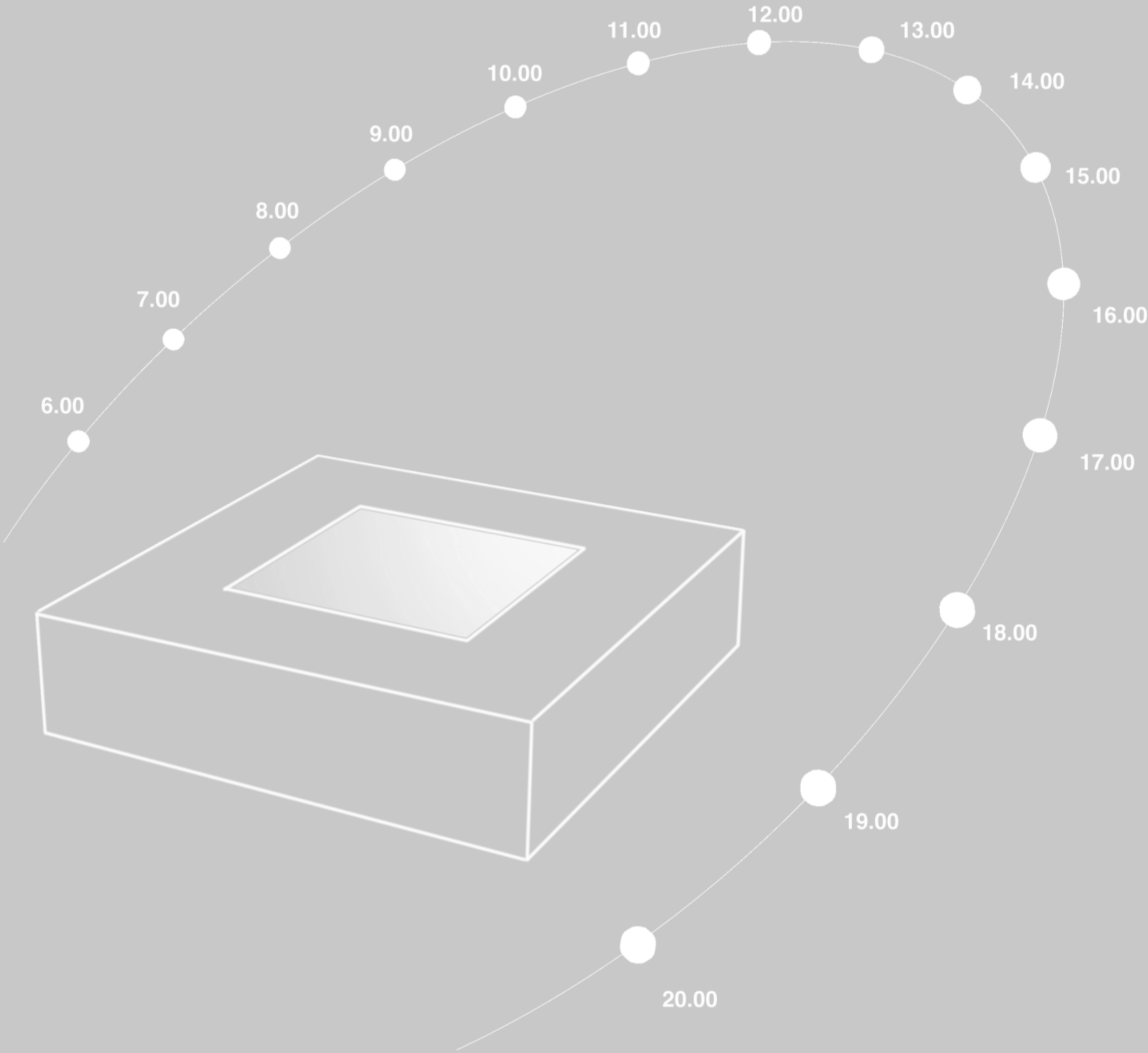
# The use of solar cells to produce energy and enhance the internal comfort of large glazed spaces




by Milan Voorhorst

# Personal information

| | |
|---|---|
| Name | M.T. (Milan) Voorhorst |
| Student Number | 4158342 |

# Studio

| | | |
|---|---|---|
| Faculty | Architecture and the Built Environment | |
| Track | MSc Building Technology:<br>Sustainable Design Graduation Studio | |
| Mentors | Arie Bergsma | (façade) |
| | Eric van den Ham | (climate) |
| Guest mentor | Barbara van Gelder | (Octatube) |
| Delegate of the Board of Examiners | Hans Wamelink | |
| Annotation Technology in Sustainable Development | Yes | |
| Version | P5: 2т June 2017 | |

---

This thesis is also available digitally at: www.repository.tudelft.nl

# Acknowledgments

During an eight months of research, I learnt a lot. I could not have done this without the help of many people who supported me both content-wise and off-topic.

First, thank you Arie Bergsma. Your clear vision and guidance helped me a lot. You inspired me to look at the subject from a broader perspective and get more out of it. Second, my other mentor Eric van den Ham. Thank you for your support and overview in the process. You were always eager to help me and tell when to dive deeper or when to stop.

Thank you Octatube for giving me the opportunity to collaborate with you. Special thanks to Barbara van Gelder who guided me intensely throughout the process. Your vision kept me constantly on the right track. Furthermore, everyone from Octatube, thank you for your interest and the good atmosphere.

Last but not least, I thank my family and friends. I really appreciate all the help and support, also financially, that you gave me during my graduation and rest of my study. Thank you Wessel for your time and Arne for your comments and improvements. Silke, thank you for the patience and understanding.

Milan Voorhorst

Delft, June 2017

# Summary

A transition from non-renewable energy to energy from renewable resources is required, the building industry consumes a significant part of the globally consumed energy. This thesis considers thermal comfort and energy production, on the building scale. The focus is on large glazed spaces. There is a trend in architecture to go as transparent as possible. However, more transparency leads to a growing heat gain. Thus, in order to keep a comfortable climate the cooling load will increase.

Different types of large glazed spaces are distinguished, based on dimension, shape and grid distribution for example. Then, a study of the characteristics of sun and sunlight is conducted. Sun heats a glass space, magnified by the greenhouse effect. The solar transmittance factor determines what percentage of solar radiation is transmitted by the building skin. The internal heat and temperature of a large glazed space is elaborated on. The dynamic temperature calculation method from standard ISO 1379:2008 is used for calculations in the analyses part. The most important parameters to control the internal temperature as a designer, are ventilation and shading. Stack ventilation is considered for the calculations since it does not require any (additional) energy.

To prevent heat gain in large glazed spaces, photovoltaic (PV) cells as shading are studied. With this approach, cooling load is reduced and energy produced, simultaneously. The current application of PV cells is not integrated effectively often. Also, the most used PV cells, mono crystalline silicon solar cells, are expensive and production requires much energy. The electrical yield depends on how PV cells are orientated and if surrounding objects shade the layout. New techniques like thin film technologies, dye-sensitized solar cells and organic PV tend to be less dependent on orientation. Also, new PV types are typically thinner, have low production energy and are easier to produce, when compared to regular crystalline silicon solar cells. However, the conversion efficiency of emerging techniques is generally lower.

Currently, designers only get visual feedback on what they make themselves. When the conceptual design is finished, it may be analysed by a consultancy agency. Small adjustments can be made, but fundamental design decisions cannot be reversed. With the analysis tool developed within this thesis, you get feedback on your design decisions in an early stage of development. You can test the behaviour of temperature and yield of PV cells on rudimentary shapes on temperature behaviour and yield of PV. Later in the engineering phase, this tool can also be used for numerical analyses. The parametric model is made in "*Grasshopper*" (for "*Rhinoceros*"), with plug-ins "Ladybug" and "*Honeybee*". These plug-ins use actual weather data from EnergyPlus. Any building geometry can be put into the model, and the hourly internal temperature (on any time of the year) can be calculated. With this model, the yield of the PV cells can also be determined. To see the significance of each parameter in the temperature calculation sheet, test data is acquired and results presented. The most important variable parameter in this thesis is the solar transmittance factor. Furthermore, the model can be used to

analyse the effect of shading on PV cells. It is not possible to cool a space sufficiently with energy that is produced by PV cells at that same moment. Test cases are conducted to show the potential of the developed analysis tool and to validate results. The PV-yield of the developed model has an error margin of about 15%, validated with actual retrieved data. With the tool, both qualitative (visual) and quantitative (numerical) feedback on radiation levels, inside temperatures and energy production of the design input are retrieved.

The last part covers a design manual for the application of PV cells in the transparent skin of large glazed spaces. Three design examples are presented, using the step-by-step morphological design overview that has been developed. To design a roof of a glazed space, all scales should be considered, from macro (geometry) to micro (panel) level. In the first two designs, conventional PV cells are used, but in an unconventional design. Respectively, thin film and crystalline silicon PV cells are applied in the first and second design. Both designs have a maximum temperature (on a summer day) decrease of 3 to 4 $^{o}$C compared to the same design without PV. However, both designs have a significantly different annual energy production. This is mainly due to the different type of PV, but panel orientation influences energy production as well. Designing with PV cells will get less delicate in terms of orientation and cost, since new PV cell types/PV materials will get cheaper and less dependent on orientation. The third design presents a future vision on what could be made with new printing techniques using dye-sensitized solar cells. Design freedom is obtained since colours, opacity and shape can be varied with this new type of solar cells. They offer new opportunities for designers able to use solar cells integrated in the building skin, both from an architecturally and energetic perspective. Since each design scale has multiple, contrary in and outputs (qualitative and quantitative). Such a design is a reasoning between those in- and outputs, there is no ‘best’ outcome.

# Abbreviations and symbols

| | |
|---|---|
| a-Si | Amorphous silicon |
| BAPV | Building added photovoltaics |
| BIPV | Building integrated photovoltaics |
| BoS | Balance of system |
| CdTe | Cadmium telluride |
| CIGS | Copper indium gallium selenide |
| DSSC | Dye sensitized solar cell |
| EPW | Energy plus weather file |
| GaAs | Gallium arsenide |
| lm | Lumen |
| LSC | Luminescent solar concentrator |
| lx | Lux |
| m-Si | Microcrystalline silicon |
| OPV | Organic photovoltaic |
| PMV | Predicted mean vote |
| PSC | Perovskite solar cells |
| PV | Photovoltaic |
| QDSC | Quantum dots solar cells |
| STC | Standard test conditions |
| STF | Solar transmittance factor |
| Wp | Watt-peak |

# List of definitions

*Light, Energy and PV*

| | |
|---|---|
| *Absorption* | Portion of solar irradiance which is absorbed (in Watt or a ratio) |
| *Illuminance* | The actual brightness of light on a surface $lm/m^2$=lux |
| *Insolation* | Amount of energy from solar irradiance that radiates a certain area ($Wh/m^2$) |
| *Irradiance (G)* | Power of light as received on a surface ($W/m^2$) |

| | |
|---|---|
| *Joule* | General unit for energy (J or Ws) |
| *Kilowatt-hour (kWh)* | General unit used for ‘amount’ of energy. Mostly used on building scale. 1000 Wh = 3.6 MJ |
| *Luminance* | ‘Brightness’ experienced by a perceiver (independent of distance) ($cd/m^2$) |
| *Reflection* | Portion of solar irradiance which is reflected (in Watt or a factor) |
| *Solar irradiance* | See *insolation* |
| *Watt* | Unit of power (“arbeid” in Dutch) (W= J/s) |
| *Watt-Peak (Wp)* | Unit for efficiency comparison of photovoltaic modules (standard test conditions e.g. 1000 $W/m^2$, radiation perpendicular on surface, 25 $^oC$) |

*Glass properties*

| | |
|---|---|
| *Solar heat gain coefficient SHGC* | Like g-value. However, the difference is that this coefficient takes the total window, door or ‘panel’ into account. Not only the glass. |
| *g-value* | Coefficient for the solar energy transmittance of glass (solar heat gain). 0 is no transmittance, 1 is 100% transmittance. This is an industry product standard, obtained by EN410. |
| *LTF* | Daylight transmittance factor, Dutch - “*lichttoetredingsfactor*” is the daylight factor, how much of the visible light transmits through glass. |
| *ZTA* | Dutch - “zon*toetredingsfactor*”, see g-value/STF |
| *R-value* | Thermal resistance, inverse of U-value. Mostly used to indicate the thermal performance of a facade ($m^2K/W$) |
| *STF or SF* | Solar (transmittance) factor, a factor for the part of the solar irradiance that passes through a transparent building skin |
| *U-value* | Heat transfer coefficient, inverse of R-value. Mostly used to indicate the thermal performance of glass products ($W/m^2K$) |

# Table of contents

# 1 Introduction and methodology

## 1.1 Background

Nowadays, the energy use of non-renewable resources needs to be limited due to sustainable demands. The built environment should react. Casini (2016, p. XII) states that currently buildings are responsible for approximately 30% of global energy use. In the USA, building operations only, use 41.7% of the annual energy consumed (figure 1.1). Furthermore, the building sector has much potential for improvement of efficiency. Especially for high density areas, decentralized energy production on buildings can contribute significantly to the energy demand (van den Dobbelsteen, 2007). Soon (±2030), all buildings should be energy neutral or close. For every building component, the energy potential should be explored to achieve this goal.

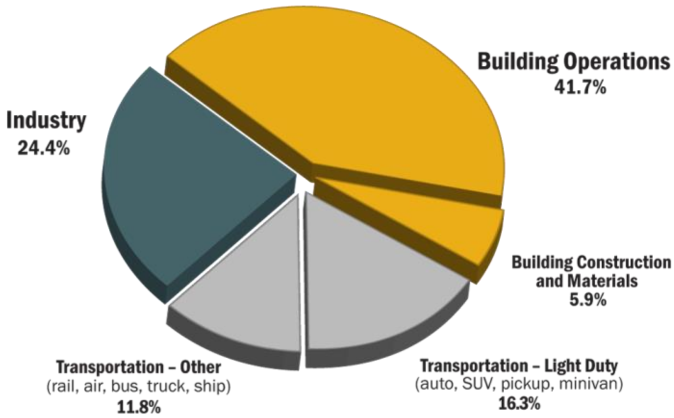



*figure 1.1: Annually energy consumption of 2013 in the US. (https://www.eia.gov/)*

In modern architecture, it is a trend to go for maximum transparency. For instance, buildings with atria. The 'atrium roof' is one example of a building component that should be researched in terms of its energy potential.

## 1.2 Problem statement

Buildings with a high glass/wall ratio bring in a lot of daylight, which is good for human comfort. On the other hand, transparency allows heat of the sun to come in, which can lead to overheating or a cooling demand. In winter situations, you can use the heat of the sun instead, to heat the space. The demand for transparency often has aesthetical origins, for example a roof over the courtyard of a monument. The courtyard should still look like outside after the intervention. Also, the daylight level should not be too low inside the covered courtyard when there are for example workplaces situated in the original building.

*Sub-problem - Measures to produce energy are hard to combine with desire for transparency in the skin of a transparent grid shell roof.*

In curved geometries, every panel has a different orientation, thus a different yield. There are very little references found on how to deal with this and what the consequences are. Furthermore, when connected in series, the least generating panel is the bottleneck for the others. Also, grid shell structures typically have a big span. This means that there are no or little vertical elements to place the cables from PV cells in. So, the detailing of the structure will be more difficult than in a ‘regular’ flat roof.

*Sub-problem – The curved geometry and big span of transparent roof structures make the layout and detailing of photovoltaic cells a complex matter.*

Another problem that is often not considered, and makes the design even more complex, is shade from the direct environment. Since the lowest yield of one cell of a row of solar cells connected in series is the bottleneck, shade from, for example the building itself or trees can influence the yield.

*Sub-problem - Shading from the direct environment is usually not considered, but can influence the yearly yield significantly.*

To conclude, there are multiple challenges when integrating photovoltaics into the skin of a grid shell or curved transparent roof structure. This results in the main problem statement:

Problem statement:
**“There is no clear solution on how to produce energy on a transparent roof structure and what the effect on the internal climate of the atrium is.”**

Hypotheses about problem cause are:

- Grid shell roofs are designed for maximum transparency, ways to capture the energy from the sun block daylight and view;
- In a curved transparent roof structure, not a single panel has the same orientation;
- Reduction of the energy demand of non-renewable resources is often not the main focus of a design.

## 1.3 Objective

The goal of this thesis is to inform designers what the options are where to base choices upon in a design for integrated solar cells in a large glazed space. With this thesis, a designer should be able to assess his design both in an early, conceptual stage and in a later engineering phase. So the knowledge normally from consultancies should be shifted forward in the design process (figure 1.2).

Sub-objective:
Show a designer/engineer what the alternative possibilities are in applicating photovoltaic cells to make a summary of what is possible, and show the consequences.

Hypothesis solution direction:

- Responsive design (smart shading/energy production);

- Orientation based solutions;
- Building integrated photovoltaic cells;
- New photovoltaic techniques (thin-film family and nano-technologies).

Scope:

- Sustainability focus: production of energy;
- Energy production by PV cells;
- Daylight level only visual and qualitative assessed;
- Heat gain reduction only by integration of PV cells in glass;
- The thesis considers a moderate climate.

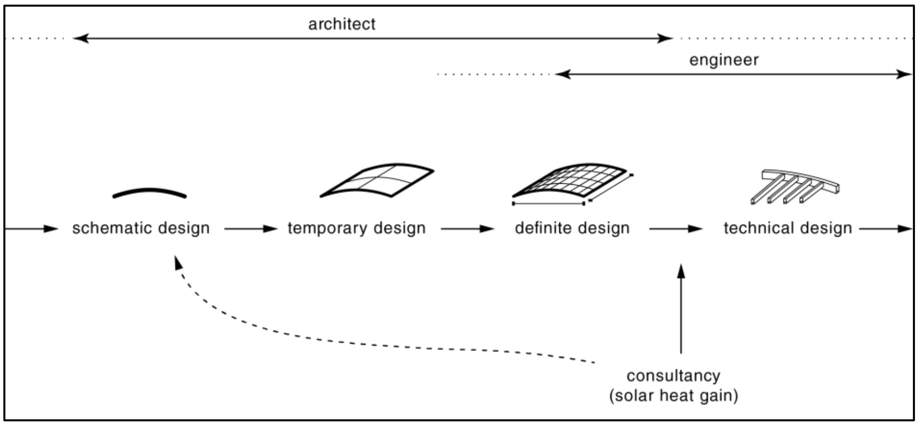



*figure 1.2: goal to shift the analysis results from consultancies to the early design phase.*

## 1.4 Research questions

*In what way, can the integration of solar cells in the skin of large glazed spaces be applied effectively and contribute positively to the internal thermal comfort?*

Sub questions:

- Which requirements should be met in a large glass covered space, regarding the internal climate?
- Which different strategies are available in transparent roof structures, to reduce the energy demand of non-renewable resources?
- How can photovoltaic cells be integrated within a transparent roof? What is the best technology to use?
- What is the consequence of different orientations for the layout of photovoltaic cells?
- How can you predict how much sun radiates the transparent roof structure?

## 1.5 Approach and methodology

*Literature study*

First, large glazed spaces are discussed. This covers the motivation to build such a building and the design parameters; which options do you have? Then, the sun, sunlight and its properties are studied. After that, the internal climate of large glass covered spaces is reviewed. Ways to reduce the energy demand of non-renewable resources in a (curved) glass covered space are pointed out.

Next, photovoltaic cells are studied, the production part of the thesis. The focus will be on transparency and integration in a curved transparent roof. This knowledge will help to make a layout of solar cells and help to understand the secondary measures that should be taken. Furthermore, it will provide an overview and comparison of different techniques. It will conclude on which techniques can be used for glazed spaces and which properties they have.

*Analyses*
After this literature study, computational tools (Rhino->Grasshopper-> ladybug & honeybee in combination with EnergyPlus weather data) will be used to get an idea how to treat a freeform/curved shape in terms of energy production and solar irradiance. It will provide information on how much energy is produced at what position and orientation. Some case studies will be done, to understand the magnitude of the energy that is produced.

This radiation information will be combined with inside thermal calculations. The significance of each parameter will be reflected on. Altogether, there will be knowledge about when and where shading should be added and how much energy is produced when PV cells are used.

*Design*
An overview with possible design options will be presented in a designer friendly morphological overview. What out- and inputs do you have, and what are the consequences of choices? All scales, from macro (geometry) to micro (panel) are pointed out. Three (conceptual) designs will be made to see the potential and they are reflected upon with the analysis tool.

| LITERATURE STUDY | → | ANALYSES | → | DESIGN | → | CONCLUSIONS |
|---|---|---|---|---|---|---|
| PART A | | PART B | | PART C | | PART D |

*figure 1.3: Structure of thesis*

## 1.6 Relevance

*Societal relevance:*
In general, there is an energy transition ongoing for unsustainable to sustainable; non-renewable to renewable. Also, there is a trend for decentralised energy production. That means, production on building level, everywhere. Now, most energy is produced by power plants, central. Decentralized production means less dependence and vulnerability of central energy sources. Also, less transport losses.

Fundamental research provided a lot of photovoltaic techniques to produce energy with sunlight. Now, it is time to implement those techniques into building components to make it more common and easier to produce energy locally on buildings.

A specific building part is chosen, namely a transparent curved roof structure. This is chosen since it touches several challenges of the integration of photovoltaics in buildings: curved transparent roof structures. For now, atria roofs do not contribute to the zero-energy balance aim of buildings, it is a research gap.

