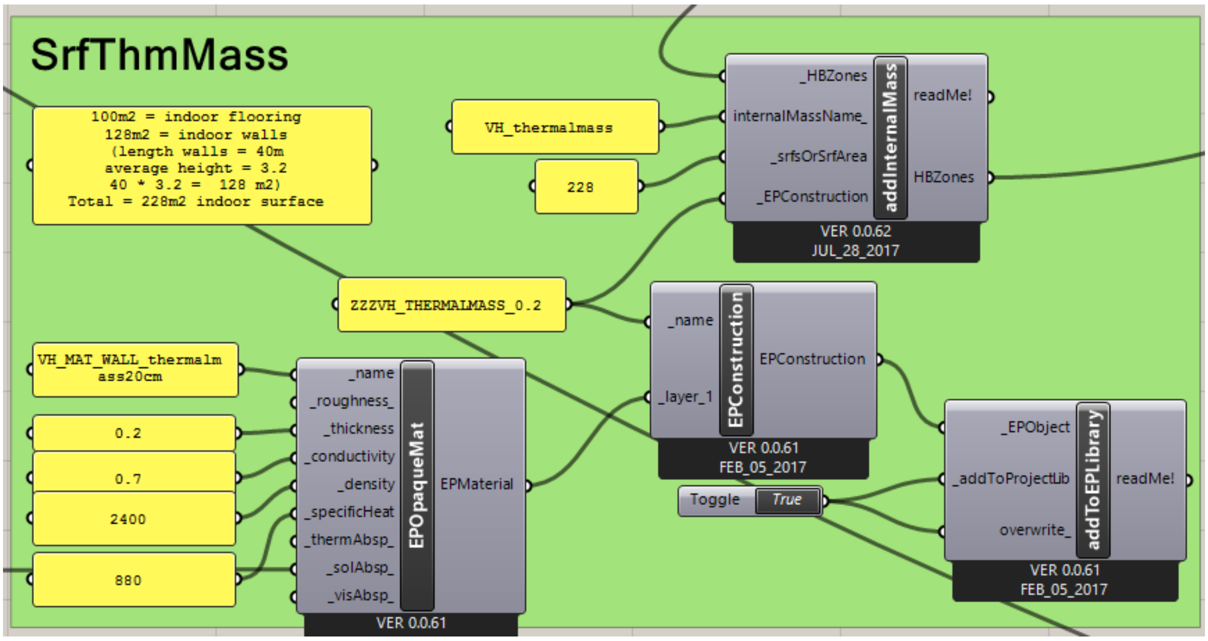
- By adjusting the construction of the floor, walls and roof
- Using the Grasshopper Honeybee ''Add internal mass tool''

In the final design, the building is covered by a big layer of earth. In the simulation tool, the construction is simplified. All surfaces part of the sphere have the same construction which consists of the following layers:

Material	Thickness [m]	Conductivity [W/m-K]	Density [kg/m^3]	Specific heat [J/kg-K]
		Inside		
Concrete structure	0.4	0.7	2400	880
Sand (slightly moist)	1.0	0.7	2000	1000
Insulation	0.15	0.03	45	1300
		Outside		

The total thickness is somewhat lower than it is in the design. The reason is that the energy simulation tool is not able to calculate with layer thicknesses of more than 1.2m. The effectiveness of 1.2m is assumed to be realistic. This sand layer is considered to be slightly moist. Assuming the outer insulating layer, the soil has a water-resistant layer and hence is dry the complete season. However, differences in humidity of the sand and respectively the conductivity, density and specific heat, should be considered.

The additional thermal mass by indoor flooring and walls is created using the Honeybee ‘’AddInternalMass’’ component. It takes a total surface area and an EP construction as input, and provides the zone with thermal mass. The total surface area of the indoor walls and flooring is considered to be 228 m^2, which is 100 m^2 by flooring and 40*3.2 = 128 m^2 by indoor walls. The material is a normal concrete wall of 20 cm, with similar properties as the concrete wall described in the table above. The figure below shows a screenshot of the implementation of additional thermal mass in the energy model.



```
100m2 = indoor flooring
128m2 = indoor walls
(length walls = 40m
average height = 3.2
40 * 3.2 =  128 m2)
Total = 228m2 indoor surface
```

12.7.3 Insulating blinds

The final design consists of dynamic blinds which protect against direct solar radiation in summer, allow the solar radiation to enter in winter, and close during the night to cover the southern window with insulation. The rotation and insulation of the blinds is not completely modellable in the simulation, so this is manually corrected in the results.

The blinds are implemented using the Honeybee EPWindowShades module combined with the EPShadeMaterial module. The EPWindowShades module takes a schedule that allows the shades to turn on or turn off. The schedule is as follows.

Month of the year	**Active schedule**		
January	ON: 00:00-07:00	OFF: 07:00-18:00	ON: 18:00-24:00
February	ON: 00:00-07:00	OFF: 07:00-13:00	ON: 13:00-24:00
March till October	OFF: 00:00-08:00	ON: 08:00-18:00	OFF: 18:00-24:00
November, December	ON: 00:00-07:00	OFF: 07:00-18:00	ON: 18:00-24:00

From the results of this simulation it can be derived that there still is a high heating loss through transmission of the glazing, meaning that the windows insulation is not increased by these blinds. In other words, the insulating capacity of the blinds does function properly. Because the insulation of the blinds is essential for the energy-flatness, this is manually corrected as follows:

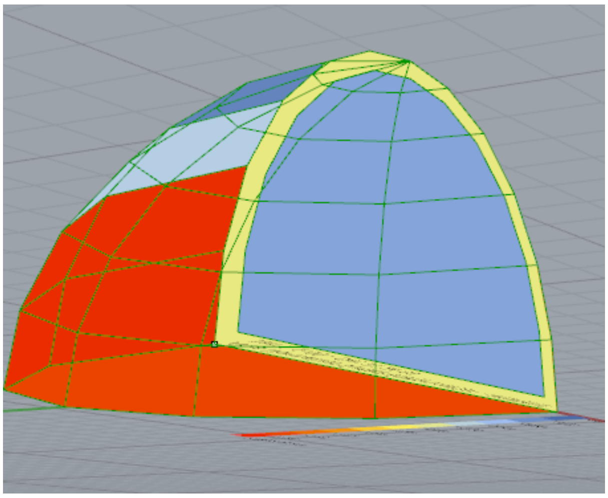
- For every moment that the shades are 'ON' according to schedule mentioned above, the value for transmission through glazing is reduced by a factor 0.2. This factor is similar to the difference of the insulating performance of the glazing without insulated blinds in front of it (U = 1.3) and the glazing with insulated blinds (U = 0.26).
- In timesteps where this correction leads to a negative heat demand, the heat load is set to 0.

Last of all, it should be noted that the design considers rotating blinds. The blinds rotate with azimuth in winter, to allow solar radiation to enter the building. During summer they rotate such that shade covers the windows, and direct solar radiation is blocked. This dynamic property is not modelled in the simulation. However, the functionality is represented by the horizontal shade surfaces being totally off during the winter (i.e. solar radiation can enter the building) and being on during daytime in summer (solar radiation can't enter the building).