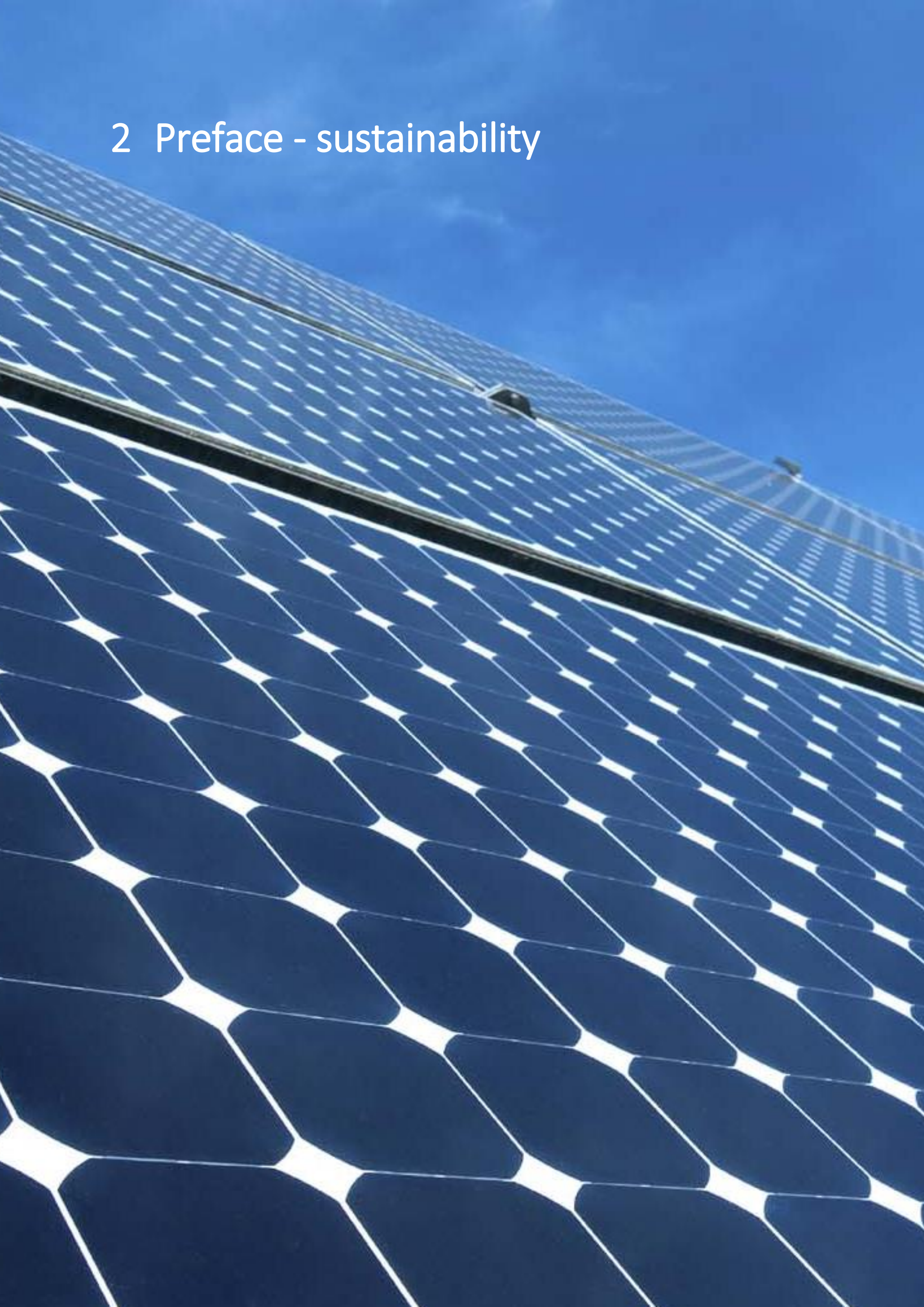
Energy produced exclusively by decentral sources, could change a lot on a social level. People will have more insight in 'what goes in, and what goes out'; are more aware of their energy use relative to what is produced. Also, storage of energy will be more common in the future, either on community or individual level. Ultimately, decentral energy production could mean a complete transition for the electricity grid. Since all electricity is produced in direct current, and most devices work with direct current, you will not need alternating current anymore.

*Projected innovation:*
An energy producing skin of a transparent roof is possible already. How to do this in an effective way on a curved surface is unknown. Furthermore, the PV cell technology that is mainly used today are mono crystalline silicon cells. This is, however, not the only way to integrate solar cells in a transparent roof. Currently there are a lot of developments, some of them still in their fundamental phase. The graduation will contribute to the development of building integrated energy producing construction elements, and show architects what is, and may be possible with solar cells in combination with sufficient shading in glazed spaces.

# Part A – literature study

A literature study is conducted. This part starts with a preface about sustainability. What can you do to make a large glazed space / atrium (more) sustainable? The choice for the focus on energy reduction and production is reasoned. Chapter 4 is about the internal climate. It starts with theory about sunlight and the path of the sun. This can be used to take (shading) context into account and learn the properties of sunlight. Then it describes heat and the internal climate in such a space, and which parameters influence it. Chapter 5 describes how solar cells work, which different techniques are available and future possibilities are explored.

# 2 Preface - sustainability



## 2.1 Introduction

One of the main challenges of the building industry nowadays is to build sustainable. There are several subjects in sustainability such as water, food, transport, education, etc. This thesis focuses on the energy part of sustainability, and is related to large glazed spaces. How can you produce energy on a transparent building component? With the new steps strategy, developed by van den Dobbelsteen (2008), the options are examined. The strategy points out the different steps to get a "sustainable" building (figure 2.1). Focused on energy, step one is to reduce the demand, relative to situation zero. Next, you should reuse flows. Subsequently, to provide for the remaining demand, you should produce energy. How these steps can be expressed within the topic of this thesis is pointed out in the next paragraphs.

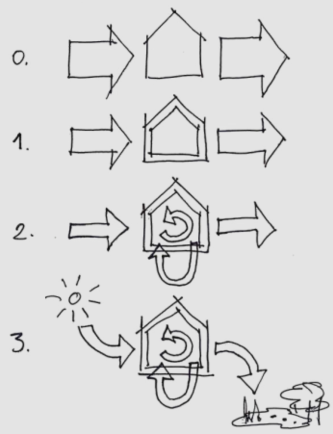



*figure 2.1: The new step strategy (van den Dobbelsteen, 2008, pp. 2 - 3); reduce, reuse, produce renewable energy and control waste flow*

## 2.2 Energy use reduction of non-renewable resources

### 2.2.1 Reduction of energy use

The first step of the strategy is the reduction of the energy used. Whether it is renewable or not renewable energy, it is a not good to just lose energy. On a building scale, the most obvious energy use reduction is insulation of the building to prevent heat to flow out. Another reduction could be avoidance of solar heat from coming in, to prevent overheating and the resulting cooling load. It depends heavily on the location and function of a building what measures should be taken.

To compare designs, for instance, the glass to wall ratio can be used as a tool. Also, you could think of smart systems like automatic lighting and programmed heating to reduce the energy demand. A large glazed space, like an atrium, could be used to pre-heat air before it goes in to the ventilation system of the rest of the building. In that case, energy is saved from heating of ventilation air (figure 2.2).

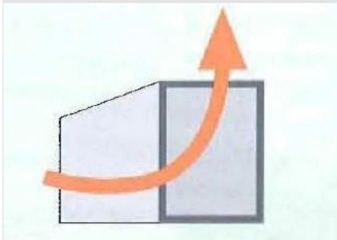


*figure 2.2: use the glazed space to pre-heat ventilation air (Blesgraaf, Ham E. R. van den, & Novem, 1996, p. 15)*

### 2.2.2 Reuse of energy

The second step in the strategy of Dobbelsteen (2008) is reuse of energy. On the building level storing heat in the ground (geothermal heating) is one example. In an atrium, you could think of exchanging heat from 'dirty' ventilation air with fresh air from the atrium (figure 2.3).

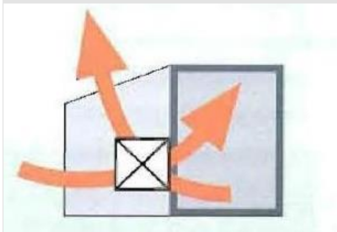


*figure 2.3: Heat from 'Warm' ventilation air can be exchanged with fresh 'cool' air to reuse the heat from inside (Blesgraaf et al., 1996, p. 15)*

### 2.2.3 Production of energy

The last step is energy production. There are several ways to produce energy on a building. The most 'common' ones are briefly described next.

*Wind*

Power from the wind is also often mentioned as an option for production of energy on the building level. Only relative high buildings with some aerodynamic features have the option to integrate wind turbines. The Strata tower in London is a good example (figure 2.4). There is a handful of examples of buildings with integrated turbines, but still, it is not a common practise. Also, often critics say that the turbines are just a symbol for sustainability since they do not always function well or produce just a very small portion of the total energy demand. To integrate turbines into a transparent roof structure, seems very difficult. Aerodynamically it is not practical, and wind power systems did not proof themselves enough to use.

*Sun:*

The sun is the biggest energy input of the earth. Ultimately, all other energy sources are, in one way or another, a result of the sun (apart from nuclear power). The sun produces far more energy annually than non-renewable reserves that are left (figure 2.5).

Next, the options to use solar energy, integrated in buildings are discussed:

*Biomass*

It is possible to use water filled (glass) panels with algae to transform sunlight into electricity. Although the algae are not expensive, construction materials and extra structure that is needed, could be. According to van den Dobbelsteen (s*ymposium energiepositief bouwen; KNAW*, 14 December 2016), algae energy production did not fulfil its promise of integration with buildings yet.

*Heat*

Solar energy can be transformed into heat. This works with a black surface and often tubes with water to exchange the heat. The result is a temperature rise in the water, thus energy in the form of heat. Since those panels are not transparent, it is not an option to integrate it into the transparent building skin.

*Electricity*

Sunlight can be transformed into electricity by photovoltaic cells. In the last decade, this technique is transformed into a common practise. Still, there is a lot potential for new technologies. Especially for building integration, and the ability to integrate solar cells in transparent enclosure. Therefore, this thesis focusses on this technology and is elaborated in chapter 5.

*Heat & electricity*

In a normal system, a panel with PV, heat is a waste product. A building integrated PV/Thermal (BIPV/T) recovers the heat produced by PV panels with either a water or an air based system. In this way the efficiency of the PV panel goes up and ‘waste’ heat is acquired. Casini (2016, p. 27) states that a BIPV/T system, depending on the design, climate and operating conditions, can produce 2 to 4 times more heat than electricity. However, it is no option to integrate such system in transparent building components, since it does not let (visible) light through.

*figure 2.4: Strata tower in London. Photo: http://www.urban75.org/blog/the-rarely-spinning-turbines-of-the-strata-tower-south-london/*

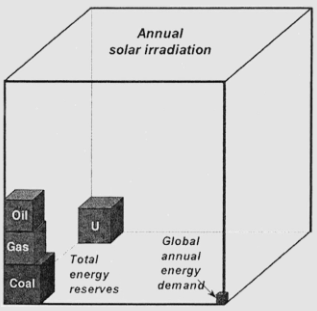




*figure 2.5: box illustrating the annual solar irradiation compared to the total energy reserves and global annual energy demand (Quaschning, 2005, p. 22)*

## 2.3 Conclusion

A designer must be aware that all steps of the new step strategy should be considered throughout the entire design and engineering process. For now, this thesis focusses on energy reduction and production. Reduction is translated into solar shading to prevent a potential cooling load by adding up to the thermal comfort and production only photovoltaic cells are considered. The latter is substantiated because it is the most proven technology, and it has the most potential as well. Furthermore, it is convenient to integrate solar cells into a transparent building component.

# 3 Large glazed spaces / atria

## 3.1 Introduction

In this chapter, a research is conducted to get understanding what kind of building part we are dealing with. Why would you build a large glazed space or atrium, and which kind of types are there to choose from?

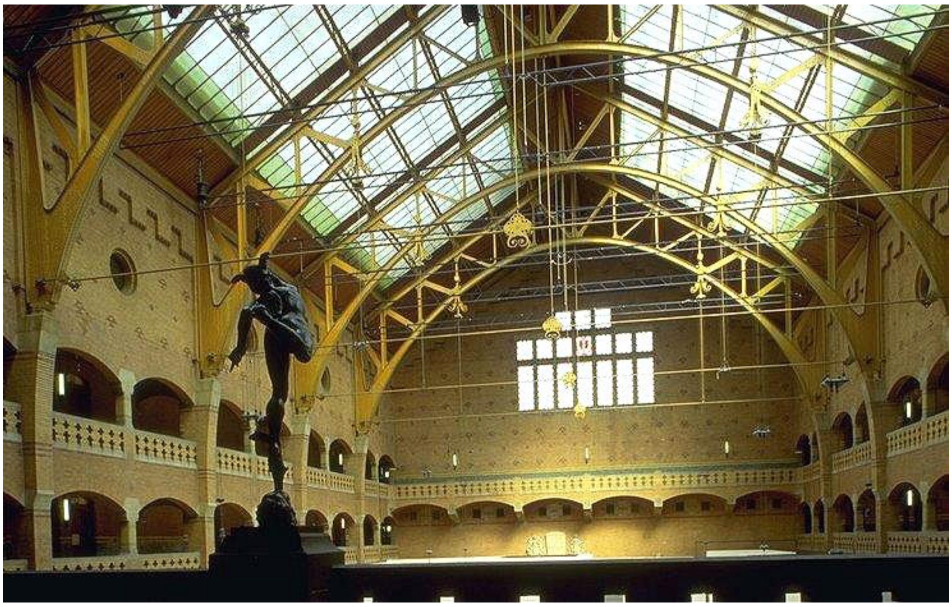


*figure 3.1: Beurs van Berlage, 1903; one of the first atria in the Netherlands.*
*Photo: https://commons.wikimedia.org/wiki/File:Beurs3.jpg*

## 3.2 General

An atrium originally refers to an outside space in the central court of a classical Roman house (Baker, 2009, p. 63). Nowadays we refer to an atrium as an enclosed space covered by a transparent roof. There are plenty of reasons why users and architects want a transparent enclosure. Since gothic architecture, there became a special focus to get as much light in a building as possible. An atrium has this spacious character; as a refurbishment, it provides extra floor space; the space is bright, thus gives a half inside/ half outside feeling. One of the first “atria” in the Netherlands is the “Beurs van Berlage” (1903). That was also the moment that it became clear that it is difficult to make a pleasant internal climate. Problems like draft and acoustical problems were present. The search for transparency in buildings currently gets an impulse from developments with thin structure principles and glass technology and structures. The Apple store in Shanghai is an example of maximal transparency that is reached nowadays (figure 3.2).

*figure 3.2: Apple store in Shanghai; maximal transparency.*
*Photo: http://www.idesignarch.com/wp-content/uploads/Apple-Store-Pudong-Shanghai_1.jpg*

Nowadays, a lot of new build hotels and office buildings have a central atrium. Also, museums or office buildings with a central (open) courtyard cover it with a transparent roof. Furthermore, shopping malls or passages have large glazed spaces, and have comparable climate properties like atria.

Additionally, often energetic arguments are used to introduce an atrium (figure 4.1). However, in a significant number of cases, the intervention costs rather energy than it saves energy (Baker, 2009, pp. 63 - 64). Especially when you treat the new space as an indoor space for permanent stay or work, it will be very unlikely to get an economic energy balance (Blesgraaf et al., 1996). On the other hand, Baker (2009) states that there is indeed a potential in covering an enclosed courtyard (as a refurbishment) for energy saving. The space needs to be considered as a "short stay" or transport. After all, it is not uncommon that an atrium will be used for more than only short stay or transport. Blesgraaf et al. (1996) makes clear that engineering an atrium is a delicate activity. Subjects like daylight, temperature, humidity, energy balance, ventilation, fire safety, acoustics and maintenance all need special attention. Climate issues are elaborated in chapter 4.

## 3.3 (Grid shell) atrium roofs

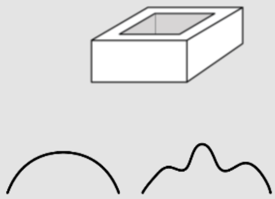
Several atria are covered with a grid shell or with somewhat curved roof structures. The shell shape gives the structure 'form stiffness' so you are able to make large spans, without columns. A grid shell is a shell structure with a grid projected onto the surface. This grid forms the structural elements of the structure.

### 3.3.1 References

Some cases are analyzed to see what is possible and which types there are:

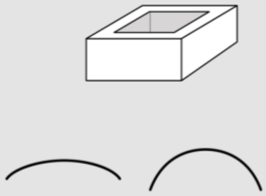
*Foster and Partners - 2007*
*Kogod Museum, Washington*

This museum covered their historic courtyard. The atrium is relatively large. The grid shell consists of three dome-like shapes.



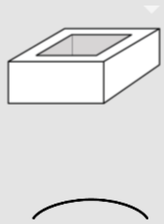
*DOK architecten - 2011*
*Scheepvaartmuseum, Amsterdam*

This grid shell roof covers the courtyard of the existing building. The shell refers to an old navy map. The structure can be defined as bent or dome-like.



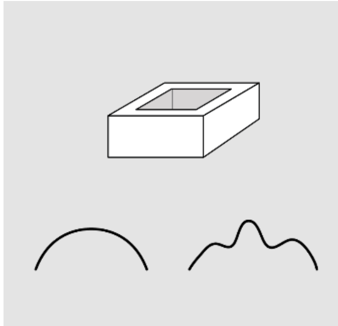
*Meyer en van Schooten architecten - 2008*
*Ministry of Finance, The Hague*

Renovation of the old office building and an additional roof to make an atrium. Now, this functions as the 'heart' of the building. The roof is a grid shell, but structurally the shell function is limited.



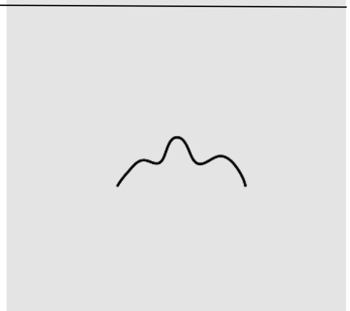
*Foster and partners - 2000*
*Great court of British museum, London*

One of the first grid shells of steel and glass. It covers the great court of the British museum. It made the central library accessible again.



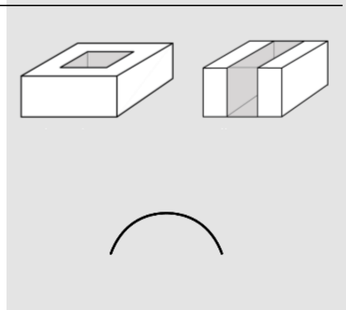
*Frei Otto - 1978*
*Multihalle, Mannheim*

This was the first large scale grid shell. It is made of timber and constructed flat from the ground. By lifting sections, the shape emerges.



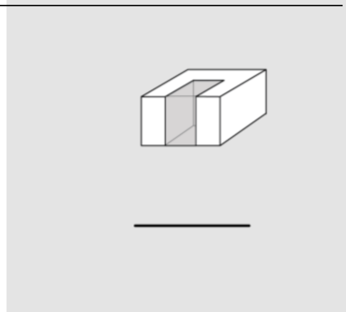
*Gerkan, Marg und Partner- 1989*
*Museum für Hamburg, Hamburg*

This beautiful example of a grid shell does not fully function a grid shell, it is supported by cables to compensate the horizontal forces.



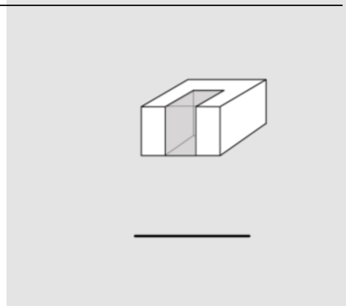
*Ector Hoogstad Architecten - 2000*
*AVRO, KRO en NCRV, Hilversum*

This office building has four open sided atria, differing in dimensions. They function as to express the transparency of the institution.



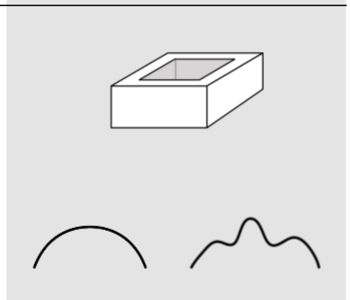
*Braaksma & Roos – 2014*
*Gemeentemuseum, The Hague*

This large atrium of 700 m$^2$ covers the old courtyard of the museum. Now, the space is used for lectures and as a coffee house.



*Jon Jerde - 2007*
*Złote Tarasy, Warsaw*

Złote Tarasy is an enormous shopping mall of 205.000 m$^2$, covered with a glass-steel transparent roof.



### 3.3.2 Grids

A shape can be separated into a grid in several ways (figure 3.3). Most common is a distribution of triangles or squares. Triangles have the advantage that they are stiff. Also, if you design a geodesic dome, it is often makeable from triangles. Squares however, have the advantage that they are easier to build with. Square panels are more mainstream and easier to produce and connect. The disadvantage is that squares are not stiff, so stiffness should come from a second, internal structural layer.

The first grid shells were made of timber like the Multihalle in Mannheim. Those grid shells were flexible during construction and fixed after. Nowadays, transparent roofs are often made of steel and glass.

## 3.4 Conclusion

There are several motivations to build an atrium or large glazed space. The main motivation is the extra daylight and the spacious character it brings. The main typologies are closed atria, large closed atria, open sided and linear glass spaces. Roof shapes can mainly be defined by flat, bent, dome-like and free-form. The grid of a transparent roof can be distributed in several ways, but essentially, grids are distributed in triangles or squares.

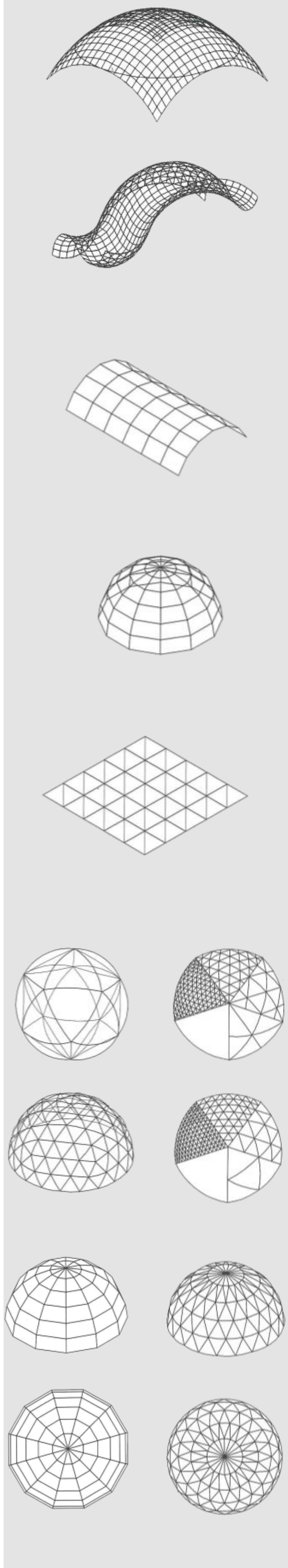
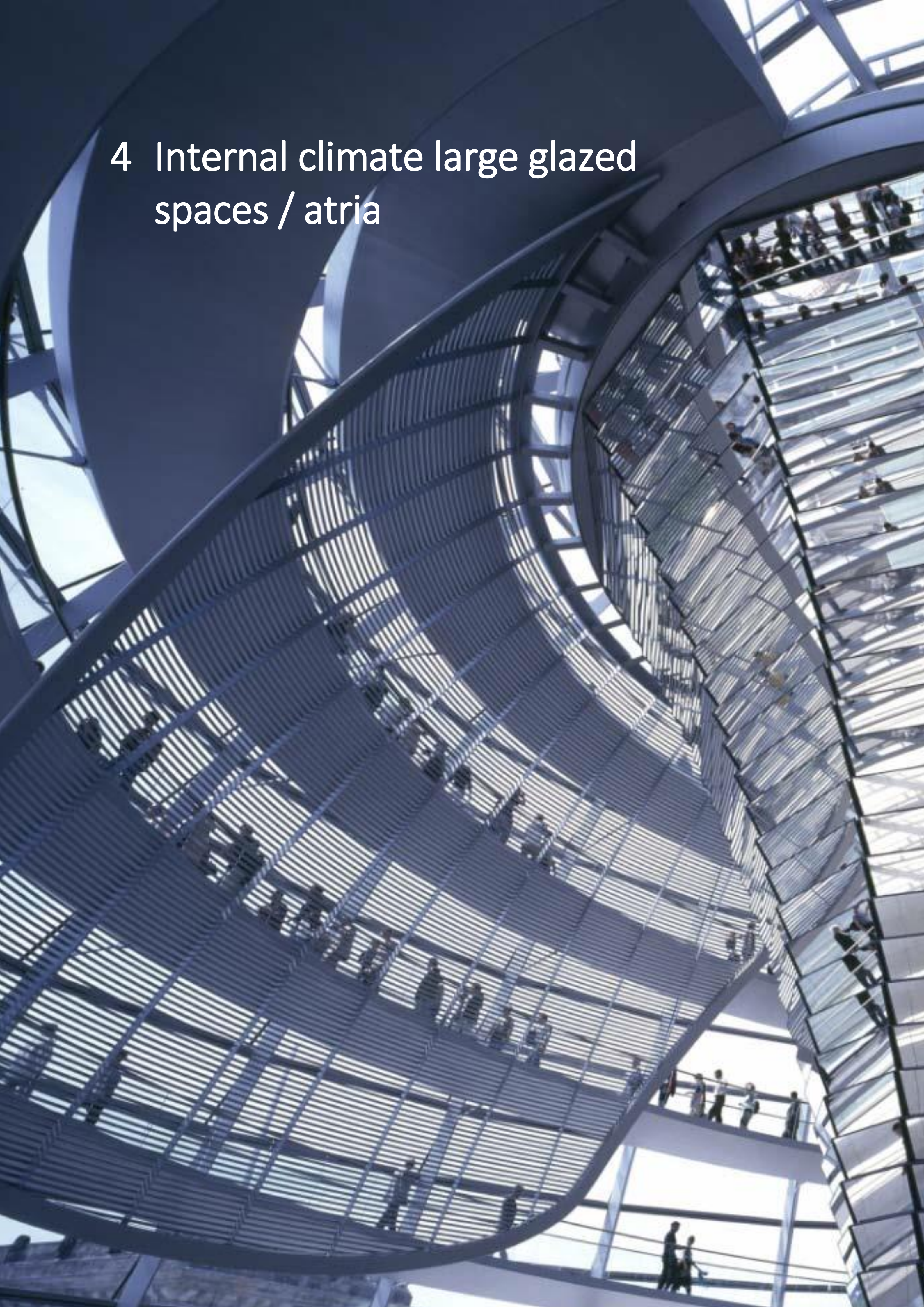


*figure 3.3: grid distribution options*

# 4 Internal climate large glazed spaces / atria



## 4.1 Introduction

Modern architecture tends to build more and more for transparency. Qualities like daylight, view, aesthetics are appreciated by architects (and users, hopefully). Next to the positive sides, some serious design climate issues of 'large' spaces covered with glass need attention. Large glazed spaces have advantages and disadvantages. Currently, it is a challenge to increase the quality of large glazed spaces to apprize the functionality of such spaces.

Sunlight and its path is studied to get a grip on how the sun radiates a building, and properties of sunlight. Next, internal heat of a 'room' is examined. What parameters influence this? This is analysed in table 4.1:

Demands of a space like this depend on the function applied to it. It scales from a buffer zone (not accessible for people) with no demands to transport area, to place for permanent stay (e.g. working). The latter has the strictest demands. The temperature should be stable and not too high or too low and there should not be draught for example. For relative large spaces enclosed with glass, it is discouraged to make it a place for permanent stay (Blesgraaf et al., 1996). Such a big volume should be conditioned actively, which is not preferable because the large quantity of air. However, when the comfort is increased in the space, the functionality will be higher. Nowadays, insulation of windows got better so the feasibility to make a qualitative climate for a large glazed space has increased.

The goal is to make an 'as comfortable, as possible' climate, without the use of "external" energy. So, to make a passive climate.

| Strength | Weakness |
|---|---|
| - aesthetics<br>- protection from outdoor environment; extra internal floor space<br>- acoustic insulation<br>- 'connection' with outside<br>- u-value inside façade less important (when glass enclosure is addition/renovation)<br>- solar heat gain in winter<br>- high daylight level | - fire safety<br>- decrease of daylight (when glass enclosure is added/renovated) |
| **Potentials** | **Challenges** |
| - pre-heat ventilation air<br>- collect heat in summer, store for winter<br>- stack effect to ventilate<br>- electricity production by sun (high probability of unobstructed sunlight) | - overheating in summer<br>- internal acoustics (reverberation time)<br>- glare prevention<br>- draught (high velocity air flow)<br>- need for fire compartmentation<br>- extra energy demand (when heated or cooled), will outweigh the saving |

*table 4.1: Climate analysis of large glazed spaces, highlighted text is within the scope of this thesis (partially based on (Baker, 2009, p. 70))*

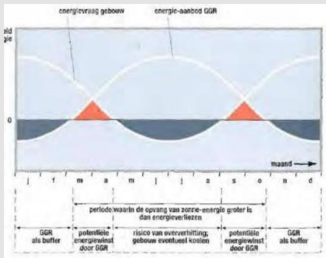


*figure 4.1: potential energy saving based on heat; mostly in spring and autumn (Blesgraaf et al., 1996, p. 44)*

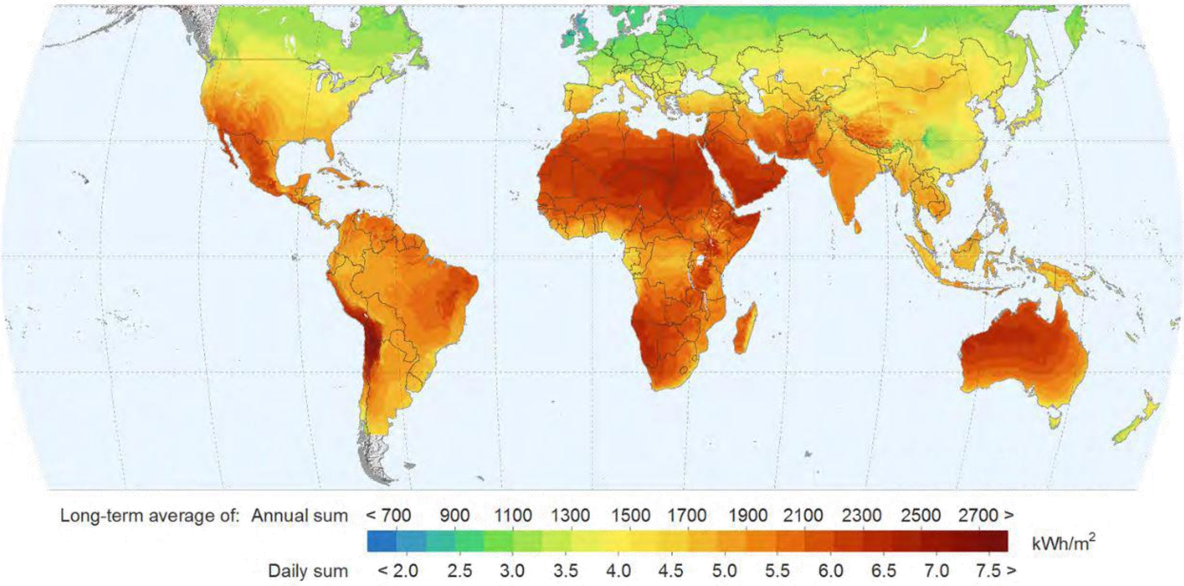



*figure 4.3: solar map of the world, annual insolation in kWh/m² (solargis.info, 2013)*

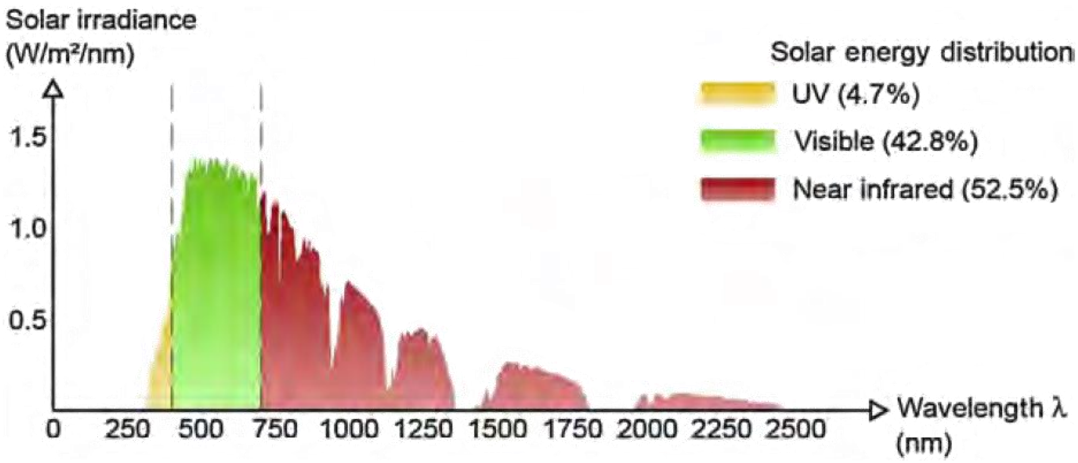



*figure 4.3: spectrum of sunlight consisting of UV, visible and IR parts (Casini, 2016, p. 223)*

## 4.2 Sunlight and solar path

### 4.2.1 Sunlight

The sun shines on the earth with a certain power. This power is usually measured in W/m$^2$. Different terms like solar radiance, solar irradiance or insolation are used to express this power. To express how much solar energy has reached a surface, over a certain period, kilowatt hour square meter (kWh/m$^2$) is often used. To get a rough idea of the power of the sun: one day of solar energy that reaches the surface of the earth, would be enough to power its entire population (of humans) for one year. You can see in figure 4.3 that the annual irradiation is in some parts of the world up to 2700 kWh/m$^2$. Even in a moderate climate with a relatively high altitude like the Netherlands, the annual irradiance is still 850 to 1000 kWh/m$^2$. You can see the influence on location in figure 4.5 for some cities.

Only a small part of the sunlight spectrum is visible for humans, which is approximately between the wavelengths 380nm and 750nm. Smaller wavelengths than visible we are called ultraviolet (UV) and larger wavelengths are infrared. The part near the visible part, is called "near-infrared". A large part of the solar energy (52.5%) is in the infrared part of the solar light spectrum (figure 4.3).

*Insolation value fluctuations*

Every year the annual insolation is different due to changed weather and different distance or angle to the sun, for example. In the past ten years, the 'worst solar year' and the 'best solar year' in De Bilt only vary 15% from the average insolation (Sampatakos, 2014, p. 22). Naturally, during the year, the solar power as well. July is on average the month with the highest monthly insolation and January the month with the least insolation. Illustrated by figure 4.4, you see the distribution of solar irradiance throughout

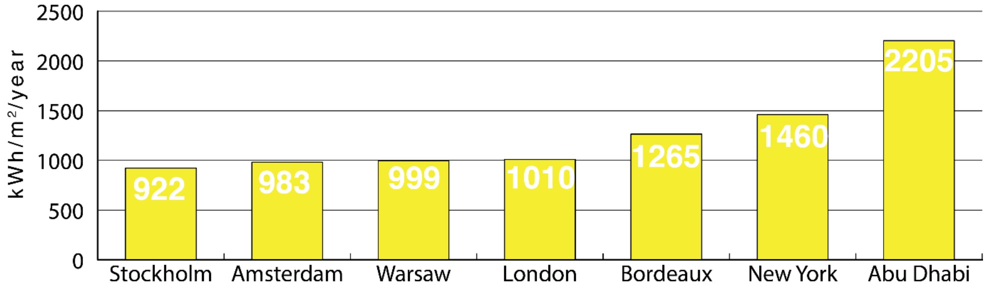



*figure 4.5: solar irradiance values dependent from location. Data from EPW*

the day and year.

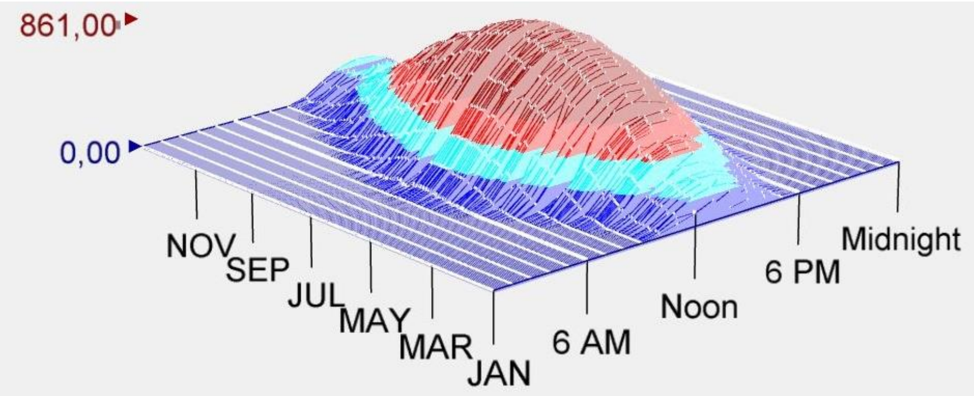



*figure 4.4: Daily averages of solar irradiance in Amsterdam; from climate consultant 6.0, input from EPW*

*Solar heat gain*

Most of the irradiance energy from the sun can go through glass. Inside, the sun heats up surfaces. This surface radiates heat but with a large wavelength which cannot transmit through glass. Heat is trapped inside the glass enclosure. This is called the greenhouse effect (figure 4.6). Which portion of energy from the solar radiation can enter the 'room', is defined as the "solar transmittance factor" (STF). This can be calculated by the next equation:

$$STF = \frac{qd + qci + qsi}{qse}$$

*Equation 4.1:*

| | |
|---|---|
| *qse=* | *totality of solar energy directed at the area (W)* |
| *qci =* | *heat that is given off inside through convection (W)* |
| *qsi =* | *heat radiation that is given off inside (W)* |
| *qd =* | *radiation that is admitted (W)* |

*(van der Linden, 2011, p. 111)*

So, the solar transmittance factor is the total of the heat that comes in because of the solar radiation. To be clear, construction in a glazed envelope is also considered in this factor, not only the glass.

For glass, there is a specific factor for to indicate the transmittance factor: the g-value (Equation 4.2). This value is tested for every glass product with standard EN410. Every form of heat what come in through the glass by sunlight is considered in the g-value. For example, the glass absorbs a part and heats up. Subsequently, the glass radiates a part of that heat to the outside and the inside. This is also considered in the g-value. So, the g-value is a part of the STF. The parametric model of chapter 6 works with the STF to calculate the internal room temperature.

$$g - value = \frac{heat\ transmitted\ through\ window\ (W)}{total\ solar\ irradiation\ (W)} = \frac{q_i}{q_z}$$ *Equation 4.2*

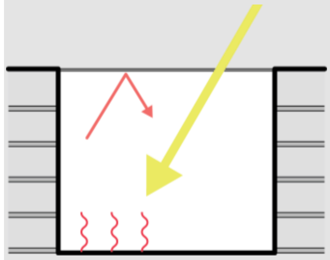


*figure 4.6: top: greenhouse effect; shortwave sunlight passes through glass, longwave heat does not (Wurm, 2007, p. 38); bottom: greenhouse effect on building scale.*

*Daylight & light transmittance factor (LTF)*

Only a part of the solar spectrum is visible to the human eye (figure 4.3). The portion that is let through by the transparent skin of a building is the light transmittance factor. Daylight is one of the main reasons to build a transparent roof, so it is important to reach sufficient daylight levels inside your space. Insight daylight has an impact to the wellness of people and experience of spaces (figure 4.7); (Veitch & Newsham, 1996). Therefore, it is important for a designer to be aware of this. However, only qualitative values are considered in this thesis, not quantitative. Nonetheless, the parametric model that is

*figure 4.8: glare prevention (and acoustical improvement) with textile blinds (Wurm, 2007, p. 124)*

| **Daylight influences people in several ways: (Veitch & Newsham, 1996, p. 97)** |
|---|
| - aesthetic judgements (assessments of the appearance of the space or the lighting); |
| - health and safety; |
| - mood state (happiness, alertness, satisfaction, preference); |
| - post-visual performance (task performance and behavioural effects other than vision); |
| - social interaction and communication; |
| - visual performance; |

| **Quality of daylight is influenced by: (Wyckmans, 2005, p. 222)** |
|---|
| - Colour; |
| - Directional properties; |
| - Glare and veiling reflections; |
| - Individual control; |
| - Luminous distribution; |
| - Visual contact with the outdoor environment; |

*figure 4.7 (l): properties of daylight and its influence on people.*

made would be, with extra work and available light transmittance data, able to calculate this as well.

Too much daylight can result in glare, but complaints about glare are not expected in atria or large glazed spaces, since this mainly concerns working places and computer screens. These are less found in atria. You can see a way to prevent glare in a large glass space in figure 4.8.

### 4.2.2 Sun path

The earth rotates around the sun yearly and around its own axis, daily. This results in changing irradiation angles and strengths. Furthermore, lengths of days and season are determined by these movements. The latitude of the location determines the altitude of the sun; the solar angle. The longitude determines when the sun comes up and when it is at its highest point. At exactly 12 ‘o clock the sun is at the highest point, in ‘solar’ time. We use GMT (Greenwich Mean time), which differs with the solar time since we use time zones. You can calculate the solar time with this formula (Broersma, 2008, p. 18):

Solar time $$= GMT + 4\left(L_{st} + L_{loc}\right)$$

*Equation 4.3:*

| | |
|---|---|
| *GMT =* | *Greenwich mean time (hours)* |
| *$L_{st}$ =* | *standard meridian* |
| *$L_{loc}$ =* | *longitude of location* |

$L_{st}$ is the standard meridian of the time zone, and $L_{loc}$ the exact longitude of the location. With this formula, for example, you can calculate the time of the highest point of the sun. Also, you can calculate the daylight hours and the angle of the solar radiation respectively to the surface of the earth. (Broersma, 2008)

Daylight hours: $$N = \frac{2}{15}\cos^{-1}(-\tan\varphi\tan\delta)$$

Angle of incident solar irradiance: $$\delta = 23.45\sin(360\frac{284+n}{365})$$

*Equations 4.4:*

| | |
|---|---|
| *N =* | *number of daylight hour* |
| *φ =* | *latitude* |
| *δ =* | *declination of sun* |
| *n =* | *$n^{th}$ day of the year* |

When you put these calculations into a computer program, you can calculate and visualise the yearly path of the sun of a location (figure 4.11). The horizontal angle is called the azimuth (A in figure 4.11). The 0$^{o}$ point is usually south, and sometimes north like in figure 4.10.

The daily highest point of the sun is in the summer (around 21 June) maximum and in winter (around 21 December) minimum. After the 21th of December the days are getting longer and after summer solstice, the days are getting shorter. The middle between winter and summer is called equinox. This is twice a year, around the 21th of March and September. At those moments, the length of the day is equal to the length of the night, everywhere on earth.