12.7.4 Solar absorption

In early versions of the simulation of the final design, a problem was encountered regarding the solar absorption. Solar absorption is the absorption of radiative solar heat by materials inside the zone. In a realistic situation, part of the solar radiation that enters a building through glazing is absorbed directly by the construction surfaces. The other part is not directly absorbed by these surfaces and warms up the indoor air. A correct balance between direct and indirect absorption is important for a representative result.

In the early model, the share of solar absorption was too high, resulting in non-realistic values. The figure below, shows the absorption of heat per surface of the zone.



This figure shows that the heat absorbed by the ground surface and the lower wall surfaces is too high. Analysis showed that this is the result of the single-zone modelling. The single zone model contains no indoor surfaces or object, resulting in all solar radiation directly beaming at the zone's surfaces. This then results in a too large solar radiation absorption by these surfaces.

To compensate for this, the solar absorption factor of the surface materials is decreased from 0.7 to 0.05. It is assumed that this is representative for the fact that inside walls, floors, furniture and furnishings decrease the share of direct solar radiation absorption.

12.7.5 Pre-heating and pre-cooling

The principle of pre-heating and pre-cooling was found to be one of the most effective solutions for energy-flatness. It considers increasing the heating setpoint when there is an energy surplus and lowering the cooling setpoint when there is an energy surplus. The simulation tool does not allow for adaptive heating and cooling setpoints based on the presence of supply. It does, however, allow for scheduled heating and cooling setpoints. Hence, to simulate the adaptive setpoints a manual iteration is made.

A simulation with a constant setpoint is run (19 for heating, 25 for cooling). Then, the hourly mismatch of this used as input for adapting the setpoints, which is done as follows. For every hour, the following script is used to create the new setpoint:

Heating

```
if y<-0.4:
    a = min(18,x-2)
elif y<-0.2:
    a = min(18,x-1)
elif-0.2<y<0.2:
    a = x
else:
    a = max(x+1,21)
```

Cooling

```
if y>0.8:
    a = max(22,x-2)
elif y>0.4:
    a = max(22,x-1)
elif -0.4<y<0.4:
    a = x
else:
    a = min(25,x+1)
```

In which

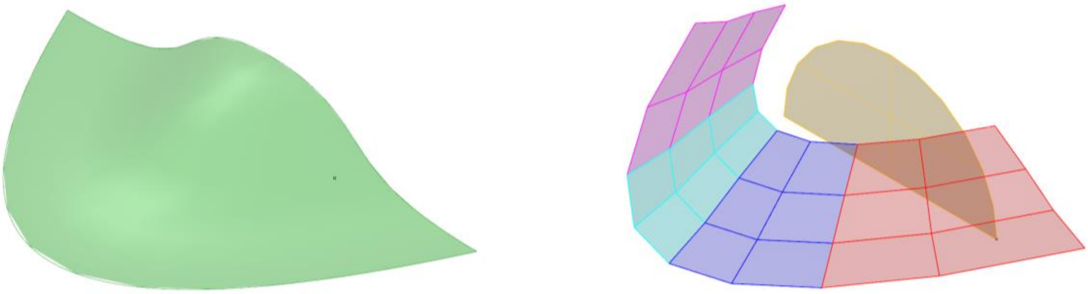
y = the mismatch of the first simulation
x = the previous setpoint
a = the new setpoint

This way, the setpoints are adapted to the supply surplus. The heating setpoint always stays between 18 and 21 and the cooling setpoint always is between 22 and 25. Because of these ranges, no moment will occur in which both the heating and cooling systems are triggered simultaneously.

The script as shown above is iterated a few times, so that the heating and cooling setpoints are adapted to the energy surplus.

12.7.6 Supply potential surface

In the reference situation, the supply surface was represented by the building surfaces of the design. In the final design, however, the zone boundaries are very different from the outer surface, because of a high amount of soil that is put on top of the building. The images below show the original surface shape, and the meshed supply potential shapes.



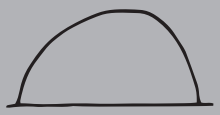
The outdoor sand surface (left) and the meshed supply potential surfaces (right)

For every surface, the total area and the total annual solar radiation is shown in the table below. N.B., the solar radiation is not equal to the supply. The right column shows the share of the solar radiation that is considered as useful supply. These shares are based on the parameter studies.

	Surface area [m^2]	**Share of solar radiation considered supply [-]**
South (orange)	80.5	0.005
West (red)	68.6	0.008
North-west (dark-blue)	45.9	0.007
Nort-east (light-blue	45.9	0.007
East (magenta)	68.6	0.008

12.8 Appendix 8: Design principles for energy-flat design

1. minimize A/V-ratio



a spherical shape has a relative low surface area compared to its volume

Strategic conservation

Load shifting

element ventilation, transmission

impact • • •

Functionality

a circular shape has a relative low surface area compared to its volume. The lower surface area reduces the transmission losses. The higher volume maximizes the internal air volume, which allows for a longer pause of ventilation and increased thermal mass.

Effect

- decreased heating load in winter, especially during the night when the outdoor temperature is low.

- relatively increased thermal mass for mitigating heating and cooling peaks

- diminished ability of losing superfluous heat by transmission, inducing a cooling load

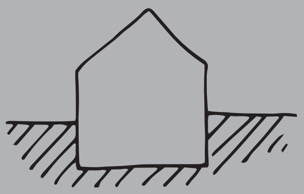
Technical

The reduction in skin surface results in a linear decrease of transmission. The energy saving potential of a higher volume depends on the ventilation rate.

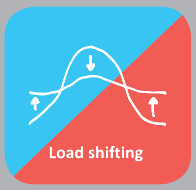
Considerations

1. This principle focuses on the lowest volume per skin area. In terms of usage, the usable floor area is in the case of dwellings often more important than the volume. Considering a consequent minimum floor height, a tube-like building might be more advantageous than a spherical building.

2. building lowered in ground



the grounds temperature is more constant than the outdoor temperarute



element transmission, storage

impact ● ●

Functionality

The ground floor of the building is lowered in the ground, which results in part of the facade being ‘underground’. Because the grounds temperature is more constant than the outdoor air temperature, the transmission losses change and storage is added.

Effect on energy profiles

- decreased heating load in winter, especially during the night when the outdoor temperature is low

- decreased cooling load in summer, because of improved ability to dispose superfluous heat.

- increased thermal mass for mitigating heating and cooling peaks

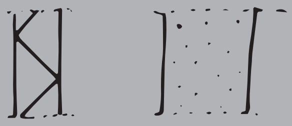
Technical

As a result of the thermal mass and conductivity of the top layer of our earth, the temperature of the ground is more constant than the outdoor air temperature. In the Netherlands, the average ground temperature is approximately 10 °C.

Considerations

1. In some cases, this principle may result in will result in higher heating or cooling losses. This is when the outdoor temperature is closer to the desired indoor temperature, than the ground temperature.
2. The location of the insulation in the detailling influences the effect of this principle.