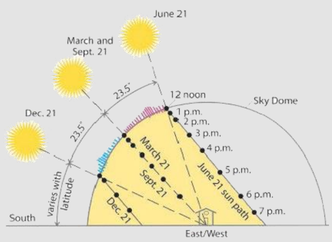
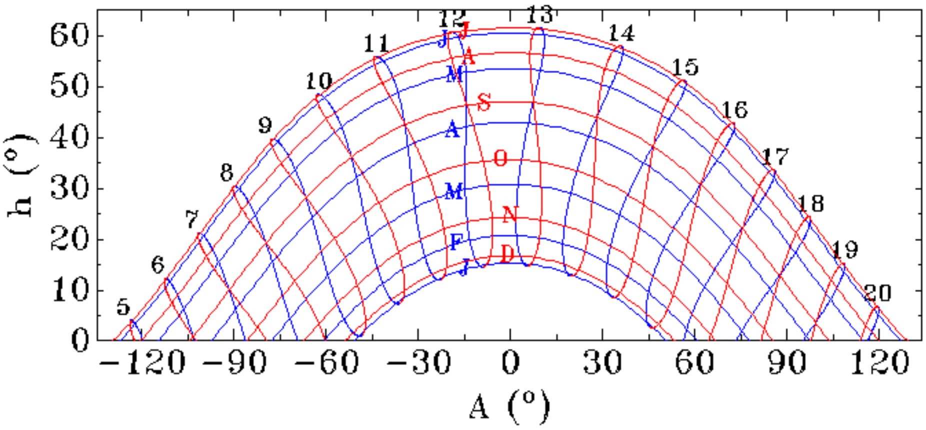



*figure 4.9: location of the sun, throughout the day and year (http://solartoday.stfi.re/2012/05/playing-angles-for-solar-responsive-design/?sf=bwkgyjz#ab)*

The difference in height of the sun during winter and summer depends on your location. At the equator, there is very little difference in height (so, also very little difference in season). The further away your latitude is from the equator, the bigger the difference becomes. Also, when your latitude is higher (or lower, on the southern hemisphere), the altitude of the sun will be lower. This also means that the solar radiance travels longer through the atmosphere, which results in weaker sunlight on earth's surface. That is basically why it gets colder the further away you are from the equator.

The Netherlands have latitudes between 50.75° and 53.50° (north). The range of longitudes is approximately between 4° and 7°.




*Computational 3d design & analysis sun path*

With new techniques and increasing data from build environment, it is getting easier to know if the building you are planning. For instance, figure 4.14 shows what you can do to get a first impression of where the location of the sun is and if there are shadings by buildings nearby. An exact method is developed in the parametric model to see how much solar irradiance a building receives (see chapter 6).

## 4.3 Thermal comfort

A focus of this thesis is to improve the thermal comfort inside large glazed spaces. When the thermal comfort is good, the probability of people actively changing the temperature (cooling or heating) is lower. So, by improving the thermal comfort also potential energy use is limited. Obviously, a comfortable indoor climate has a positive effect on the well-being of people. Also, the durability of a building increases with a high quality climate. (van der Linden, 2011)

*What is a comfortable temperature?*

To test the outcome of the parametric model (chapter 6), you need to know what an appropriate temperature is. However, there is not just one 'perfect' temperature since people adjust their needs. People dress different depending on the outside temperature but there is also phycological adaptation. People tend to accept higher temperatures when it is warm outside, for instance. Furthermore, the comfortable temperature heavily depends on the activity people do. For public buildings, the metabolism of people is between 105 and 160 W. Lastly, the preferred temperature is very personal. Even when the temperature in a building is 'perfect', still five percent of the people will feel dissatisfied with it. (van der Linden, 2011)

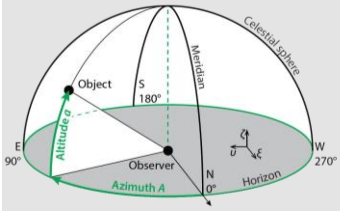



*figure 4.10: Location of the sun; dependent on altitude and azimuth (Smets, Jäger, Isabella, Swaaij, & Zeman, 2016, p. 226)*

*figure 4.11: elevation of the sun per month and day (http://aa.quae.nl/nl/antwoorden/zonpositie.html)*

*Fanger's model*

Commonly, the thermal comfort can be determined by the model of Fanger (1970). It works with a predicted mean vote (PMV) of people. The scale goes from -5 to 5, where -5 is inadmissible cold and 5 is inadmissible hot. Neutral (0) is defined for an unclothed person by an air temperature of 29 °C, relative humidity of 30% and an air speed of 0.1 m/s. The score of comfort is influenced by the cloths people wear, the clo value. In summer people wear average 0.7 clo and in winter 0.9 clo (inside).

To summarize, thermal comfort is mainly dependent on:

- air / radiation temperature;
- relative humidity;
- air velocity;
- outside temperature;
- clothing ($I_{clo}$ value);
- gender;
- metabolism (activity.

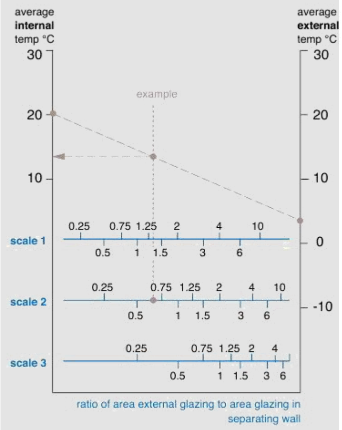



*figure 4.12: nomogram for initial prediction of the average temperature of an atrium by Baker (2009, p. 64)*

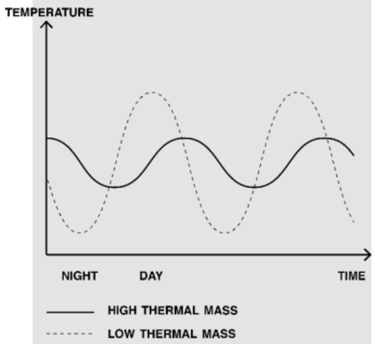


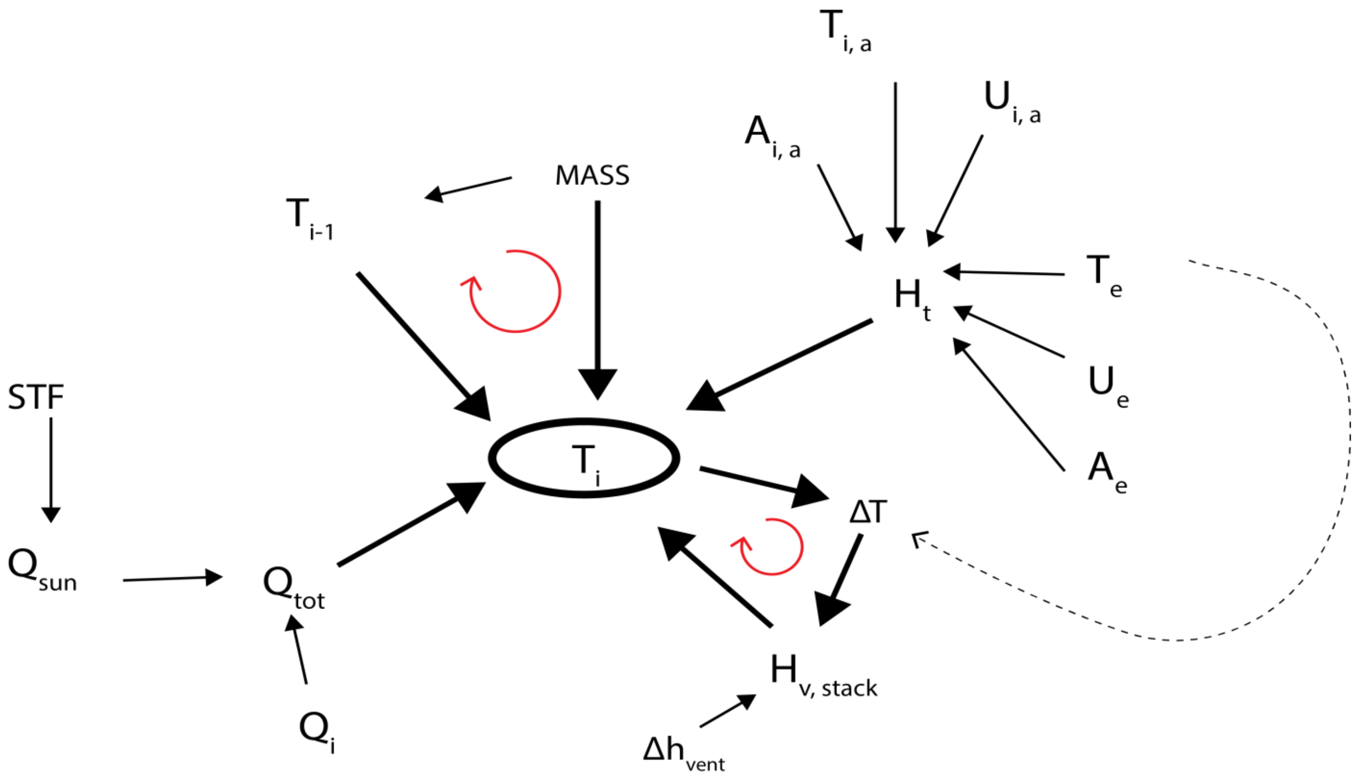

*figure 4.13: thermal mass has a buffering effect, so the temperature peaks and valleys are less extreme in a building with high thermal mass relative to a building with low thermal mass.*

## 4.4 Internal temperature

One of the fundamental contrarieties for an atrium in a moderate climate are the winter and summer situation. In winter, there is need for heat. That is why solar heat gain can be beneficial. In summer when the sun is stronger and the outside temperature higher, then it is likely to have a cooling demand. The heat demands can vary every day. For instance, a cold spring morning, solar heat gain is helpful and a warm early October afternoon does not benefit from heat gain by the sun.

In a building, there are several heat sources. Most common sources, in a passive system, are: sun, electronic gear such as computers and people. To get a grip on the magnitude: people produce approximately 80 to 160 W (depending on their activity) and sun in summer can be up to 1600 W/m$^2$. Heat flow through the building skin can either be a heat loss or gain. The same counts for ventilation air, which typically is in winter a (large) heat loss and in summer either a heat gain or loss. A first estimation can be done with this nomogram (figure 4.12) by Baker (2009, p. 64). This gives you a rough idea to design with

*figure 4.14: sunny and shady side of Delft (left: picture from south, right: picture from north); software like google maps makes it easy to give a quick first insight where sun is coming from and if there are shading obstructions present.*




| Factors | | | Affected by |
|---|---|---|---|
| Inside temperature (°C) previous hour | ($T_{i\text{-}1}$) | → | Parameters of previous hour |
| Inside temperature (°C) on a certain hour of the day | ($T_i$) | → | All parameters, but mostly by mass, ventilation and STF |
| People and equipment (W) | ($Q_i$) | → | Amount, power (kind of use space) |
| Solar heat gain (W) | ($Q_{sun}$) | → | Area glass, g-value / solar transmittance factor (STF), solar irradiance (W/m$^2$) |
| Transmission external skin (W/K) | ($H_t$) | → | U-value external skin ($U_{ext}$), external temperature ($T_{ext}$), external surface area ($A_{ext}$) |
| Transmission internal skin (W/K) | ($H_t$) | → | U-value internal skin adjacent building ($U_{int}$), internal temperature adjacent building ($T_{int}$), internal surface area adjacent building ($A_{int}$) |
| Ventilation transmission by stack effect (W/K) | ($H_{v,\ stack}$) | → | Quantity, external temperature, height difference inlet/outlet |

*figure 4.15: parameters for internal temperature in the dynamic temperature calculation model; Various variables influence the inside temperature. Also, multiple parameters are dependent of each other, which create calculation 'loops'. (see also table next page for symbols)*

in the initial design stage. In a later stage, a more precise calculation of the operating temperature is desired. There a several parameters that influence the inside room temperature (visualized in figure 4.15). Several calculation methods are available, some of

them are explicated in the next paragraph. The following paragraphs discuss different temperature calculation methods and the most significant parameters that influence the inside temperature. The table and figure below show the factors that influence the internal heat in a room. Many factors influence each other, so it is a complex matter to

predict which parameter is important and which is less significant.

### 4.4.1 Temperature calculation

*Steady state heat temperature calculation*

With the steady state temperature model, you can calculate the temperature of a room on one particular moment. Basically, it works with the sum of heat (W) coming in and going out. The heat is calculated by the transmission through the skin and heat gain s or losses through ventilation. Especially for relatively heavy buildings, this calculation method tends to have high inside temperature results because it does not take mass into account (figure 4.13).

$$T_i = \frac{\left(U_e \cdot A_e + \rho c V_e\right) T_e + U_i \cdot A_i \cdot T_{i,a} + (Q_{sun} + Q_i)}{U_e \cdot A_e + U_i \cdot A_i + \rho c V_e}$$

*Equation 4.5*

*Dynamic state temperature calculation*

The dynamic temperature calculation takes the mass of the building into account. In this way mass is taken considered, so you get a result that is more realistic. Several formulas can be used to calculate this, like the Euler method or the analytical method. The following equation is from the standard ISO 1379:2008, and is used since it proved to be the most stable one.

$$T_i = \frac{\left(H \cdot T_e + \frac{M}{3600} \cdot T_{(i-1)} + (Q_{sun} + Q_i)\right)}{\left(H + \frac{M}{3600}\right)}$$

*Equation 4.6*

Both Equation 4.5 and Equation 4.6 show that the internal temperature (the adjacent building) is not very important. Usually, the temperature difference is not very big between the adjacent building and atrium. Also, the insulation value of the adjacent building is generally higher than the external (glass) skin of the atrium. Furthermore, the equation shows that external temperature together with ventilation rate and heat by sun (Q) are important parameters. To what extent, is calculated with the developed parametric model and elaborated on in chapter 6.

| | |
|---|---|
| $A_e$ = | *area external (glass) façade ($m^2$)* |
| $A_i$ = | *area internal façade (adjacent building), ($m^2$)* |
| $H$ = | *total heat transmission by ventilation and heat (e.g. solar); (W/K)* |
| $M$ = | *thermal active mass (kg)* |
| $Q_i$ = | *sum of internal heat sources (e.g. people or equipment), (W)* |
| $Q_{sun}$ = | *heat by sun / solar irradiance (W)* |
| $T_e$ = | *outside air temperature (K)* |
| $T_i$ = | *internal (air) temperature in the calculated space (K)* |
| $T_{i,a}$ = | *Internal (air) temperature in the adjacent building (K)* |
| $T_{i-1}$ = | *internal (air) temperature in the calculated space of the previous hour (K)* |
| $U_e$ = | *external heat transmission coefficient ($W/m^2K$)* |
| $U_i$ = | *internal heat transmission coefficient, for adjacent walls ($W/m^2K$)* |
| $V_e$ = | *ventilation air from outside ($m^3$)* |
| $\rho c$ = | *thermal capacity of air (1200 $J/m^3K$)* |

*Equation 4.5: Steady state temperature model*

*Equation 4.6: Dynamic temperature formula (per hour) used for calculations in analysis from standard ISO 13790:2008*

## 4.4.2 Insulation of glass (transmission external skin):

Generally spoken, a lot is done already to reduce the energy use of large glazed spaces. There are certain factors an atrium can affect regarding energy use. The variables for heat exchange through the skin are convection, conduction and radiation. The value for insulation of glass is the U-value. Currently, best insulating glass products have insulation values of around 1 $m^2K/W$ (see Appendix II). This decreased a lot in the last decade so large glazed spaces suffer less from heat loss and draft.

Also, with certain coatings the thermal behaviour of glass is influenced. One example is the low-e coating (figure 4.16). The optimal coating would be one which transmits daylight 100% and can adjust from transmitting all (near)infrared (when it is cold), and block all (near)infrared when there is no heat needed.

## 4.4.3 Ventilation

This paragraph only considers the heat exchange between inside and outside and the effect on the internal temperature. The calculations in the parametric model only use passive ventilation; stack effect. However, it is possible to ventilate actively. As a rule of thumb for mechanical ventilation, you can take approximately 1 $kw/m^3$. Considering the large amounts of air, active ventilation is discouraged.

Passive ventilation is conducted by the stack effect. 'Hot' air rises, cold air goes down. Especially in summer, when the space heats up, you will get a vertical temperature difference (Baker, 2009, p. 67). With fresh air in the bottom of the space, and 'dirty' air in the top. With ventilation openings in the top and bottom, a 'passive' air flow arises (figure 4.17). This effect can be calculated by the following equations:

$$\frac{1}{A_{eff}^{\ 2}} = \frac{1}{A_{bottom}^{\ 2}} + \frac{1}{A_{top}^{\ 2}}$$

$$\mathrm{H}_{v,stack} = C_d \cdot A_{eff} \sqrt{2gh\frac{\Delta T}{T_i}} \cdot \rho c$$

$$Q_{v,stack} = H_{v,stack} \cdot \Delta T_{i-1}$$

*Equations 4.7*

It is important to have similar dimensions for top and bottom; this has a big effect the effective opening area. Especially the bottom ventilation area is sometimes forgotten or not valued enough.

Since atria have big volumes, the ventilation demand for fresh air is low. So, in winter, if not highly occupied, an atrium will not demand high ventilation rates (Baker, 2009, p. 65). This is an advantage, since in winter the temperature difference between inside and outside is relatively large. High ventilation rate would cause the space to cool down

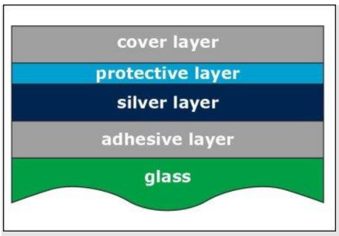
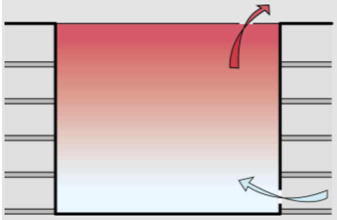
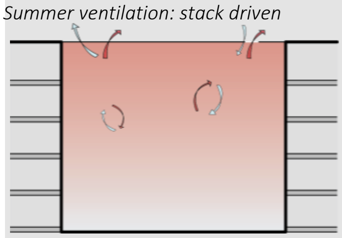



*figure 4.16: conceptual drawing of glass with a low e-coating (Elstner, 2008)*



*Summer ventilation: stack driven*



*Winter ventilation: high elevation ventilation*

*figure 4.17: ventilation in winter and summer. Ventilation in summer by stack effect, with unequal temperature distribution in room. In winter, ventilation only by opening in top, gives a relative equal temperature mixture (based on Baker (2009, p. 67)).*

*Equations 4.7 used for thermal calculations (Bokel, 2014)*

| | |
|---|---|
| $A_{bottom}$ = | area ventilation opening bottom ($m^2$) |
| $A_{eff}$ = | area effective ventilation opening ($m^2$) |
| $A_{top}$ = | area ventilation opening top ($m^2$) |
| Cd = | discharge coefficient |
| g = | gravitational acceleration ($m/s^2$) |
| h = | height difference between ventilation openings |

radically. With only the top ventilation opened, you can achieve a low rate of passive ventilation. Cold air will descend and dirty and fresh air mix in the space (figure 4.17).

As a rule of thumb, an atrium needs approximately 4 to 6.5% ventilation opening of the floor area (Blesgraaf et al., 1996, p. 41). However, the results from the parametric calculation model which is developed, show that for large atria this is not sufficient anymore (chapter 6).

| | |
|---|---|
| $H_{v,stack}$ = | *heat transmission by stack ventilation (W/K)* |
| $Q_{v,stack}$ = | *heat by ventilation (W)* |
| $\Delta T$ = | *temperature difference outside/inside* |
| $\Delta T_{i-1}$ = | *temperature difference outside/inside previous hour* |

### 4.4.4 Shading/solar control

To reduce the solar heat gain, shading can be added to a glass façade or roof in roughly three types: external, integrated and internal shading (figure 4.21). These are discussed in the next paragraphs.

*External shading*

External shading is very efficient energy-wise. Heat from sunlight is reflected outside the building, External shading may be adjusted so the shading can be adapted to the user demands like (figure 4.18). A disadvantage of external shading is that is not protected weather influences (e.g. wind and snow). Also, the need for extra construction materials is a disadvantage (relatively to integrated shading).

*figure 4.18: top: adaptable external shading of tower Al Bahar tower. Middle and bottom: external shading with PV (Wurm, 2007, p. 133)*

*Integrated shading*

Shading integrated into the glazed façade means that it is attached on or in the glass product. So, the shading can be located at the outside, inside or for example in the cavity of double glass. How much of the solar heat gets inside, depends on which layer the shading is located. The more the shading is placed to the outside, the less heat comes in. This can be calculated with Appendix III: STF with integrated PV. Aesthetically, integrated shading has an advantage since these measures can be nearly invisible. Photovoltaic cells in glazed roofs are often integrated in the glass panel. The next chapter goes into depth about the options for solar cells integrated in glass. 'Regular' measure to prevent solar heat gain are discussed below:

- Dichroic coating: filters light result is a colour
- Enamelling: a ceramic, corrosion resistant coating. Only suitable for thermal toughened glass since this can withstand high thermal stresses caused by the pigments.
- Silk-screen printing: colours and patterns are printed and then baked in an oven.
- Fritting: a ceramic deposition on the interlayer of laminated glass
- Coloured glass: is dissolved (e.g. turpentine), then applied to the glass and baked.

(Herzog, Krippner, & Lang, 2004, pp. 186 - 188)

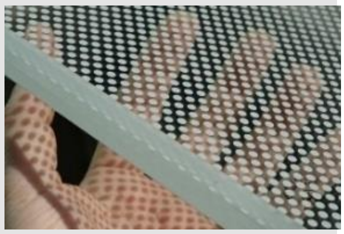


*figure 4.19: fritted glass*

With all these techniques, designers have much freedom. So, these approaches can produce glass art.

*Internal shading*

One of the options to shade an atrium is internal shading. An advantage of internal shading is that the system is not exposed to the outdoors environment. Especially with a dynamic system this could be a relevant advantage. Moving parts do not have to be water resistant and wind is cannot damage them for instance. An example is the shading system of the Reichstag in Berlin (figure 4.20). It follows the sun and shades direct sunlight. A disadvantage is that heat is not effectively reflected, so the heat load is bigger than the two alternative systems. However, internal shading can be very effective to prevent glare.

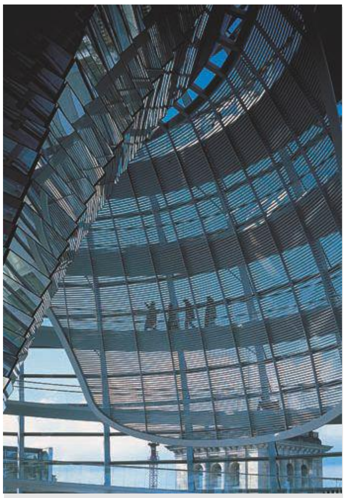


*figure 4.20: rotating metal screen controls solar gain in Reichstag, Berlin (Wurm, 2007, p. 133)*

## 4.5 Conclusion

The solar path and the insolation values of the location should be studied. For transparent roof structures, the solar transmittance factor (STF) is one of the most important parameters to calculate the internal temperature. A detailed study on how to analyse the solar behaviour in combination with a building case, is elaborated on in chapter 6. Several calculation methods are available, ISO 1379:2008 is used in this thesis for calculations. It is important that mass is considered in temperature calculations to get a realistic result. Passive ventilation is important to lose heat in summer, without energy use. During design, an adequate ventilation opening area should be kept in mind, both in the top and bottom. There are roughly three types of shading: external, integrated and internal shading. External shading is most effective in keeping the heat out, but has some practical disadvantages. Integrated shading is aesthetically a good option and gives designers much freedom. Internal shading is from an energetic point of view not the best choice (reflect solar irradiance), but can be very effective against glare for example. Concluding you can say that engineering the climate of a large glazed structure is a delicate practise. Many parameters are considered for temperature calculation.

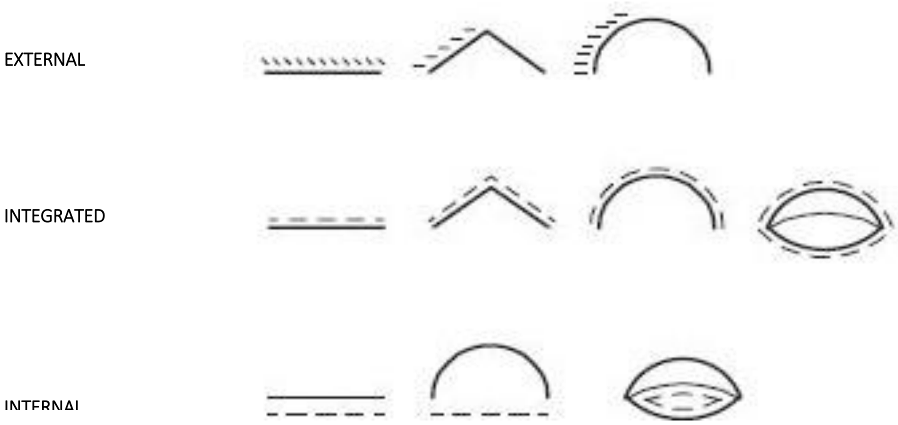



*figure 4.21: Solar control measures for glass roofs (Wurm, 2007)*

# 5 Photovoltaic cells - integrated in the transparent building skin

## 5.1 Introduction

Some people say that there is an energy usage problem and not an energy problem, since there is so much energy from the sun on earth. It is expected that PV will be the main resource for on-site generation of electricity (Casini, 2016, p. 21). Photovoltaic cells (PV) are electronic devices that convert solar energy of sunlight into electricity (Gevorkian, 2008, p. 1). The word photovoltaic is a combination of photo, which means light in Greek, and volt which is the unit for electric potential difference (named after physicist Alessandro Volta). This is done by semiconductors which have a 'photovoltaic effect'. When there is sunlight, solar cells produce electricity and without sunlight there is no production. Photovoltaic cells are unique energy producers since they do not have any moving parts. This makes the cells less vulnerable for wear. The conversion efficiency of commercial available PV cells ranges from approximately 7 to 23%. Because energy that is produced is a renewable and there is no pollution in the use phase, PV is considered as a sustainable way to make energy. However, the total lifecycle of PV cells should always be considered because this can influence the energetic payback time.

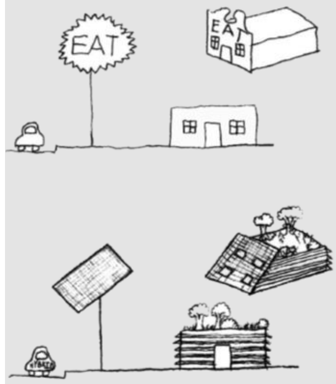



*figure 5.1: decorated shed versus the 'greenwashed' shed by (Mackey, 2015, p. 21) based on Venturi's duck and decorated shed.*

Currently, the choice to use solar cells is not made in the first phase of the design process. Often, they are added later, to give a building a sustainable appearance. The consequence can be that cells are not applied efficiently or aesthetically. This is illustrated by figure 5.1, a 'greenwashed' shed; PV cells only added to show or make impression that the building is 'sustainable'. When solar cells are considered early in the design phase, only then solar cell can get truly integrated. There is a huge potential to integrate PV in building elements. There are two types of PV integration:

- PV units are integrated in the aesthetic design but are solely used to generate energy;
- PV units are used to generate energy and replace a function of a building component.

Furthermore, almost all building elements of the skin, of a building are suitable for the installation of PV states Casini (2016, p. 21). You could think of roof mountings with standard PV modules, roof tiles or slates, glass laminate (transparent) PV, double glazed PV, sunshades (figure 5.2); (Mark, 2012). In the case of integrate PV cells into a transparent roof structure, there are several possible technologies to use, which are discussed in this chapter.

*figure 5.2: integrated PV cells in sunscreens with multiple function: shade and produce energy (Kaan & Reijenga, 2002) .*

Translucent (integrated) PV can be used to lower the cooling demand in buildings, which is often the case with spaces with a large area of glass. One could see semi-transparent PV as a sophisticated alternative for tinted or ceramic fritted glass. It will reduce the solar gain and generate solar electricity. You can achieve semi-transparent PV with spaced opaque crystalline cells or thin-film transparent PV cells for example. (Casini, 2016, pp. 36 - 37)

The aim of this chapter is to inform how solar cells work and how to apply in a transparent roof, to use them both for shading as energy production.

*figure 5.3: Bejar market in Spain; semi-transparent, integrated PV in a glass roof (Yang & Athienitis, 2016, p. 888).*

## 5.2 Solar cells and the system

This section elaborates on how solar cells work and which options do you have as a designer to integrate them in a transparent roof. Only techniques that are feasible to use on the building scale (e.g. cost) and with the ability to integrate in a glass product are considered. Appendix I – overview PV technologies, gives an overview of all PV technologies that are investigated. Also, the boundary of a semi-transparent result should be kept in mind.

### 5.2.1 How does a solar cell system work?

A layout of photovoltaic cells consists of several electronic devices. The total system is called the "balance of system" (BoS). A basic understanding from the whole system is needed to work with solar cells as a building.

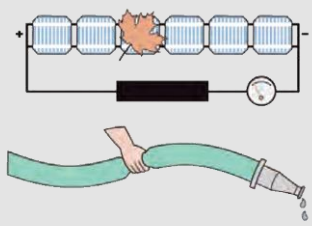


*figure 5.4: the effect of local shading in a PV string can be compared with squeezing a hosepipe (Roberts & Guariento, 2009)*

*Layout*

The solar cell layout affects the total yield. The efficiency of most inverters is not high with low voltages (Roberts & Guariento, 2009). Since the voltage of the grid is relatively high (between 110 and 240V), it is preferable to get an output from the solar panels with high voltage. This can be achieved by connecting the solar cells in series. In series, the voltage goes up with every solar cell and the current stays low. However, an important downside of series connection is the vulnerability to shading, illustrated by figure 5.4. When connected parallel, the voltage stays low and the current goes up with every cell. The

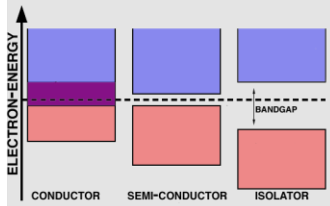



*figure 5.6: semi-conductor is between the conductor and isolator. Based on https://sv.wikipedia.org/wiki/Bandgap#/media/File:Isolator-metall.svg*

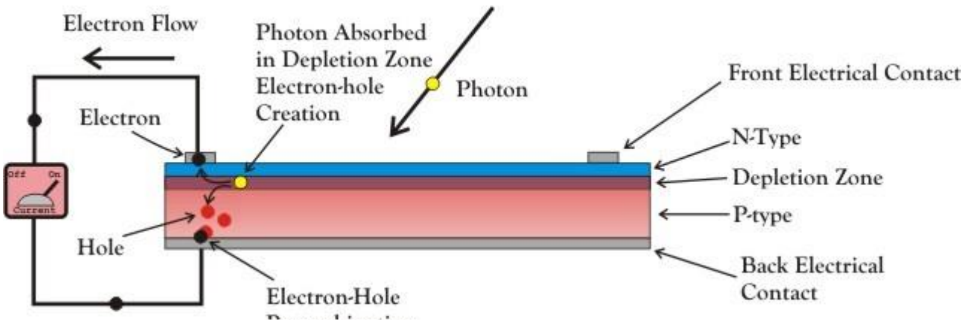



*figure 5.5: The principle of a solar cell (https://www.electrical4u.com/solar-cell/)*

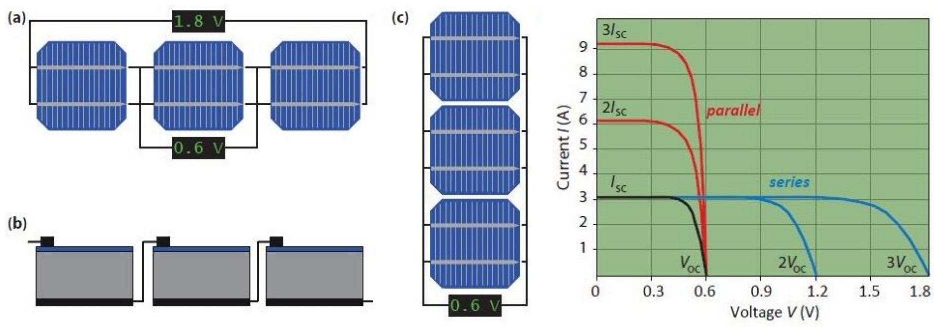



*figure 5.7: effect of series or parallel connection of solar cells (Smets et al., 2016, p. 253)*

**Parallel:** Voltage (U) = $U_1 + U_2 + .... + U_n$
**Series:** Current (A) = $I_1 + I_2 + .... + I_n$

consequence of a parallel connection are thicker, or more cables per solar panel. Also, it will lead to very high resistive losses (Smets et al., 2016, pp. 256-258).

*Solar cell*

PV cells are constructed from semiconductor material. The material which is used in most solar cells is (crystalline) silicon (Si). A semiconductor has conducting properties which are in between a conductor (copper, gold, iron, etc.) and an insulator (glass); (figure 5.6). Conductors have loosely bound electrons so they can be detached very easy by an electric current. Insulators have very strong bound electrons so they do not conduct electricity. A semiconductor has, just as an isolator a band gap, but a relatively small one. Photons from sunlight can 'push' electrons over this bandgap is the energy is sufficient (figure 5.5). In that way, a current starts and electricity is produced. (Gevorkian, 2008, pp. 1 - 20)

The power output of a PV layout is calculated by the following equation:

$$P = \eta \cdot R \cdot A_{cell}$$

*Equation 5.1: P = power (W), $A_{cell}$= area covered with PV cells ($m^2$), R= solar irradiance ($W/m^2$), η = efficiency (Sánchez & Izard, 2015)*

*Inverter*

The output of solar cells is a direct current (DC). 'Normal' electricity from the grid, is alternating current (AC). Power from a PV cell is converted most of the times to AC so it can be used just like electricity from the grid. This is done by an inverter, which has an efficiency of around 98%. If the power produced by the PV layout is to low, it could lead to extra power loss; if the power is to high the inverter may be damaged (Ferrara et al., 2017, pp. 241 - 242). Usually, a small layout needs just one inverter, but bigger scale layouts (e.g. public buildings), often need several inverters.

*Bypass diode*

As mentioned, the downside of a series connection is that the weakest link in the chain determents the maximum output. When partial shaded, it is possible this will heat up and eventually cause fire. These so-called 'hot-spots' damage cells already before fire; thus, reduce the lifetime of a PV system. When the connection of cells attempts to drive the relatively high currency through the shaded cell, the voltage becomes negative. So, this shaded cell will use energy instead. This power that it uses is converted to heat. (Smets et al., 2016, pp. 256-258)

Bypass diodes are often used in PV systems to protect the system for overheating and minimizing the yield reduction effect of partial shading. When the current becomes negative due to partial shading, a bypass diode passes the current to the next cells in the (sub)string, instead of that it is let through the shaded cell. The point when a cell switches from energy producing to consuming differs per PV cell type. Also, when the diode passes a cell/sub-string depends. Normally, a bypass diode will skip a sub-string when there is a difference of approximately 20% of energy yield. Usually, speaking of crystalline solar cells, every 20 cells get a bypass diode. So, when a string of cells consists for example of 60 cells, the panel will get four bypass diodes creating ‘sub-strings’. (Solar Edge, 2010)

### 5.2.2 Orientation

The total yield of a PV array is also effected by the orientation of the cells. The dependence of the angle of incident of sunlight varies per technology (figure 5.8). Crystalline solar cells, for example, are sensitive for angle change. The optimal slope angle in the Netherlands is about 36° (0° = flat, 90° = vertical). The optimal azimuth is 178° (Almost south, 2° rotated to the east); (calculated with the tool of Huld and Dunlop (2017)). Typically, thin film technologies are less dependent the of angle of incident since they also work with lower light levels. With a suboptimal orientation, this could mean that it is possible the thin film panel has a higher yearly yield. Even though the Watt-Peak per square meter of a crystalline silicon panel is higher.

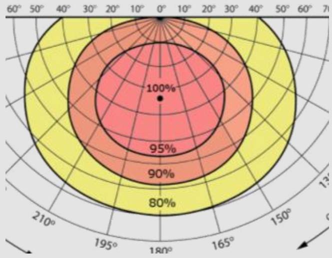



*figure 5.8: efficiency crystalline silicon solar cell depends on surface orientation*

### 5.2.3 Payback time

Two sorts of payback time are considered: the energy payback and the payback time in terms of cost. Both should be at least within their lifetime to make to make the use of photovoltaic modules affordable, both economic as environmental.

*Energy payback time*

Until the moment a PV module is installed on a building, a certain amount of energy is put in, to get it there. This is the invested energy (figure 5.9). Gathering raw materials, production and transport should be considered. Also, the frame which hosts the PV needs energy to make, it depends on the technique how much. During its lifetime, the PV module produces a certain amount of energy. The time that it takes to level the invested energy and the produced energy, is called the energy payback time (Equation 5.2). For monocrystalline silicon solar cells, this is approximately two years (figure 5.10). Of course, this is highly dependent of the location, orientation, shades, etc. The energy produced during its lifetime, is about seven times higher than the invested energy. To produce crystalline silicon cells, silicon is melted at a temperature of approximately 1400 °C. New techniques like several thin film and nano technologies use (potentially) little energy for their production. Some because they use much less material like amorphous silicon (roughly 100 times thinner than crystalline silicon). Others use different materials, for example organic PV. No rare metals are used, which otherwise should be mined. Total energy input

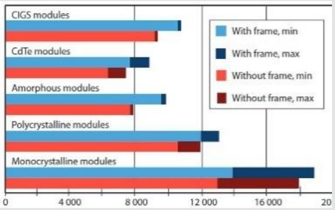



*figure 5.9: primary energy use for manufacturing different PV systems ($kWh/kW_p$); top to bottom: CIGS, CdTe, a-Si, poly c-Si, mono c-Si. The three upper techniques (thin films) use about 30 to 50% less primary energy relative to crystalline silicon cells. (Smets et al., 2016, p. 346)*

$$Energy\ payback\ time\,(years) = \frac{total\ energy\ input}{annual\,energy\ yield}$$

*Equation 5.2*

*Economic payback time*

People who invest in solar cells are especially interested in the costs, and its payback time. A solar system will always be more expensive than a regular building component without solar energy production. Prices of solar modules are built from the PV module price itself and the price of everything besides that (frame, cables, inverter, construction, etc.), what is called the balance of system (BoS). Prices are expressed in cost per Wpeak (Wp). According to Campbell (2017, p. 854) the cost of a PV module in 2008 was $5.92/Wp (PV: $4.02, BoS: $1.77). In 2015 this was just $1.33 (PV: $0.55, BoS: $0.68), which was just 22% of the price in 2008. Like figure 5.12 shows, cost is going down when the production of solar cells goes up. Both for crystalline silicon as for thin film cost is reducing rapidly and significantly.

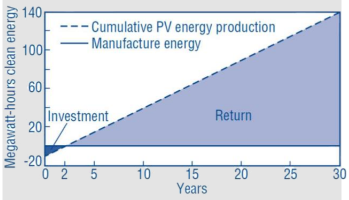



*figure 5.10: PV module (c-Si) energy payback time of 2 years; during expected lifetime of nearly 30 years, the module produces multiple times the invested energy (U.S. Department of Energy, 2004, p. 2)*

## 5.2.4 Second order effect: heat gain reduction by shading with PV:

Photovoltaics applied in a transparent building skin do not only produce energy, but can also contribute significantly to initial energy savings (besides energy production). Research shows that a c-Si system can reduce the solar heat gain by 65%, over the year. Thus, also an optional cooling load reduces. Theoretical and practical test results show that the annual electricity consumption can be reduced by up to 28% (James et al., 2009); (figure 5.11). Of course, it depends on the specific case how much energy can be saved, but this shows that you cannot only judge the payback time (energetic and economic) on the PV system itself. So, also second order effect have to be taken into account to calculate the energetic and economic payback time. (Skandalos & Karamanis, 2015, pp. 317-318)

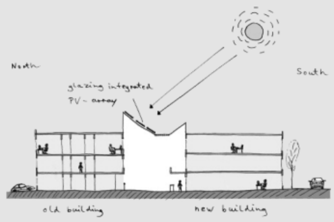



*figure 5.11: PV cells as a replacement for shading, placed on the most intensely radiated part of the roof (James et al., 2009, p. 222)*

Exactly this combination is tested in the developed parametric model and method (Part B – analyses)

## 5.2.5 Static versus dynamic

Static solar radiation control systems are not enough to meet the modern demands of sustainability and indoor comfort quality according to Casini (2016, p. 302). Even a system which is fixed but optimized to the solar path, will not react on the weather of that day or a cold summer day. Such a system is always bound to averages. A dynamic system has the advantage that it will change per current environment condition. Also, in most cases it can

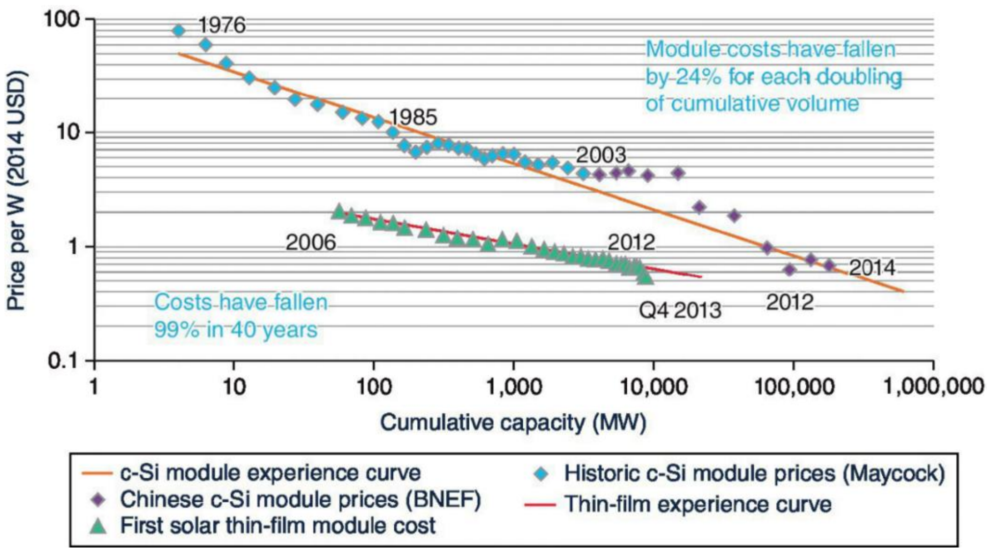



*figure 5.12: cost reduces when capacity increases (Campbell, 2017, p. 853)*

be manually adapted to the preferences of a user of that moment. For example, the system blocks glare, but on that moment, a person also wants to look outside.

Three practical examples of responsive design are (Wyckmans, Aschehoug, & Hestnes, 2007, p. 91):

- Switchable glazing;
- Mechanical daylighting and shading devices;
- Pneumatic structures;

A dynamic system is only profitable when pays itself back during its lifetime. Namely, a dynamic system will always cost more than a static one. Also, new concepts are developed with dynamic PV, such as the example in figure 5.13. Below, you can see the extra yield that can be gained with a pneumatic system with mono-c-Si panels:

*figure 5.13: PV Shade: Lamella's are angle selective, provide glare control, generates energy and is still (semi)transparent (Ferrara, Wilson, & Sprenger, 2017, p. 241)*

However, with the information of this thesis, it is believed that new technologies with less angle of incident dependence, do not need tracking as much as c-Si panels. Also, with semi-transparent properties PV can be transparent and producing energy, at the same time.