3. choose the right insulation material



the insulative values of materials differ. A lower conductivity value results in higher insulation.

Strategic conservation

Strategic growth

element transmission

impact ● ●

Functionality

Every layer of a surface has certain insulating properties. Most often, in opage surfaces one layer is dedicated to insulation alone. Increased insulation results in a lower energy exchange between indoors and outdoors. The thickness and thermal conductivity of a layer both linearly influence the insulation respectively the transmission. This principles focuses on the thermal conductivity.

Effect on energy profiles

- decreased heating loads in winter as a result of lower transmission losses

- increased cooling loads in summer as a result of the disability to dispose superfluous heat

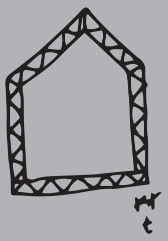
Technical

The thermal conductivity of modern insulation materials can be as low as 0.018 W/mK according to manufacturers (Kingspan Insulation Ltd, 2017). This considers non-natural materials. Most of these high-insulating materials have no air permeability, so their building physical effects should be considered.

Considerations

1. Having a very low thermal conductivity is only required when a bigger thickness is undesired. After all, theoretically every insulative value can be reached as long as the thickness is high enough.
2. High insulation values require extra attention in terms of humidity control.

4. thicken the insulation layer



the thickness of a material linearly affects its insulative performance.

Strategic conservation

Strategic growth

element transmission

impact • •

Functionality

Every layer of a surface has certain insulating properties. Most often, in opage surfaces one layer is dedicated to insulation alone. Increased insulation results in a lower energy exchange between indoors and outdoors. The thickness and thermal conductivity of a layer both linearly influence the insulation respectively the transmission. This principles focuses on the thickness

Effect on energy profiles

- decreased heating loads in winter as a result of lower transmission losses

- increased cooling loads in summer as a result of the disability to dispose superfluous heat

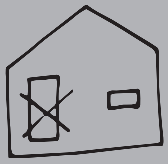
Considerations

1. Thick insulation layers result in thick walls. Thick walls influence the possibilities of passive solar gain. A thick wall may cast a shadow on a window.

2. Increasing the insulation value is not endlessly beneficial for energy-flatness. From a certain insulative performance, other energy flows become more significant relative to the transmission losses.

3. For energy-flatness, a dynamic insulation value would be most beneficial. This way, the disadvantage of insulation in terms of overheating in summer, would be compensated.

5. reduce the window share



windows have a relative low insulation value and negatively affect the average insulation.

element transmission, solar gain

impact ● ●

Functionality

Windows have a lower insulation value than opaque surfaces. Hence, they negatively influence the average insulation of the building. However, windows also allow for passive solar gain, which decreases when the window share drops.
A balance must be found between solar gain and improved insulation, but in general, the window share should be minimized on all orientations except the southern one in terms of energy-flatness.
Thisprinciple focusses on the benefits of reducing the window share.

Effect on energy profiles

- reduced heating load as a result of lower transmission losses (to some extent compensated by an increased heating load due to lower solar gain).

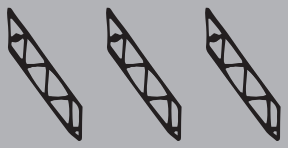
- increased cooling loads in summer as a result of the disability to dispose superfluous heat.

Considerations

1. The reduced window share is positive in terms of reduced transmission losses, but it results in a reduced solar gain. The right balance should be considered.

2. Windows have an architectural purpose (e.g. light, outsight) which should not suffer from energetic principles.

6. insulated blinds



the low insulation of windows is compensated by insulated blinds, at any time desired.

element transmission, solar gain

impact • • •

Functionality

The low insulation value of windows can be compensated by mounting blinds in front of it which have higher insulation values. Insulated blinds can be turned 'on' or 'off' dynamically, which allows for optimal adaptation to outdoor conditions. The downside is that the ability of the window to allow for light and solar radiation penetration vanishes. This principle focusses on the benefits of dynamically increasing the insulation of the windows.

Effect on energy profiles

- reduced heating load as a result of lower transmission losses through the window

- adaptive lowering heating or cooling load by closing the blinds

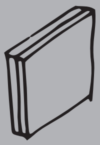
Technical

Building insulated blinds without any building physical problems is hard. Coldbridges and humidity problems must be prevented, while the blinds must withstand the outdoor conditions. The thickness of the blinds determines the insulation value. Thicker blinds, however, will be harder to install, harder to rotate and will block more of the sunlight.

Considerations

The design of insulated blinds should consider the effect on passive solar gain when the blinds are 'open'. The blinds will most probably cast as a shadow on the window or influence the architecture.

7. use HR++ glazing



triple glazing, low conductive gasses and reflective coatings can improve the insulation value of glass

element transmission, solar gain

impact •

Functionality

The relative low insulation value of windows can be compensated by applying HR++ glazing, which is glazing with a relatively high insulation value (up to a U-value of 0.9 W/m2K). The high insulation reduces heating losses.

Effects on energy profiles

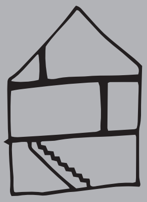
- reduced heating losses as a result of improved insulation

- depending on the specific type of glass; increased cooling loads because of increased insulation, or decreased cooling loads because of reduced solar gain by the reflective coatings of the glazing.

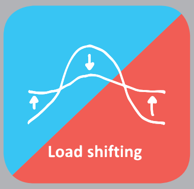
Considerations

1. Coatings affect both energy losses from inside to outside, but may negatively influence the solar radiation gain. So, the specific type of glazing used should be considered.

8. heavy indoor surfaces



making indoor surfaces from heavy materials increases the total amount of thermal mass



element storage

impact • •

Functionality

By choosing heavy materials for indoor wall- and floor surfaces, the thermal mass of the building is increased. Thermal mass allows for the temporal storage of thermal energy, hence mitigating temperature fluctuations. This results in a more stable heating and cooling demand.

Effects on energy profiles

- shifted loads as a result of temporal thermal energy storage

- peak clipping as a result of the slowed down heating up and cooling down of the zone

Technical

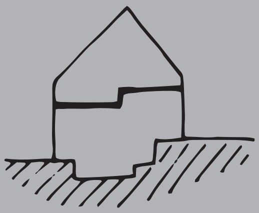
Heavy materials in this case relates to materials that have a high specific heat and a high conductivity (e.g. a high specific heat without a high conductivity is useless, for the heat will not be distracted from the space).

Examples of useful building materials are concrete and limestone.

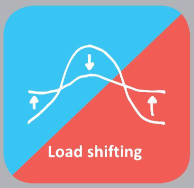
Considerations

The thickness of the heavy materials is important. Thermal energy takes time to enter a material, so the deeper the point in the material, the longer it takes to affect the flucutations. Practically, only the first 6 centimeters are effective within the scope of one day (N.B. depending on the material).

9. increase mass surface area



the surface area is often a bottleneck for thermal mass due to its slow thermal energy absorption



element transmission, storage

impact •

Functionality

The amount of energy that thermal mass can absorb at a time, depends on both its conductivity and its surface area. Most often, the speed of thermal absorption is such, that the surface area is the bottleneck. So, by increasing the surface area of the mass, the thermal mass is used more effectively.

Effects on energy profiles

- shifted loads as a result of temporal thermal energy storage

- peak clipping as a result of the slowed down heating up and cooling down of the zone

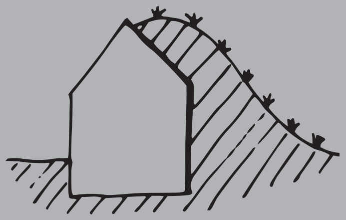
Technical

Increasing the surface area does not necessarily mean increasing the total amount of mass. By implementing more corners and edges, the area-to-volume ratio increases. This can be done by making concrete stairs or pit seating.

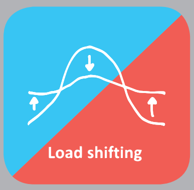
Considerations

Implementing many edges and level differences may increase the thermal mass surface area, but it may also cause inefficient architecture. For example, if a buildings level has to be much bigger due to some level differences, it might cause inefficiencies on other aspects that influence thermal mass.

10. build within earth and soil



a thick layer of earth is effective for mitigating peaks over longer periods.



element storage

impact • • •

Functionality

By covering a building with a layer of earth and soil, the thermal mass of the building greatly increases. Because the amount of thermal mass that is created by this measure, the earth will eventually achieve a more or less constant temperature.

Effects on energy profiles

- shifted loads as a result of temporal thermal energy storage. The shifting can eventually take up very long periods due to the high amount of (deep) thermal mass.

- peak clipping as a result of the slowed down heating up and cooling down of the zone

Technical

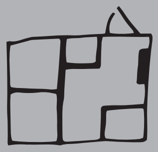
The thermal properties of earth and soil are not constant, due to humidity changes. The type of soil and the context should be considered.

It is also important to consider the location of the insulation. When the insulation is placed near the zones surface, the mass will significantly take the outdoor airs temperature. If the insulation is place in the top of the earth layer, the earth will take the the indoor airs temperature.

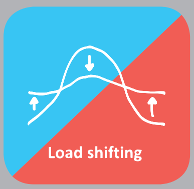
Considerations

Both construction and architure are subject by a layer of earth. It will not always be possible to apply this principle. In general goes; the more earth coverd surface there is, the better the mass works.

11. increase amount of surfaces



a bigger amount of indoor surfaces results in more thermal mass



element storage

impact •

Functionality

The amount of energy that thermal mass can absorb at a time, depends on both its conductivity and its surface area. Most often, the speed of thermal absorption is such, that the surface area is the bottleneck. So, by increasing the amount of indoor surfaces, the thermal mass is used more effectively.

Effects on energy profiles

- shifted loads as a result of temporal thermal energy storage

- peak clipping as a result of the slowed down heating up and cooling down of the zone

Technical

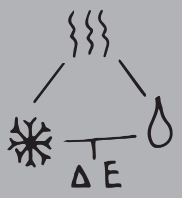
Increasing the surface area does not necessarily mean increasing the total amount of mass. By implementing more corners and edges, the area-to-volume ratio increases. This can be done by making concrete stairs or pit seating.

Considerations

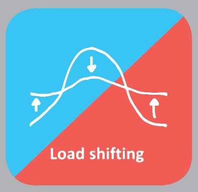
1. Increasing the amount of surfaces may affect the zoning of the building, which might result in more internal temperature differences, resulting in a worse functionality of the mass in these sub-zones.

2. The thickness of the surfaces is important for the functionality of the thermal mass. Thick massing results in load shifting over longer periods, whilst thinner mass will be effective in smaller time intervals.

12. use PCM (Phase Change Materials)



PCM's have a high thermal energy storage density and can be most effective on desired temperatures.



element storage

impact ● ●

Functionality

PCM is a form of laten thermal energy storage. Due to a phase change at a favourable temperature (e.g. 20 °C), it withdraws or deposits a large amount of energy in this phase change. The major difference compared to sensible thermal energy storage (i.e. thermal mass) is the higher energy storage density.

Effects on energy profiles

- shifted loads as a result of temporal thermal energy storage. This shift of loads only occurs when the PCM's phase change material is reached.

- peak clipping as a result of the slowed down heating up and cooling down of the zone. This clipping only occurs at the PCM's phase change temperature.

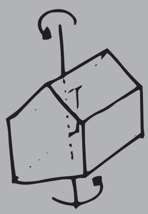
Technical

Several types of PCM's exist. Different types have different densities, latent heat capacities and different. Similar to sensible thermal energy storage, the bottleneck for PCM's is its surface area. Measures should be taken to increase the surface area, or to increase the speed at which it can conduct energy (e.g. by increasing the air speed along it).

Considerations

PCM is only an effective thermal energy storage at its phase changing temperature. In other temperatures, it does not compete with other 'typical' mass. A combination of thermal mass and PCM should be considered.

13. building that can rotate



a building that is able to rate can orient itself towards the sun when desired. A rotating building is a technical challenge


Strategic conservation


Peak Clipping


Valley filling

element solar gain

impact ● ● ●

Functionality

The sun is the source of passive solar gain for a building, and can highly influence the additional thermal energy demand. In summer, however, it can also overheat the building. A rotational building allows for an adaptive switching between solar gain and solar blocking. A building that can rotate is technically hard to realize and not possible in most locations.

Effects on energy profiles

- reduced heating load during daytime by increasing the share of solar gain

- peak clipping the cooling load, by turning the back (i.e. non-solar gaining surface) of the building towards the sun

- valley villing by tactically gaining more or less passive solar heat in times it is desired.

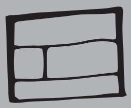
Technical

Examples of rotational buildings exist, but often it is hard to accomplish due to the great weight and size of a building. Moreover, connections to the earth should be adapted to the movement. A feasible solution is building on water, in which the rotation is easier.

Considerations

Rotation to block passive solar gain, might negatively effect the orientation of supply elements (e.g. PV)

14. tactical zoning



functional zoning in relation to building orientation, may result in higher comfort and lower energy demand

element solar gain, transmission, ventilation

impact ● ●

Functionality

A dwelling has different rooms, which have different demands on terms of comfort, like temperature and ventilation. Tactical zoning means that the location of the rooms in relation to each other and in relation to the orientation of the building, is based on these temperature and ventilation demands.

Effects on energy profiles

- reduced heating loads as a result of a smaller space to keep within certain temperature ranges or air quality.

- a slightly more flexible load shape, because less energy is required to manage the comfort in the building

Technical

In most examples of tactical zoning in the temperate climate, the liveable zones are oriented to the south because these generally have higher temperatures as a result of solar gain. Less frequently used rooms (e.g. storage, technical room) are located near each other.

Considerations

Tactical zoning has a high relation to the geometry and orientation of the building. It might influence the placement of windows and shapes of facades. Moreover, it affects the logistics of a building.