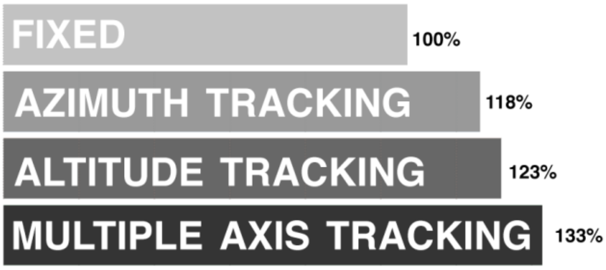



*figure 5.14: extra electrical yield with 'regular' single and multiple axis tracking systems for mono-crystalline silicon PV panels (based on Broersma (2008); Skandalos and Karamanis (2015))*

## 5.2.6 Other factors to consider

*Temperature*

Generally, solar cells work best at low temperatures. When the temperature of a PV panel rises, the efficiency goes down with a rate of 0.3-0.5% per degree (Casini, 2016, p. 83; Gaglia, Lykoudis, Argiriou, Balaras, & Dialynas, 2017). When the temperature increases, the current goes slightly up, but the voltage decreases significantly. Furthermore, high temperatures can damage solar cells. So, to guarantee the lifetime and efficiency rates of solar cells, proper thermal management is needed (U.S. Department of Energy, 2013). Also, when you consider solar cells in a transparent enclosure, this heat production is an indirect heat gain. This effect can be included in a solar heat gain (g-value) calculation.

*Wavelength*

Solar cells absorb just a part of the solar spectrum (figure 4.3). A portion is reflected and another portion passes through. From the part that is absorbed only a relatively small part is turned into electricity (U.S. Department of Energy, 2013). The remaining, relative large part, is turned into heat or reflected. The 'absorption' spectrum depends on which technology and colour are used. In figure 5.15 you can see the absorption spectrum of different technologies. However, the (semi) transparency in practise heavily depends on the thickness of the cell and if present, spacing of cells. Obviously, if integrated in glass, the total of all layers (e.g. glass-PV cell-glass) should be considered to assess the transparency.

For integration into transparent building components the goal would be 100% absorption of the near infrared part, and 0% in the visible part. In that way 52.2% of the solar energy would be stopped at the façade, prevented to heat the internal space. This is exactly what Powerwindow tries to do (see page 57).

*Reflection*

A cells efficiency is affected by the amount of light that is reflected from the surface. For example, untreated silicon reflects around 30% of the incident light. The reflection coefficient is reduced by anti-reflection coatings (e.g. $TiO_2$). Obviously, also the material which covers the cell should be considered (usually glass). When the incident angle decreases, the reflection goes up. (U.S. Department of Energy, 2013)

*Detailing*

Important issues that should be taken into account with integrating PV into a building skin are (Chartered Institution of Building Services Engineers, 2000, p. 11):

- avoid shading (upstands, other components of the system, handrails etc.);
- thermal movement;
- insulation (if heat is prevented from leaving the back of a PV array local temperatures may exceed 100 °C);
- how and where to run electrical wiring.

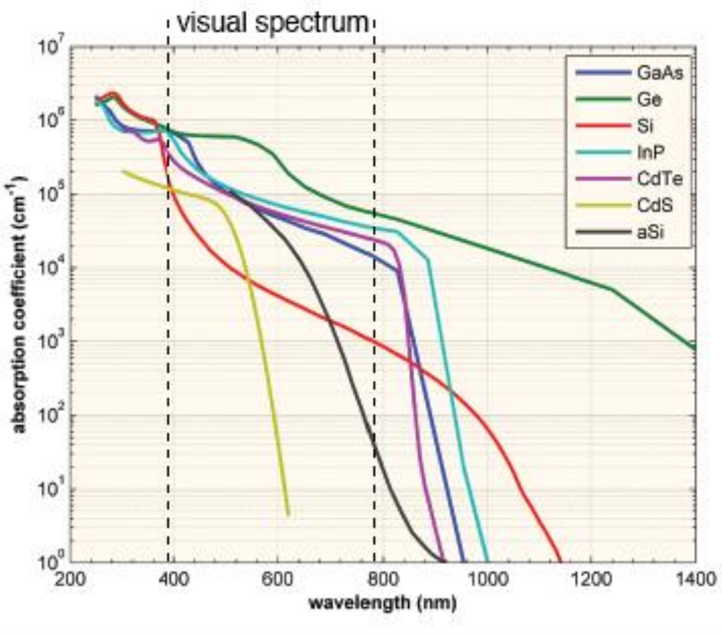



*figure 5.15: absorption coefficient of different solar cell technologies. Based on (Honsberg & Bowden, 2016)*

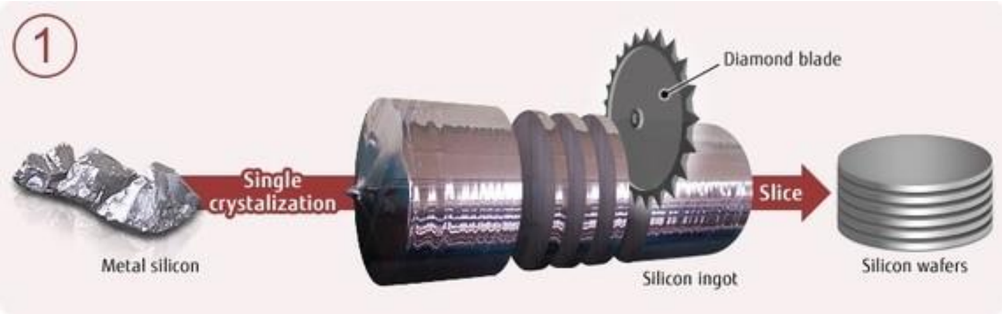



*figure 5.17: The production of monocrystalline silicon wafers*

*figure 5.18: 'regular' crystalline silicon laminated in a double glazed module (Casini, 2016, pp. 329, 331)*

*left: in the early days, the cells were not sawn into rectangles.*

*right: bended cells in warm bended glass*

| Cells/m$^2$ | Transparency (%) | Power (Wp) |
|---|---|---|
| 12 | 70 | 48 |
| 18 | 55 | 72 |
| 24 | 41 | 96 |
| 30 | 27 | 120 |
| 36 | 12 | 144 |

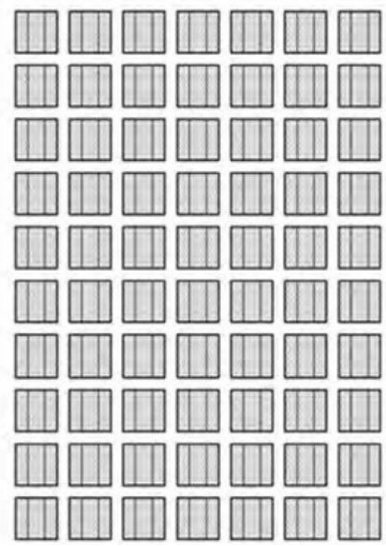


*figure 5.19: polycrystalline silicon glass-glass module yields (Casini, 2016, p. 333)*

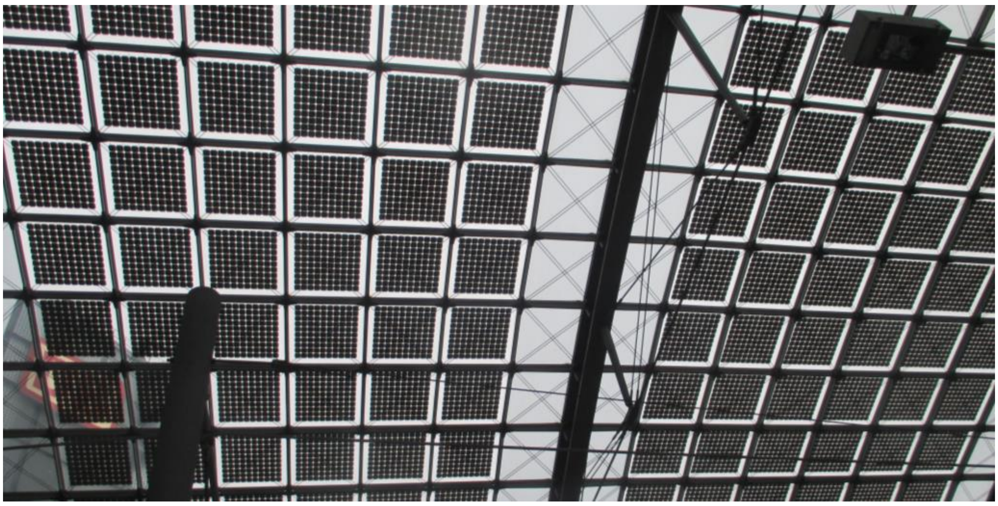


*figure 5.20: close spaced mono c-Si cells in the roof of Hauptbahnhof in Berlin (photo by Silke Prinsse)*

## 5.3 (semi) Transparent building integrated PV cells

### 5.3.1 Conventional systems

*Crystalline silicon*

The application of crystalline silicon (c-Si) solar cells is considered as a well-established. They count as the first generation of solar cells. Crystalline silicon is widely used, and there are many examples of the application in glass-glass semi-transparent window systems. In this system, crystalline cells are placed in between two glass panes, encapsulated in an (ethylene vinyl acetate) or polyvinyl butyral (PVB) film (figure 5.21). The outer pane is made of a highly transparent one. Solar energy conversion to electricity efficiencies range from 16 to 24%. The Wp/m$^2$ is relatively high, but the Wp/cost is also rather high. The main cost of a c-Si system comes from the wafers itself, not the rest of the BoS. (Skandalos & Karamanis, 2015, p. 307)

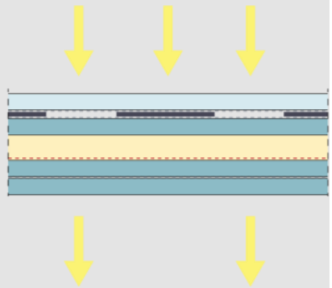


*figure 5.21: crystalline solar cells are typically located at the second layer in the glass product. Out glass pane has high translucency and has an anti-reflection coating.*

c-Si cells can be divided into two types: mono- and polycrystalline silicon. Mono c-Si have the best conversion efficiencies and are more expensive. The wafers are cut from a circular silicon ingot. Hereafter, they are cut in to rectangular or square pieces. Standard dimensions are 150x150mm. Poly c-Si cells are made of recycled silicon wafers or cut losses and have less even aesthetics; they are less visually attractive. Also, the conversion efficiency is typically lower.

Crystalline silicon cells are opaque, so a semi-transparent will always consist of transparent and closed parts. This is a compromise in the terms of architectural aesthetics, since architects will always strive for an equal look in windows. Only when this is a specific goal, an unequal look can be admissible. Quality of daylighting is limited, since the outside view is obstructed to a certain extend. However, when density of the cells increase, the energy production goes up, and the cooling loads down. To balance the density of the cells and the open parts, is an important trade-off. (Skandalos & Karamanis, 2015, p. 307)

| **Cell density (%)** | 11.1 | 13.1 | 16.5 | 19.0 | 27.5 |
|---|---|---|---|---|---|
| **Power (W/m$^2$)** | 13.1 | 15.0 | 18.8 | 21.5 | 31.0 |

(see Appendix II)

*Thin film family*

The thin film family is the second generation of PV. Most common members of the family are amorphous silicon (a-Si), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe). A typical property of thin film technologies is that they can be flexible. Because of the extreme small thickness of solar cell, the flexibility mainly depends on the substrate it is on. Glass as a substrate is mainly used. In most cases the thin film is located at the interlayer of laminated glass, just like crystalline silicon cells. In a roll-to-roll process, thin film technologies are easy to produce (Reinders et al., 2017, p. 296). The thin film family consist of several technologies with comparable properties. The most use thin films are: amorphous silicon (a-Si),

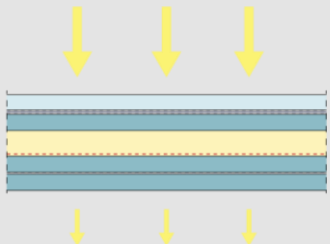


*figure 5.22: Thin film located in the second layer (from outside).*

Thin film techniques perform, relative to crystalline techniques, good in diffuse sunlight. Casini (2016, p. 333) states that this fact can even overcome the peak performance of regular crystalline cells. The yearly energy yield can be 15% higher, depending on the climate. This becomes even higher if installations are shaded often, since shading affects thin film less than crystalline silicon (Sampatakos, 2014, p. 48). Also, the manufacturing cost and energy is lower than c-Si solar cells (Casini, 2016, p. 333; Gevorkian, 2008, pp. 11 - 12).

*figure 5.23: checkered pattern of thin film on glass (Sampatakos, 2014, p. 42)*

### 5.3.2 Emerging systems

*Dye-sensitized solar cells (DSSCs)*

Dye-sensitized solar cells are made of both inorganic and organic materials. For the anode side, titanium dioxide ($TiO_2$) is used, since it is transparent (Casini, 2016, p. 341). The cathode side is fluoride, tin oxide (also transparent). The PV cells itself consist of a organic pigment, the dye. In that sense, you can call DSSCs artificial photosynthesis. You can see in figure 5.25 the aesthetics that DSSCs can add, since the dyes are available in various colours. For architects and artists, a whole new option pallet emerges for PV window design.

DSSCs have several benefits: they are easy and cheap to produce. Roll printing techniques are possible and for example, screen printing too (figure 5.29). The efficiency is relatively high and the embodied energy low. Like thin film PV cells, DSSCs perform relatively good in diffuse light and low light levels (Hagfeldt, Boschloo, Sun, Kloo, & Pettersson, 2010, p. 6599). Also, the technique is less vulnerable for local shading compared to regular c-Si panels (figure 5.26). Thus, DSSCs have a short energetic (<1 year) and (potential) econmic payback time. On the building scale, DSSCs are not applied very often. The technology is in full development, so there are some challenges to overcome. The main challenge for fundamental researchers is how to maintain the high efficiency and ensure a long lifetime.

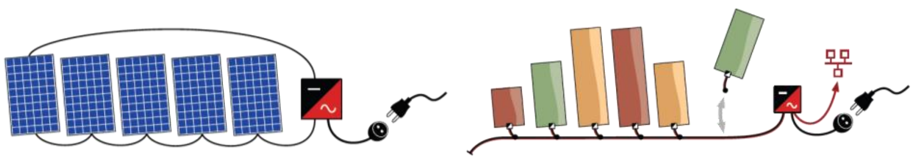


*figure 5.26: The way that DSSCs (right) are connected to the string, is less vulnerable for local shading than regular solar panels (left) (solaronix, 2017, p. 4).*

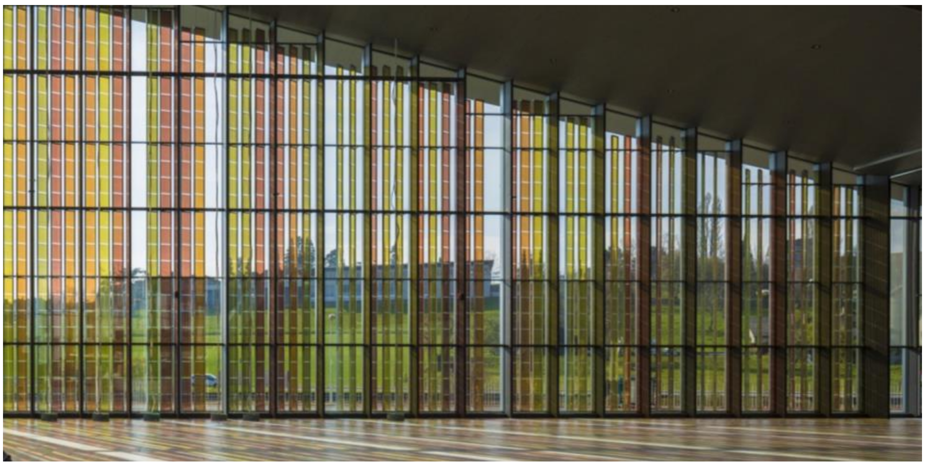


*figure 5.25 (above): freedom to design with colours and shapes*

*figure 5.25 (l): DSSC building application, Swiss tech convention center. Photo: Fernando Guerra*

This thesis makes the assumption that within several years problems like the limited lifetime are overcome. (Lin, Huang, Chen, & Kung, 2015)

*Organic PV (OPV)*

Organic PV has various similar (dis)advantages as DSSCs. However, it seems that the printing and production techniques has even more potential. Especially on flexible products, OPV stands out. Again, freedom of design is a big advantage like the example of figure 5.27. One big disadvantage is the stability. It suffers from photochemical degradation (Reinders et al., 2017) (Gevaerts, 2017).

*Sphelar*

Sphelar is a product of 3d shaped mono-crystalline silicon. In this way, the conversion efficiency, it is less dependent for the angle of incident of sunlight. Furthermore, this product has a uniform aesthetic, especially compared to regular crystalline silicon as described before. (Biancardo et al., 2007)

*Solar cells not in plane (e.g. Powerwindow, Pythagoras glass)*

These products try to redirect as much of the invisible part and as little as possible of the visible part of the spectrum to an area perpendicular to the glass. Powerwindow is a product in development from the start-up “PHYSEE”. In the frame, CIGS solar cells convert the light to electricity, with high efficiency. Their coating makes use of the element Thulium (Tm) which transmits a large part of the visible light (see paragraph 4.2.1), but reflects an important part of the near infrared spectrum (1134nm and 1218nm). (de Jong et al., 2015, p. 1)

Grapperhaus and Kesteloo (2016) claim that the coating can be applied to any transparent surface (glass, plastics, etc.) and curved surfaces are not a problem. The ‘most transparent’ window has an efficiency of 20 W/m$^2$ and a little darker tinted window would produce 45 W/m$^2$. Apparently, some of the visible spectrum is also reflected since the transparency goes

*figure 5.27: OPV art in glass (Reinders, Verlinden, van Sark, & Freundlich, 2017, p. 434)*

*figure 5.28: Sphelar 3d mono c-Si in glass. . http://www.sphelarpower.com/)*

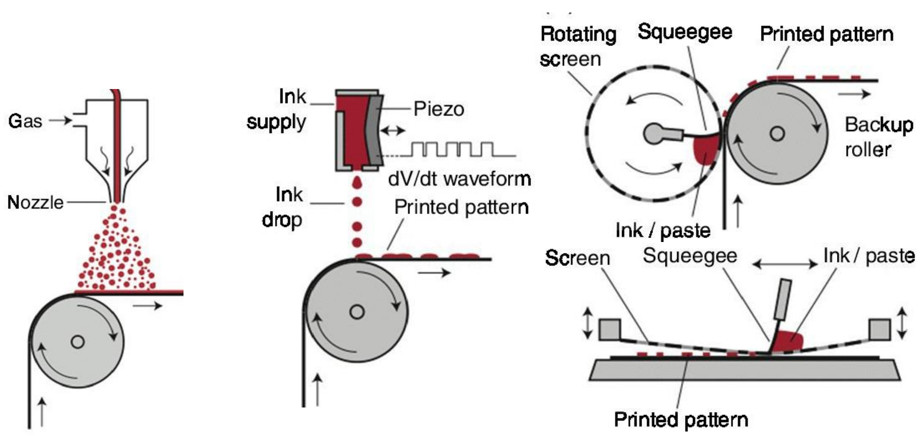



*figure 5.29: some of the printing techniques available for OPV and DSSCs (e.g. inkjet and screen printing); (Kettle et al., 2015).*

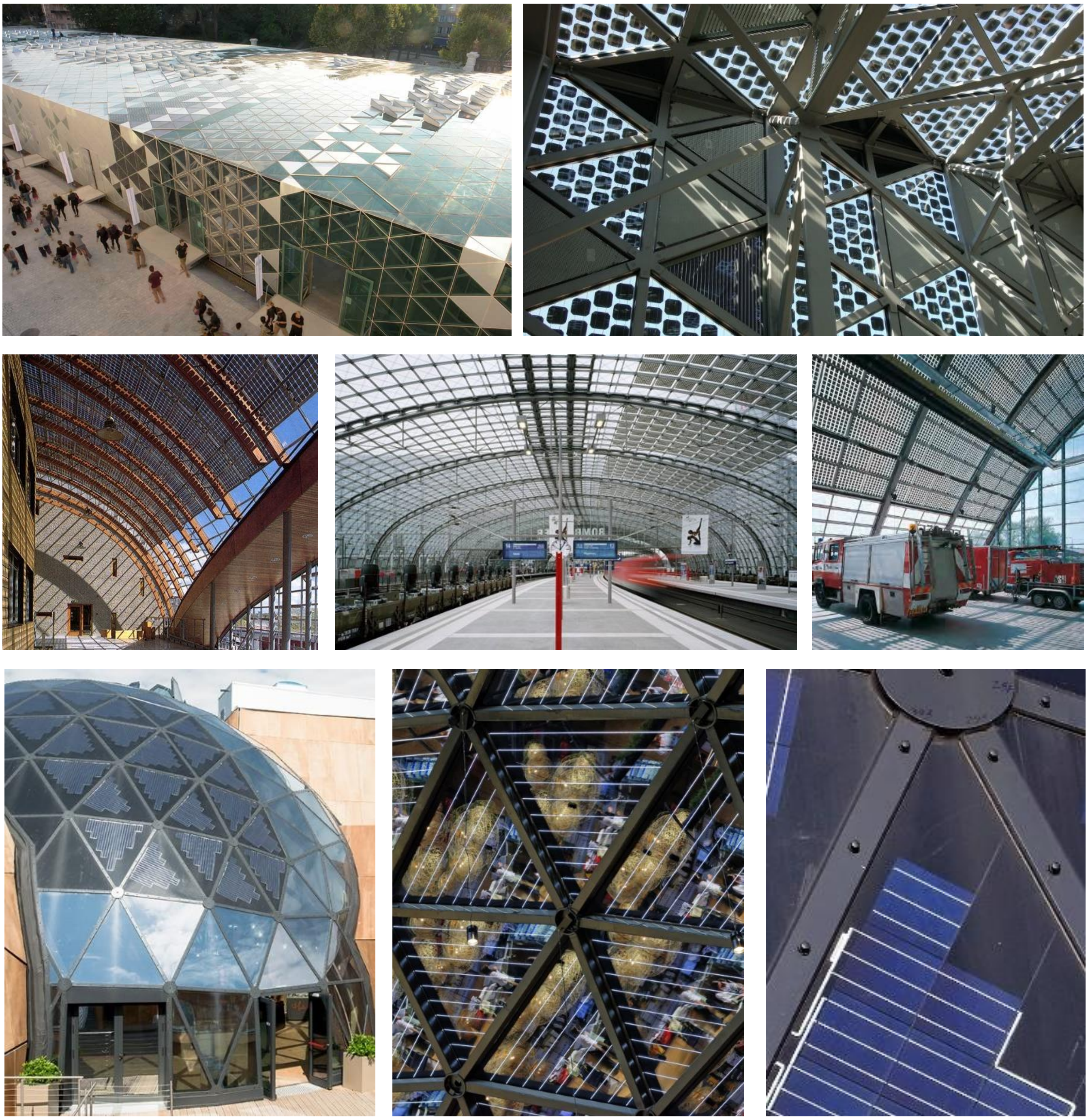


*figure 5.30:*

*top: Crystalline silicon and thin film mixed in a design made of triangles; Cite du Design in Saint-Étienne*

*middle: PV integrated in single curved glazed roof; ECN building in Petten, hauptbahnhof in Berlin, fire station in Houten*

*bottom: Grid shell with integrated PV; Belgium pavilion at expo Milan in 2015 (http://www.patrickgenard.com/en/projects/-pabellon-belga-expo-milan-2015)* down with the more efficient version. Pythagoras glass does somewhat like Powerwindow, but the efficiency is little higher and it is more visible; has a lower light transmittance factor.