15. radiative heating

radiative heating can compensate for lower air temperature, and is more energy-efficient

Strategic conservation

element	transmission, ventilation, infiltration
impact	•

Functionality

The operative temperature is a combination of the air temperature and the radiative heat present. In that line, radiative heat can compensate for a lower air temperature. Moreover, radiative heat is a more efficient way of bringing heat from the source to the receiver (i.e. human). The lower air temperature results in a reduction of heating energy, because a lower ΔT results in a lower energy flow for transmission, infiltration and ventilation.

Effects on energy profiles

- reduced heating load as a result of lower indoor air temperature

Technical

The operative temperature is calculated as follows:

$$t_o = \frac{(h_r t_{mr} + h_c t_a)}{h_r + h_c}$$

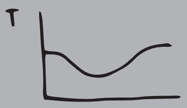
where,

h_c = convective heat transfer coefficient
h_r = linear radiative heat transfer coefficient
t_a = air temperature
t_{mr} = mean radiant temperature

Considerations

Maintaining thermal comfort is an essential functionality of a building.
The downside of radiative heating is that it has a direction. That means that radiative elements should also be direct towards the receiver (i.e. inhabitants) and that it will only heat the side of the receiver that is oriented to the radiative element.

16. adaptive thermal comfort



studies have shown that lower indoor temperatures are accepted in times of lower outdoor temperatures.

element transmission, ventilation, infiltration

impact ● ●

Functionality

To maintain the desired indoor comfort, certain heating and cooling setpoints are assumed by most standards. These setpoints, however, are constant all year and studies have shown them to be not representative for an actual comfortable temperature. Adaptive thermal comfort relies on the seasonal changes in comfortable indoor temperatures based on the running mean outdoor temperature. This means a lower heating setpoint in winter and higher cooling setpoint in summer.

Effects on energy profiles

- reduced heating loads and reduced cooling loads as a result of lower differences between the indoor air temperature and outdoor temeprature.

- a slightly more flexible load shape, because less energy is required to manage the comfort in the building

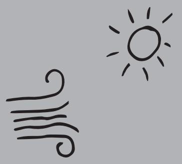
Technical

The adaptive thermal comfort studies regard changes in thermal comfort over the season. It might be interesting to also have adaptive thermal comfort within the timeframe of one day, so energy can be saved during the night, in favour of energy-flatness.

Considerations

The adaptive thermal comfort might be combined with radiative heating for even better energy-flat performance.

17. comfort by air velocity



similar to radiative heating, a higher cooling setpoint can be compensated by higher air velocities

element	transmission, ventilation, infiltration
impact	•

Functionality

Thermal comfort is not only determined by the indoor air temperature. In times of high indoor temperatures, an increased air velocity can imprrove thermal comfort. Hence, similar to radiative heat does for heating, an increased air velocity can allow for maintaining comfort at higher indoor temperatures. The higher temperature results in a reduction of heating energy, because a lower ΔT results in a lower energy flow for transmission, infiltration and ventilation.

Effects on energy profiles

- reduced cooling load as a result of lower indoor air temperature

- peak clipping by temporarily allowing high temperatures whilst compensating it with moving air

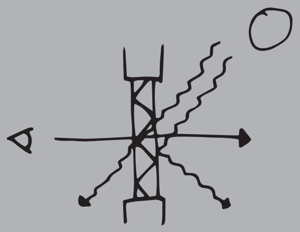
Technical

Air velocity might also cause discomfort. This occurs when the air velocity is too high. Moreover, the creation of moving air in a space is hard to control and may often require energy by itself. A right balance between energy savings and thermal comfort should be found.

Considerations

Maintaining thermal comfort is an essential functionality of a building.

18. utopian window



ideally, a window has a high insulation value, allows for visual transmittance and can toggle solar radiation gain

Strategic conservation

Peak Clipping

element transmission, solar gain

impact ● ● ●

Functionality

This principle is rather a wish than a practically applicable principle. The window plays an important role in the heat balance and energy-flat performance of a building, based on its solar transmitting properties as well as its low insulation value. Ideally, the insulation of the window is as high as an opaque wall, resulting in lower heating losses. Simultaneously, it should have the property to switch between high transmittance of passive solar gain and low transmittance. This way, the window becomes an adaptive energy gainer, without having the downside of low insulation.

Effects on energy profiles

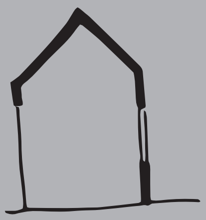
- reduced heating loads because of improved insulation and increased passive solar gain in times it is desired

- reduced cooling loads by blocking passive solar gain when it is not desired. This also may be used as peak clipping, by only blocking solar gain in times of high solar gain peaks

Technical

This principle is not practically executable yet. The highest possible insulation for transparent windows is around 1.0 W/m2K. Higher insulation while maintaining transparency is possible using Aerogel, which has a of 0.013 W/mK. This,however, blocks the passive solar gain, let alone creating the possibility to switch this on and off.

19. different window types



On south, high g-values are desired for solar radiation gain. On north, high insulation is more important.

Strategic conservation

element	transmission, solar gain
impact	•

Functionality

On different orientations, different solar gains are possible. In all cases, high insulation is desired. However, high insulative windows often have a lower g-value resulting in lower passive solar gain. To have best of both worlds, it is most beneficial to select different window types based on the orientation of the window. This way, high insulated (and low solar gaining) windows are placed on northern orientations, and more solar gaining windows (which insulate less) are placed on southern directions.

Effects on energy profiles

- reduced heating loads as a result of higher solar gain and improved isulation

Technical

Most windows have improved insulation values by invisible reflective coatings. These coatings block a selective share of the light spectrum, namely the share of infrared heat radiation. This way, heat radiation from outside is blocked. A result is that also heat radiation from the inside is blocked. The location of the coating (i.e. on the inner or outer window pane) affects the performance of the window, by either creating a hot air cavity in winter (i.e. coating on inner pane) or a cold air cavity in summer (i.e. coating on outer pane)

Considerations

The exact placement of a window type will result from simulations

20. high south window share

larger windows on the south side are effective for low heating loads. On the north, windows are undesired.

Strategic conservation

Strategic growth

element transmission, solar gain

impact • •

Functionality

Energy-flatness studies showed that large windows on the south side result in lowered heating loads, as a result of the passive solar gain. On the northern orientations, windows do not benefit from this passive solar gain in winter; because the day is short and the solar power on the non-south orientations is weak. Windows on these orientations, however, do have the disadvantage of low insulation. That is window share on northern sides must be minimized, and share on southern sides must be maximized

Effects on energy profiles

- reduced heating loads because of increased passive solar gain in times it is desired

- if no shades are used, a large southern window results in a high cooling load due to too much passive solar gain

Technical

Both the latitude and solar power are different in winter and summer. Solar gain calculations should be done to determine the right window share on the south side; after all, a too large window may result in big fluctuations in energy flow (e.g. big losses at night due to low insulation and too big gains during the day by solar gain)

Considerations

Overheating in summer may be compensated using shades

21. adaptive sunshading

rotating sunshades allow to block solar radiation when undesired, and to let it in when it is desired

Strategic conservation

Peak Clipping

element solar gain

impact • • •

Functionality

Passive solar gain is the result of solar radiation. Big windows to allow this radiation to enter the building are nice in winter, but may cause overheating in summer. Sunshading is a solution, but this often finds a balance between blocking radiation in summer and letting it in in winter. Adaptive sunshading changes between solar gain and solar blocking by rotating opaque elements away from or towards the sun.