These techniques have a large potential since it blocks a large part of the incoming IR, which limits the solar heat gain. However, the efficiency of this system is not very high, relative to other PV technologies. But, if in the future it is feasible to coat all windows in a building, maybe a low efficiency does not matter anymore.

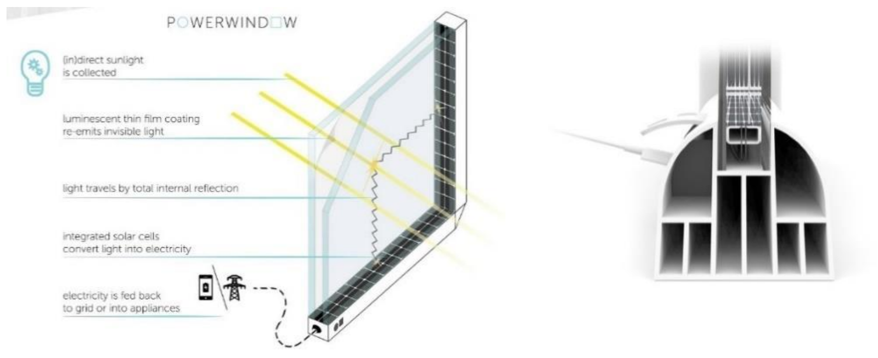



*figure 5.31: powerwindow by PHYSEE (de Jong, Kesteloo, & van der Kolk, 2015; Grapperhaus & Kesteloo, 2016); reflect mainly the invisible part of the spectrum to the frame where it is converted to electricity by CIGS solar cells,*

## 5.4 References integrated PV in glass – shading and energy production

Some references are elaborated on, which make use of the shading character of PV cells and have them integrated in glass.

*Cite du Design - Saint-Étienne (figure 5.30, top)*

The skin of this building is made of triangles. This example is interesting because solar cells are truly integrated into the design, both aesthetical and functional. Closed, thin film and triangles with c-Si alternate to vary the transparency. Also, it stands out that two different PV technologies are used.

*ECN building – Petten, Hauptbahnhof – Berlin and fire station -Petten (figure 5.30, middle)*

These buildings have single curved glass roofs. A big part of the glass panels has crystalline silicon solar cells integrated. All these examples only have PV cells on the south side (figure 5.32).

*Pavilion Belgium – Milan (figure 5.30, bottom)*

This project is a pavilion on the building expo in Milan (2015). The south side is closed on this geodesic dome. The inside is very ‘smooth’ finished’. The outside, however, the c-Si cells are not well integrated. This is an example of how difficult it is to integrate solar cells in triangular panels.

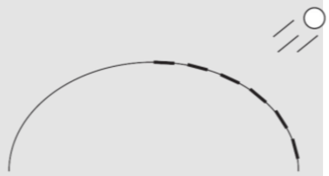
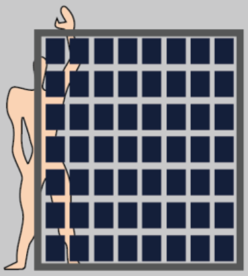
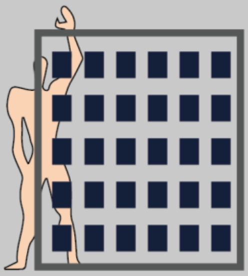


*figure 5.32: concept of shading with PV cells on the south side of a curved transparent structure.*

## CRYSTALLINE SILICON (mono/poly)



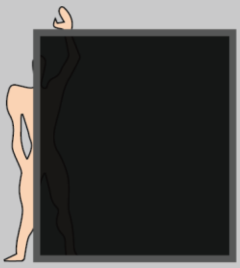
C-SI IN GLASS - 75%



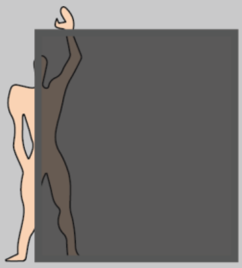
C-SI IN GLASS - 35%

- 20% efficiency ✓
- performance sub-optimal orientation ✗
- embodied energy ✗
- design freedom ✗
- (potential) cost ✗

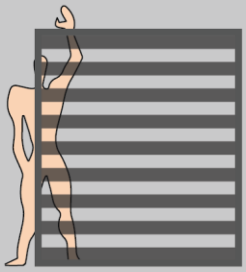
## THIN FILM (a-Si, CIGS, CdTe, CZTS)



THIN FILM - 90%



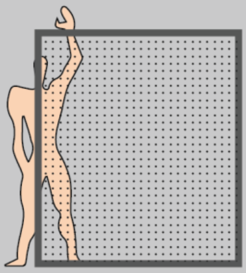
THIN FILM - 50%

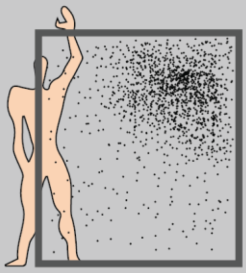


THIN FILM ZEBRA PATTERN

- 10 - 14% efficiency ✓/✗
- performance sub-optimal orientation ✓
- embodied energy ✓/✗
- design freedom ✓/✗
- (potential) cost ✓/✗

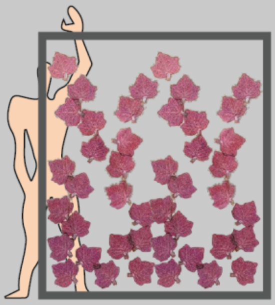
## ‘SPHELAR’ (mono crystalline silicon)



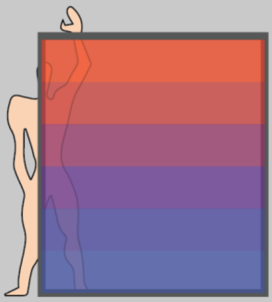


- 20% efficiency ✓
- performance sub-optimal orientation ✓
- embodied energy ✗
- design freedom ✓
- (potential) cost ✗

## ORGANIC PV / DYE-SENSITIZED



ORGANIC PV / DYE-SENSITIZED



- 5-15% efficiency ✓/✗
- performance sub-optimal orientation ✓
- embodied energy ✓
- design freedom ✓
- (potential) cost ✓

## 5.5 Conclusion

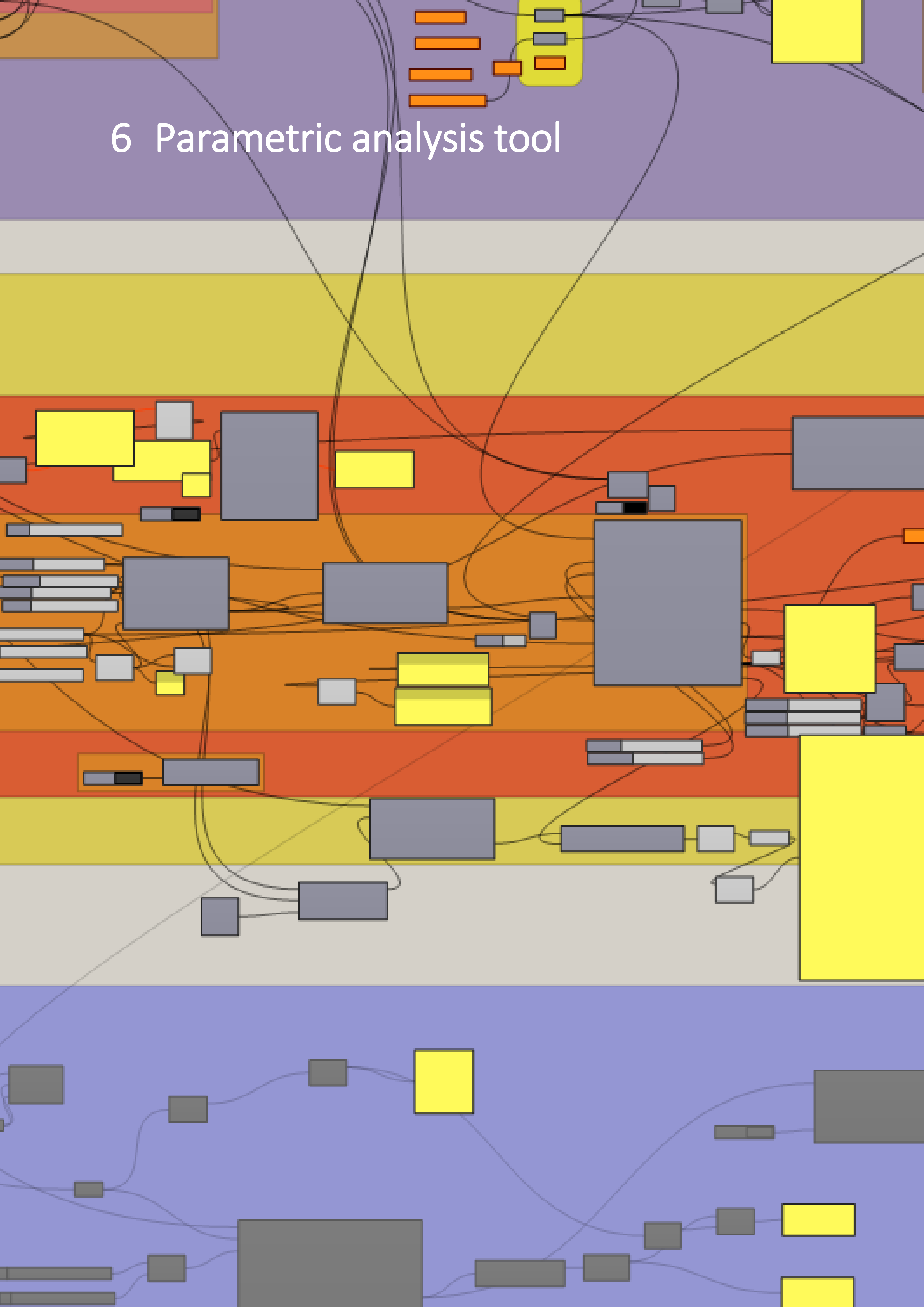
To use solar cells in a glazed space, integration is very important. PV cells can shade the space (reduction of cooling demand) and physically be integrated in the interlayer of two glass sheets. For optimal performance, (local) shading should be considered in a design. New PV technologies like thin films and DSSCs have (potentially) lower production costs and energy use. However, conversion efficiency is often lower than mono c-Si. New printing techniques and the use of colour, especially for DSSCs are very promising and give more freedom to design with.

To conclude an overview is made, shown on the opposite page. These techniques are most convenient to integrated in a transparent roof. Pros and cons are summed up.

# Part B – analyses

This part describes the analyses and how they are executed. First, the workflow of the developed parametric method is elaborated on. Then a parameter study is done to investigate the significance of parameters that influence the internal temperature. The analysis tool is tested and validated on some test cases in chapter 7.

# 6 Parametric analysis tool



## 6.1 Introduction

Currently, as a designer, you get only visual feedback on what you are making. When the conceptual design is finished, maybe it will be analysed by a consultancy agency. Small adjustments can be made, but no fundamental design decisions can be turned back. With this analysis tool, you can get feedback on your design decisions in an early stage. You can test rudimentary shapes on temperature behaviour and yield of PV. But, also later in the engineering phase, this tool can be used for numerical analyses.

This chapter starts with a description about how the calculation model works, what it can do, and what not. To goal is to make the reader familiar with the model and to show insight in how the sun radiate the surface of the roof structure. Adjacent buildings are considered, since they can shade the surface. With solar radiation results, specific for the location and building, a calculation is done to find the internal temperature of the space. With adjustments of parameters (like the STF), the result can be adjusted to the required maximal internal temperature. Or, the geometry can be adjusted and the analysis rerun, to get a satisfactory result.

In paragraph 6.3 a study is executed with the developed analysis tool, to understand the significance of different parameters in the temperature calculation formula.

## 6.2 Workflow

The parametric analysis tool is made in the grasshopper, with plug-in ladybug. Ladybug is a plug-in for grasshopper, which is a plug-in for Rhinoceros. It allows a designer to get visual and qualitative feedback to base decisions in the early design stage on. This plug-in makes it possible, for example, to combine information about solar irradiance with wind speed, precipitation or air temperature. Due its immediate feedback, one can see the consequence of changes in the design almost directly. Furthermore, with this method the potential of a layout of PV cells on a geometry can be calculated. In the design phase the layout can be optimized for the yield, for example. (Roudsari, Pak, & Smith, 2013) Next, each step of the workflow is elaborated on.

*Input weather data (EPW)*

The core of the parametric model is the weather data it works with. Ladybug works with data from EnergyPlus (.epw files). This is developed by the U.S. Department of Energy, Building Technologies Office, and National Renewable Energy Laboratory (2016). It is very important that the information used represents a 'typical' year; not a single year. A single year can never resemble this typical year statistically. This thesis uses weather data files with the format "IWEC" which is "Test Reference Year-type" data (Crawley, 1998). EnergyPlus has weather data from all over the world, so for many locations, an accurate model can be made.

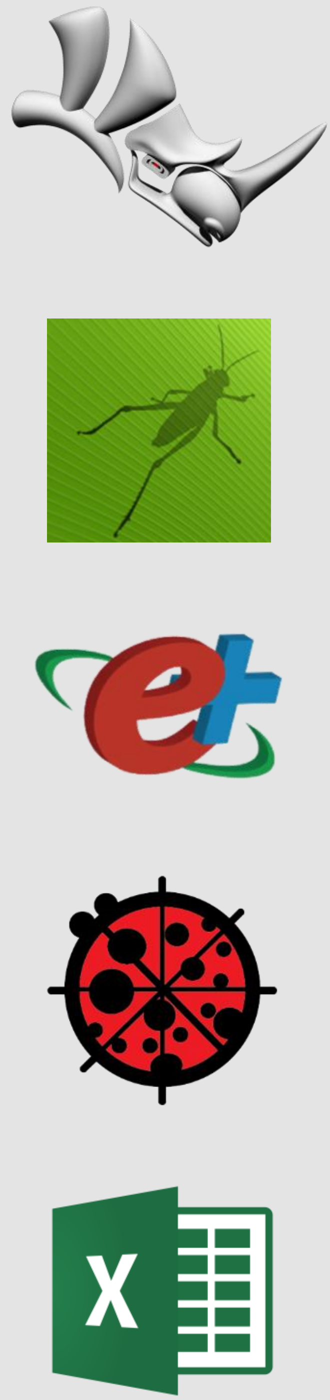


*figure 6.1: workflow top to bottom: Rhinoceros for modeling geometries; Grasshopper for to use ladybug in and manage data lists; Energy plus weather data for climate data of the specific location; Ladybug plug-in to combine geometries and weather data for climate calculations (radiation levels; Microsoft Excel to calculate the hourly inside temperature throughout the year.*

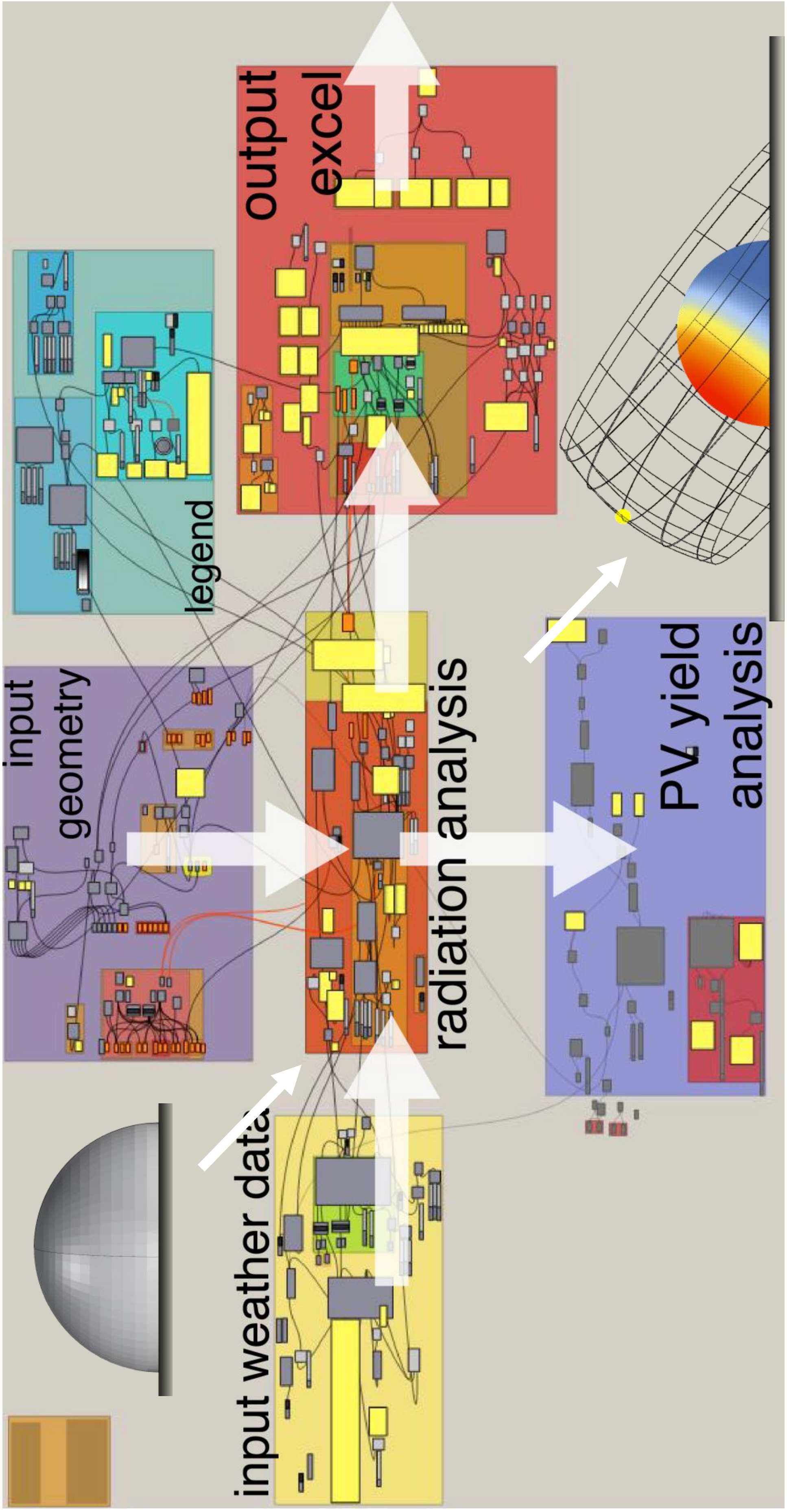
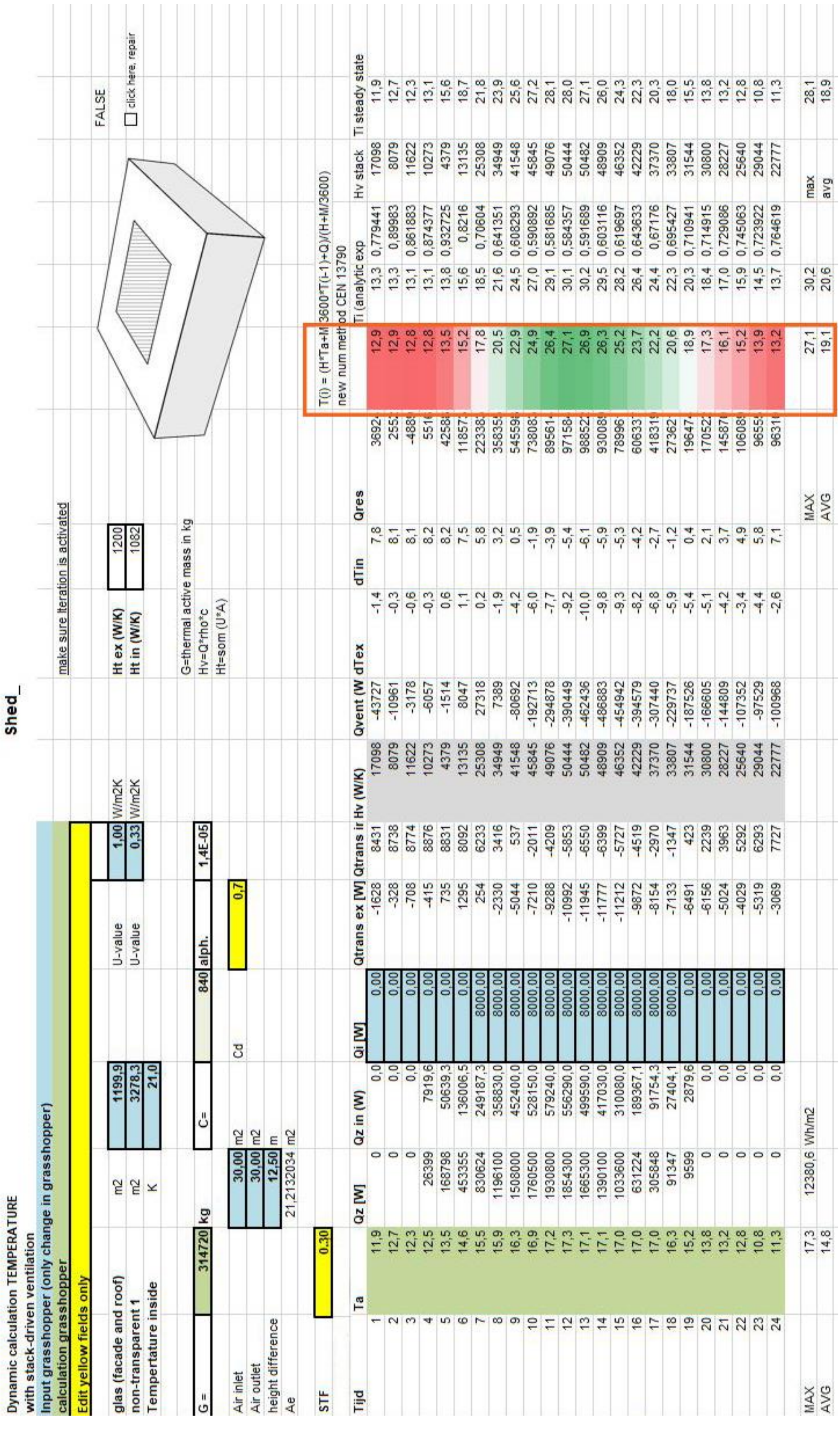