Effects on energy profiles

- reduced cooling loads by blocking solar radiation when it is desired, while maintaining solar radiation benefits inw inter

- reduced peak cooling loads, by only blocking solar radiation in times of peak power.

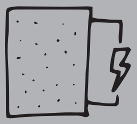
Technical

To let adaptive sunshades contribute to energy-flatness, it would be beneficial to have a smart system that controls the shades. This can either move them towards the sun, when heat is desired, or block the sun, when coldness is desired.

Considerations

The design of the adaptive blinds should consider the effect of the blinds on passive solar gain when the blinds are 'open'. The blinds won't 'disappear' and thus they will most probably cast as a shadow on the window or influence the architecture.

22. electrochromic glazing



this modern technique changes the g-value of a window by an electric current, being in adaptive sunshading.

Strategic conservation

Peak Clipping

element transmission, solar gain

impact ● ●

Functionality

Electrochromic glazing (a.k.a smart glass) is a modern technique in which the transparanency of a window is changed when a voltage is applied. The changed transparency results different window properties, including a lower g-value. This change in g-value is completely integrated in the window, meaning that no additional elements on the facade are required. Moreover, the switch between transparent and opaque can be made within seconds, allowing for high adaptivity.

Effects on energy profiles

- educed cooling loads by blocking solar radiation when it is desired, while maintaining solar radiation benefits in winter

- reduced peak cooling loads, by only blocking solar radiation in times of peak power.

Technical

Electrochromic glazing is a very recent technology. It is still expensive and probably not practically possible to build a complete house with it. Maximum sizes currently are around 1.5m x 3.0m.

Considerations

Electrochromic only affects the transparency of a window, it does not affect its insulation properties.

23. horizontal shading

horizontal shading uses the latitude difference of the seasons, blocking solar in summer and gaining it in winter.

Strategic conservation

Peak Clipping

element solar gain

impact • • •

Functionality

Passive solar gain is the result of solar radiation. Big windows to allow this radiation to enter the building are nice in winter, but may cause overheating in summer. Sunshading is a solution, but this often finds a balance between blocking radiation in summer and letting it in in winter. Adaptive sunshading changes between solar gain and solar blocking by rotating opaque elements away from or towards the sun.

Effects on energy profiles

- reduced cooling loads by blocking solar radiation when it is desired, while maintaining solar radiation benefits inw inter

- reduced peak cooling loads, by only blocking solar radiation in times of peak power.

Technical

To let adaptive sunshades contribute to energy-flatness, it would be beneficial to have a smart system that controls the shades. This can either move them towards the sun, when heat is desired, or block the sun, when coldness is desired.

Considerations

The design of the adaptive blinds should consider the effect of the blinds on passive solar gain when the blinds are ‘open’. The blinds won’t ‘disappear’ and thus they will most probably cast as a shadow on the window or influence the architecture.

24. natural ventilation

natural ventilation uses pressure differences to drive air and so requires no additional electrical energy

Strategic conservation

element	electriciy demand
impact	•

Functionality

Natural ventilation makes use of pressure differences to drive the air. This way, no additional energy is required to move the air. The pressure differences are created by both height differences of openings and wind pressure differences. For energy-flatness, natural ventilation can be a solution at night, when there is no energy available. In that sense, it does not influence the heat balance itself, but mostly affects the electricity balance.

Effects on energy profiles

natural ventilation (compared to mechanical ventilation) does not directly influence the heat balance. It influences the electricity balance, by reducing energy required for ventilation.

- the electricity demand for ventilation is highly reduced.

Technical

The pressure differences as a result of differing heights of openings and different external wind pressures, are only high enough when the openings have a high spacing between them.

Considerations

One major consideration for natural ventilation is the lack of controlability; the ventilation rate can not be precisely determined. Moreover, it almost always requires an additional mechanical ventilation system for optimal reliance.

25. night ventilation

in summer the relative cold nights can be used to cool the building to reduce the cooling load in daytime

Strategic conservation

Peak Clipping

element ventilation, storage

impact • • •

Functionality

The main concept of night ventilation is to improve ventilation rates during summer nights, to withdraw superfluous heat from a building. Inherently, a requirement for this ventilation strategy is a certain amount of thermal mass. The energy reduction by night ventilation depends on the temperature difference between day and night, the amount of thermal mass and the rate of ventilation. This concept works especially good for modern, high-insulated buildings, which often have the problem of the incapability of disposing superluous heat.

Effects on energy profiles

- reduced cooling loads during day and nighttime by using the outdoor air temperature in summer nights

- reduced peak cooling loads, by having a pre-cooled building at night

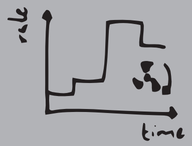
Technical

Night ventilation works most effective of all of a buildings air is exchanged. This means that closed rooms with little ventilation, can decrease the effect of night ventilation. For optimal performance, an inclusive ventilation strategy should be found.

Considerations

Because this principle depends on the nocturnal outdoor air temperature, it can not always be relied upon. It is therefore a means to reduce cooling load, not to solve it.

26. adaptive ventilation rate



adapting the airflow based on the temperature difference and supply profile results in a better match

Strategic conservation

Load shifting

element ventilation, storage

impact ● ● ●

Functionality

By having an adaptive ventilation rate, which means a different airflow depending on the time of the day, the heatlosses or gains can be shifted. Energy losses by ventilation are relatively high in a well-insulated building, and are linearly depended on the air volume exchange. By having an adaptive air flow rate, there is an adaptive energy loss. This way, the largest losses can be shifted to times that the ΔT of the indoor and outdoor air temperature is minimal.

Effects on energy profiles

- a reduced heat load by moving the highest air flow rate to times with a lower ΔT.

- a shifted load, because the total amount of fresh air should remain constant

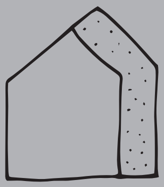
Technical

An adaptive ventilation rate requires a mechanical ventilation system. This could also control which rooms should be ventilated, this could be combined with the principle of zoning, as explained earlier.

Considerations

A comfortable indoor air quality should always be remained. This means that the rate can not be shifted too much. One elemental factor in this, is the total amount of air available in a room. A larger volume results in a larger ability to 'pause' the ventilation. This, however, contradicts with most principles that aim to reduce the heat load by smaller geometry.

27. extra volume



extra volume to store fresh air allows for temporal ventilation stop in times of no supply.

Strategic conservation

Load shifting

element ventilation, storage

impact ●

Functionality

This principle strongly relates to the principle of adaptive ventilation rate. An adaptive ventilation rate results in a shift of heating and cooling loads, by changing the timing of air exchange between indoors and outdoors. Because a comfortable indoor air quality should alway be remained, the ventilation can only be shifted for a limited time. Increasing the volume of a building, increases this time and so the potential to save energy

Effects on energy profiles

- a reduced heat load by moving the highest air flow rate to times with a lower ΔT for a longer period

- a shifted load, because the total amount of fresh air should remain constant

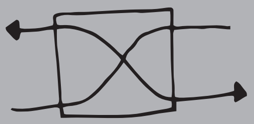
Technical

The energy saved with this principle depends on the heat-exchange efficiency of the ventilation system.

Considerations

1. Increasing the volume results in larger surfaces, which is disadvantageous. Solutions should be found in which the volume is increased, but the downside of larger energy losing surfaces is compensated
2. How long the ventilation can be stopped, depends on the number of inhabitants and their activity. It would be best to include sensors in the system, that measure the air quality and adapt the rate based on this data.

28. ventilation heat exchanger



a heat exchange system use the energy from exhaust air to preheat or precool the supply air, resulting in a lower demand

Strategic conservation

element ventilation

impact ● ●

Functionality

A ventilation heat exchanger, also known as ventilation heat recovery, is commonly used in modern buildings. A heat exchanger exchanges the heat (or coolth) from the exhaust air with the inlet air, thereby pre-heating or pre-cooling the air. The heat exchanger reduces the amount of energy that is lost with ventilation air. A boundary condition is that the inlet-airflow and exhaust-airflow cross each other, often resulting in a system that has complete mechanical ventilation.

Effects on energy profiles

- a reduced heat load in winter by moving energy from the exhaust air back to the air inlet

- a reduced cooling load in summer by extracting energy from the inlet air by using the low temperature of the exhaust air

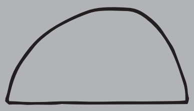
Technical

A heat exchanger becomes especially effective in well-insulated buildings, because ventilation energy losses are significant in these buildings. The efficiency of a heat exhanger depends on many factors, but in general ranges from 50 - 99 %.

Considerations

Heat exchange ventilation can not be combined with most natural ventilation principles, because the inlet and outlet air have to cross.

29. homogenous & few corners



a more homogeneous construction with fewer corners results in less seams that are vulnerable for infiltration

Strategic conservation

element infiltration

impact •

Functionality

A homogenous building with few corners has less gaps and seams, hence diminishes the amount of infiltration losses. Infiltration lossese should be prevented at all times, because they can not be controlled and inevitably result in unwanted energy losses. Almost every connection between two or more materials or surfaces results in an air leakage and infiltration, hence the idea is to reduce the total length of these connections

Effects on energy profiles

- a reduced heat load by having less uncontrolled air flow

- a reduced cooling load by having less uncontrolled air flow

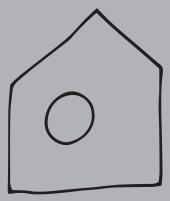
Technical

The amount of energy lost depends highly on the pressure differences between indoors and outdoors. Some spots in a building might be more vulnerable to infiltration than others. This idea, might contribute in effectively choosing where to minimize seams and gaps.

Considerations

The illustration on the left shows a bowl shape. This theoretically has fewer connections. However, shapes by which the connections become more complex hence more vulnerable to air leakages, should be prevented.

30. high surface/ seam ratio



a higher ratio results in a lower seam length. It can be achieved by circular windows or having fewer separate windows

Strategic conservation

element infiltration

impact ●

Functionality

Every building has seams caused by different surfaces nearing each other. A high surface/seam-ratio works similar to the principle of "homogeneous building & few corners", it diminishes infiltration losses. Infiltration losses should be prevented at all times, because they can not be controlled and inevitably result in unwanted energy losses. Almost every connection between two or more surfaces results in an air leakage and infiltration, hence the idea is to reduce the total length of these connections

Effects on energy profiles

- a reduced heat load by having less uncontrolled air flow

- a reduced cooling load by having less uncontrolled air flow

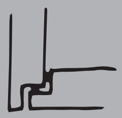
Technical

The amount of energy lost depends highly on the pressure differences between indoors and outdoors. Some spots in a building might be more vulnerable to infiltration than others. This idea, might contribute in effectively choosing where to minimize seams and gaps.

Considerations

Shapes that might have a higher surface/seam-ratio, but by which the connections become more complex hence more vulnerable to air leakages, should be prevented.

31. choose right materials



some materials allow for better airtightness detailling than others. Smart selection improves the airtightness

Strategic conservation

element infiltration

impact •

Functionality

Seams and gaps are inevitable. However, infiltration losses should be prevented at all times, because they can not be controlled and inevitably result in unwanted energy losses. By choosing materials that allow for airtight detailling, infiltration losses can be diminished.

Effects on energy profiles

- a reduced heat load by having less uncontrolled air flow

- a reduced cooling load by having less uncontrolled air flow

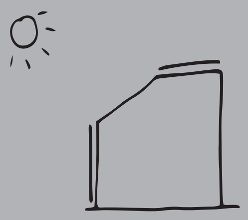
Technical

The amount of energy lost depends highly on the pressure differences between indoors and outdoors. Some spots in a building might be more vulnerable to infiltration than others.

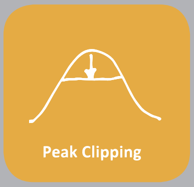
Considerations

The significancy of reducing infiltration losses depends on the quality and share of other energy losses. As the transmission and ventilation losses of a building are reduced, by improved insulation and heat-exchange for example, reducing infiltration becomes more important as well. In that line, a right balance must always be considered and airtightness should not be overdone.

32. horizontal supply surfaces



horizontal elements thave a higher share of diffuse radiation.Vertical supply on the south as well.



element supply potential

impact ● ●

Functionality

The energy-flatness studies had shown that a more stable supply is desired. Northern or horizontal supply surfaces depend on a higher share of indirect radiation. Indirect radiation is less strong than direct radiation, but its power is much more constant. The power difference between summer and winter is smaller, and also the power difference between cloudy and clear days. This more constant power prevents extreme supply surpluses.

Effects on energy profiles

- peak supply potentials are diminished, because the supply elements depend more on the constant, indirect radiation

- in the early morning and late evening, there might be a slightly higher power due to elements that are optimized for more indirect radiation.

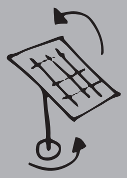
Technical

In current technologies, amorphous solar panels have proven to make the most effective use of indirect solar power. Their total efficiency is lower than other types of PV (e.g. poly-crystalline)

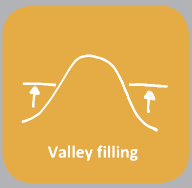
Considerations

The lower power that is gained by focussing on northern and horizontal surfaces, creates a dilemma; the PV would produce more energy in its lifetime if oriented straight to the south. Does this approach outweigh this un-used solar potential?

33. freely orientable supply



a system that is able to change the orientation of the supply elements can adapt to high and low supply demands.



element supply potential

impact • • •

Functionality

Obviously, the sun's path is different every day and the more directly a solar element is oriented to the sun, the higher its potential. So, elements that are movable and can always rotate towards the sun will have the highest yield. Another benefit of freely orientable supply elements is that, if required, it can also be oriented away from the sun, to reduce supply surplus.

Effects on energy profiles

- an increased total solar yield due to more efficient use of the solar potential surface

- valley filling as a result of effective orientation

Technical

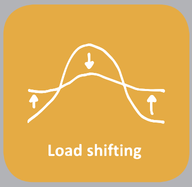
Freely orientable supply might be a mechanical challenge. Especially when it comes to a large share of surfaces. Moreover, it most probably results in the elements being hard to integrate in the architectures surfaces.

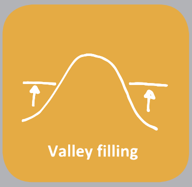
Considerations

Energy-flatness studies have shown that the highest annual yield, leads to big surpluses. In that sense, the freely orientable elements are mostly beneficial because on can choose whether to make most effectively use of the solar potential, or completely neglect it. However, actively blocking solar potential creates the dilemma as explained in the previous principle.

34. wind or other RES

using other renewable energy sources results in potential supply in times of little solar, for example during nighttime





element supply potential

impact • • •

Functionality

In the energy-flatness studies of this research, only solar was considered a supply potential. The main challenge was the lower solar power in winter and the lack of solar power at night. By using wind, or other renewable energy supplies, the intermittencies of the supply are dependent on other factors, and thus they will have a different supply potential. Wind is known to have higher potential in winter, which is desirably opposite to the seasonal potential of the sun

Effects on energy profiles

- shifted loads because the total supply power is distributed over different supply systems, which have different intermittencies

- valley filling by implementing supply sources that are active in times of low solar potential

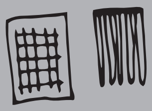
Technical

One of the reasons that solar power is the most commonly used renewable energy source in the residential context, is that it is easy to install and can be cost-effective at small scales. Although new developments are entering the market, it is harder to effectively generate wind energy in the residential context.

Considerations

It must always be considered whether local RES is more effective than centralized RES.

35. combine PV and solar collectors



depending on the demand, either PV or solar collectors can be a more effective way to fulfill the demand.

Strategic growth

Strategic conservation

element supply potential

impact ● ●

Functionality

Photovoltaic elements generate electricity from the suns power and solar collectors collect heat from the suns power. Depending on the type of demand, either solar collectors or PV can be more effective. Tactically combining these technologies might results in a more effective match of supply and demand.

Effects on energy profiles

- an increased total solar yield due to more effective use of the supply potential surface

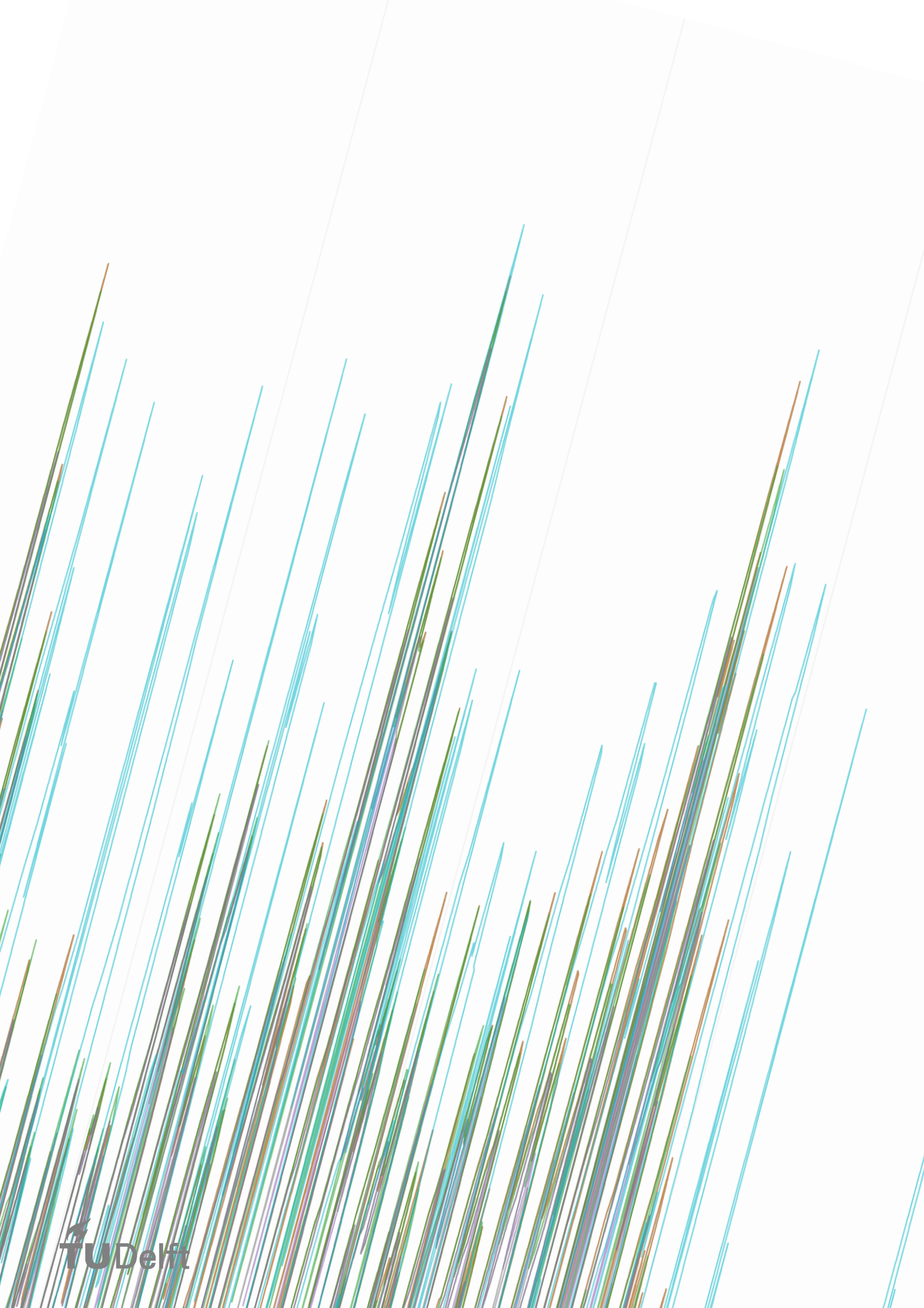
- a reduced heating shortage by generating a more effective match

Technical

The efficiencies of modern photovoltaic solar panels can be up to 20%. The efficiency of solar collectors can be up to 80%. In that sense, the solar collectors make more effective use of solar radiation. However, electricity can be used for much more different purposes. Cooling, for example, can not be created using solar collectors.

Considerations

In the energy-flat design studies, it was shown that using only photovoltaics was more effective that using a combination of PV and SC. This is because the design was optimized such that a high cooling load was accepted in summer to minimize supply surpluses.



TU Delft