*figure 6.2:*

*Overview grasshopper model*

## *Workflow*



Dynamic calculation TEMPERATURE
with stack-driven ventilation
Input grasshopper (only change in grasshopper)
calculation grasshopper
Edit yellow fields only

**Shed_**

make sure Iteration is activated

FALSE
click here, repair

| | | | | | | |
|---|---|---|---|---|---|---|
| glas (facade and roof) | m2 | 1199,9 | U-value | 1,00 | W/m2K | |
| non-transparent 1 | m2 | 3278,3 | U-value | 0,33 | W/m2K | |
| Tempertature inside | K | 21,0 | | | | |

| | | |
|---|---|---|
| Ht ex (W/K) | 1200 | |
| Ht in (W/K) | 1082 | |

| | | | | | |
|---|---|---|---|---|---|
| G = | 314720 | kg | C= | 840 | alph. 1,4E-05 |

G=thermal active mass in kg
Hv=Q*rho*c
Ht=som (U*A)

| | | | | |
|---|---|---|---|---|
| Air inlet | 30,00 | m2 | Cd | 0,7 |
| Air outlet | 30,00 | m2 | | |
| height difference | 12,50 | m | | |
| Ae | 21,2132034 | m2 | | |
| STF | 0,30 | | | |

T(i) = (H*Ta+M 3600*T(i-1)+Q)/(H+M/3600)
new num method CEN 13790

| Tijd | Ta | Qz [W] | Qz in (W) | Qi [W] | Qtrans ex [W] | Qtrans ir | Hv (W/K) | Qvent (W | dTex | dTin | Qres | new num method | Ti (analytic | exp | Hv stack | Ti steady state |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11,9 | 0 | 0,0 | 0,00 | -1628 | 8431 | 17098 | -43727 | -1,4 | 7,8 | 3692 | 12,9 | 13,3 | 0,779441 | 17098 | 11,9 |
| 2 | 12,7 | 0 | 0,0 | 0,00 | -328 | 8738 | 8079 | -10961 | -0,3 | 8,1 | 2552 | 12,9 | 13,3 | 0,89983 | 8079 | 12,7 |
| 3 | 12,3 | 0 | 0,0 | 0,00 | -708 | 8774 | 11622 | -3178 | -0,6 | 8,1 | -4889 | 12,8 | 13,1 | 0,861883 | 11622 | 12,3 |
| 4 | 12,5 | 26399 | 7919,6 | 0,00 | -415 | 8876 | 10273 | -6057 | -0,3 | 8,2 | 5516 | 12,8 | 13,1 | 0,874377 | 10273 | 13,1 |
| 5 | 13,5 | 168798 | 50639,3 | 0,00 | 735 | 8831 | 4379 | -1514 | 0,6 | 8,2 | 42588 | 13,5 | 13,8 | 0,932725 | 4379 | 15,6 |
| 6 | 14,6 | 453355 | 136006,5 | 0,00 | 1295 | 8092 | 13135 | 8047 | 1,1 | 7,5 | 118573 | 15,2 | 15,6 | 0,8216 | 13135 | 18,7 |
| 7 | 15,5 | 830624 | 249187,3 | 8000,00 | 254 | 6233 | 25308 | 27318 | 0,2 | 5,8 | 223383 | 17,8 | 18,5 | 0,70604 | 25308 | 21,8 |
| 8 | 15,9 | 1196100 | 358830,0 | 8000,00 | -2330 | 3416 | 34949 | 7389 | -1,9 | 3,2 | 358355 | 20,5 | 21,6 | 0,641351 | 34949 | 23,9 |
| 9 | 16,3 | 1508000 | 452400,0 | 8000,00 | -5044 | 537 | 41548 | -80692 | -4,2 | 0,5 | 545598 | 22,9 | 24,5 | 0,608293 | 41548 | 25,6 |
| 10 | 16,9 | 1760500 | 528150,0 | 8000,00 | -7210 | -2011 | 45845 | -192713 | -6,0 | -1,9 | 738083 | 24,9 | 27,0 | 0,590892 | 45845 | 27,2 |
| 11 | 17,2 | 1930800 | 579240,0 | 8000,00 | -9288 | -4209 | 49076 | -294878 | -7,7 | -3,9 | 895614 | 26,4 | 29,1 | 0,581685 | 49076 | 28,1 |
| 12 | 17,3 | 1854300 | 556290,0 | 8000,00 | -10992 | -5853 | 50444 | -390449 | -9,2 | -5,4 | 971584 | 27,1 | 30,1 | 0,584357 | 50444 | 28,0 |
| 13 | 17,1 | 1665300 | 499590,0 | 8000,00 | -11945 | -6550 | 50482 | -462436 | -10,0 | -6,1 | 988522 | 26,9 | 30,2 | 0,591689 | 50482 | 27,1 |
| 14 | 17,1 | 1390100 | 417030,0 | 8000,00 | -11777 | -6399 | 48909 | -486883 | -9,8 | -5,9 | 930089 | 26,3 | 29,5 | 0,603116 | 48909 | 26,0 |
| 15 | 17,0 | 1033600 | 310080,0 | 8000,00 | -11212 | -5727 | 46352 | -454942 | -9,3 | -5,3 | 789961 | 25,2 | 28,2 | 0,619697 | 46352 | 24,3 |
| 16 | 17,0 | 631224 | 189367,1 | 8000,00 | -9872 | -4519 | 42229 | -394579 | -8,2 | -4,2 | 606337 | 23,7 | 26,4 | 0,643633 | 42229 | 22,3 |
| 17 | 17,0 | 305848 | 91754,3 | 8000,00 | -8154 | -2970 | 37370 | -307440 | -6,8 | -2,7 | 418319 | 22,2 | 24,4 | 0,67176 | 37370 | 20,3 |
| 18 | 16,3 | 91347 | 27404,1 | 8000,00 | -7133 | -1347 | 33807 | -229737 | -5,9 | -1,2 | 273621 | 20,6 | 22,3 | 0,695427 | 33807 | 18,0 |
| 19 | 15,2 | 9599 | 2879,6 | 0,00 | -6491 | 423 | 31544 | -187526 | -5,4 | 0,4 | 196474 | 18,9 | 20,3 | 0,710941 | 31544 | 15,5 |
| 20 | 13,8 | 0 | 0,0 | 0,00 | -6156 | 2239 | 30800 | -166605 | -5,1 | 2,1 | 170522 | 17,3 | 18,4 | 0,714915 | 30800 | 13,8 |
| 21 | 13,2 | 0 | 0,0 | 0,00 | -5024 | 3963 | 28227 | -144809 | -4,2 | 3,7 | 145870 | 16,1 | 17,0 | 0,729086 | 28227 | 13,2 |
| 22 | 12,8 | 0 | 0,0 | 0,00 | -4029 | 5292 | 25640 | -107352 | -3,4 | 4,9 | 106089 | 15,2 | 15,9 | 0,745063 | 25640 | 12,8 |
| 23 | 10,8 | 0 | 0,0 | 0,00 | -5319 | 6293 | 29044 | -97529 | -4,4 | 5,8 | 96555 | 13,9 | 14,5 | 0,723922 | 29044 | 10,8 |
| 24 | 11,3 | 0 | 0,0 | 0,00 | -3069 | 7727 | 22777 | -100968 | -2,6 | 7,1 | 96310 | 13,2 | 13,7 | 0,764619 | 22777 | 11,3 |
| MAX | 17,3 | 12380,6 Wh/m2 | | | | | | | | | MAX | 27,1 | 30,2 | | max | 28,1 |
| AVG | 14,8 | | | | | | | | | | AVG | 19,1 | 20,6 | | avg | 18,9 |

*figure 6.3: Calculation sheet excel*

*From input radiation results parametric model, to temperature results on the representative day. Also hourly analyses for a complete year are possible.*

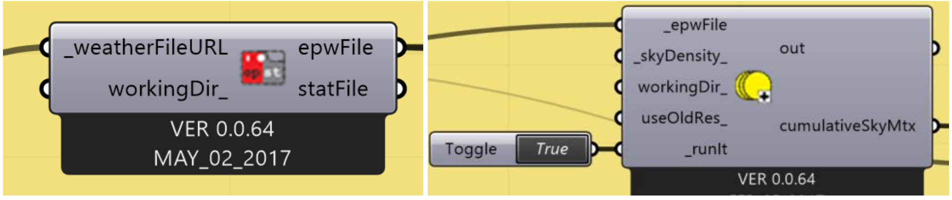



*figure 6.5: ladybug/grasshopper components import EPW file and calculate cumulative sky matrix.*

The key components of this part are the EPW import component and the cumulative sky matrix (figure 6.5). The first one links to the URL location of the specific EPW source. The cumulative sky matrix component calculates the radiation levels for each hour of the year. The "*sun path*" component makes a 3d scene in rhino of path of the sun (figure 6.4).

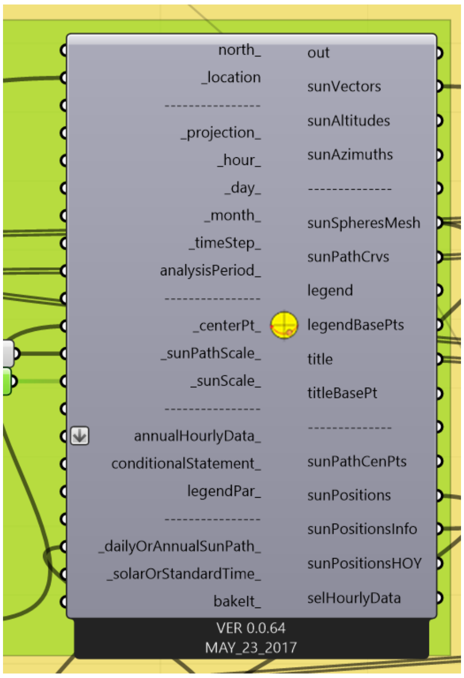
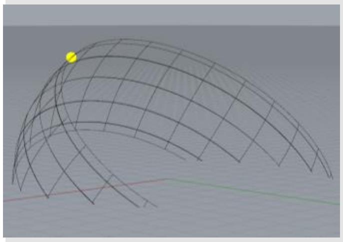



*figure 6.4: ladybug/grasshopper component "Sun path" makes a 3d scene in Rhino of the sun path.*



*Input geometry*

Geometry that is put in can either be surfaces of meshes. Next to the building and building components, also context can be put in to take shading into account. Even trees can be added that have leaves in summer, and leave them in winter. All geometry can be linked to grasshopper with brep's (boundary representation); (figure 6.11). Analyses will take longer if the number of surfaces increases, especially for long analysis times. So, the analysed geometry should be kept to a minimum; only the geometry that blocks the sun. Also, surfaces have a direction in rhino. Only for the "front" of a surface the radiation levels are calculated. So, make sure that this side faces the sun.

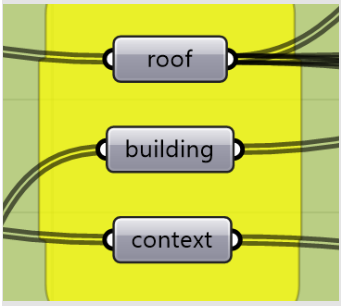



*figure 6.6: grasshopper geometry linked to brep's that is used as input for the radiation analysis*

*Radiation analysis*

With the input of the weather data and geometries, the 'radiation analysis' group produces radiation data for every test point, for the selected analysis period. With the analysis period block, you can select the analysis span (figure 6.7). Without the component, all hours of the year will be calculated. Together with the "select sky matrix" component, data from the cumulative sky matrix block is selected. This, "selected sky matrix", contains data about solar levels and directions, and is used as input for the

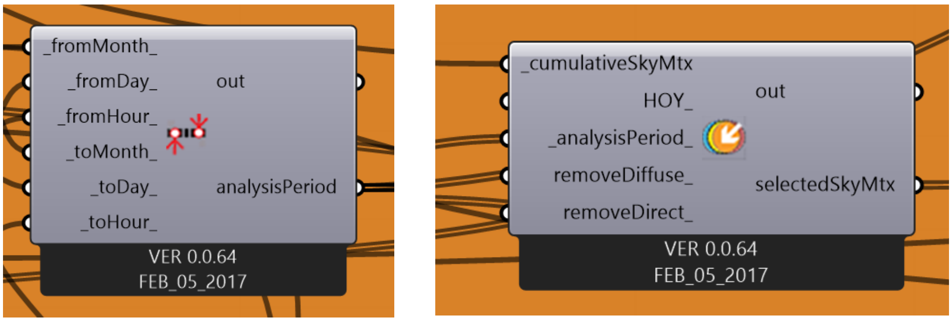



*figure 6.7: ladybug/grasshopper components analysis period, select sky matrix.*

"radiation analysis" block. Together with the geometry's, the block calculates the radiation levels for the selected analysis period (figure 6.8). The output of the radiation analysis is made visible with meshes. Next to the visual output, there you can see the hourly calculation results.


*figure 6.8: ladybug/grasshopper component radiation analysis.*

*PV yield analysis*

The PV component can calculate the PV yield over a selected analysis period. As input, there is a database with PV products (modules library file, figure 6.9 left). The downside is that new techniques, like OPV or DSSCs are not in this database, since they are not commercial available yet. This means you cannot calculate in the precision you can with crystalline silicon or thin film technologies. With new techniques, you use an existing product in the tool and adjust for example the efficiency. The downside with that approach is that other factors, like dependence from incident angle of sunlight, are not considered in the yield of the system. For example, for new nano-techniques like DSSC and OPV, the analysis result of the calculation will be too conservative. Please note that only planar

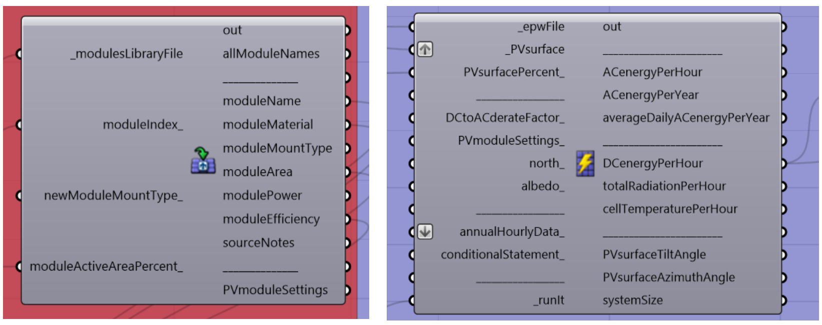



*figure 6.9: ladybug/grasshopper components PV yield analysis.*

surfaces can be put in, so a curved surface should be split into several flat surfaces. Reduction factors can also be added in this component (figure 6.9, right).

*Excel temperature calculation*

All data is collected in a grasshopper block, to keep the file organized (figure 6.10, left). Hourly data from the radiation analysis is exported via grasshopper components into the right cells in the excel calculation sheet (figure 6.10, right figure 6.13). When the write block is set to 'overwrite', values from grasshopper are 'live' placed in excel. For instance, if you change the geometry of the transparent part, all numbers are updated, put in excel and calculated again. Parameters that can be changed in grasshopper are blue and parameters that should be changed in the excel sheet are yellow (figure 6.3). With this 'live' link between excel and grasshopper, a designer gets directly feedback on his design.

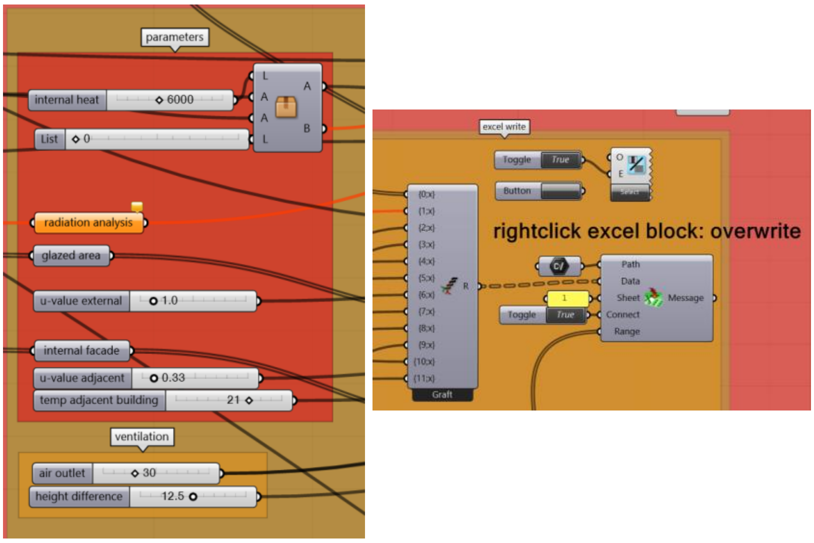



*figure 6.10: grasshopper components write to excel (live)*

## 6.3 Parameter study - internal temperature

### 6.3.1 Baseline model

To see the significance of the parameters that influence the calculation, a model is made with baseline settings. These parameters are shown in figure 4.15. When you have an idea how much influence each parameter has on your internal climate, you know what design options you have that significantly affect you design. For the tests, every time only one of the parameters is changed. The focus of the baseline model is: How does this atrium performs on a summer day? Since overheating in atria is accounted as the most

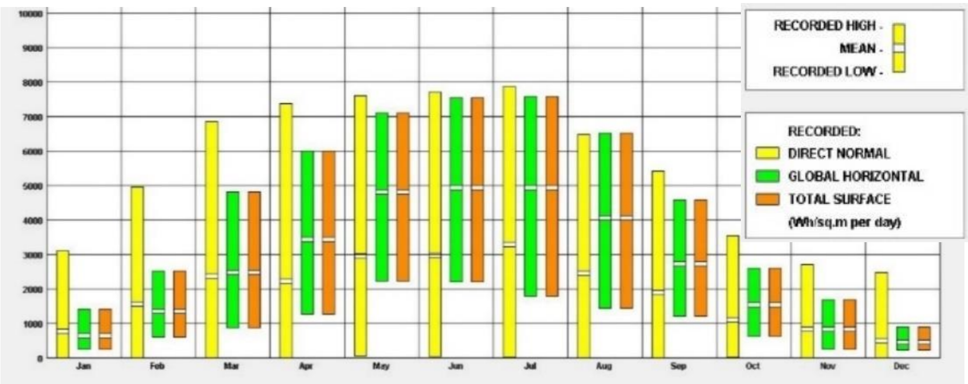
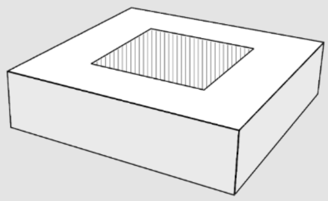



*figure 6.11: daily solar irradiation values throughout a year in Amsterdam. This data is EnergyPlus Weather data, viewed in Climate consultant. This similar data is used in the 3d grasshopper model analysis.*

problematic issue in atria nowadays. First, we must determine what a representative summer day is. The mean insolation in July is around 5000 Wh/m$^2$ per day. For the simulation, there is only one day simulated. The data which is put in works with a 'theoretic' reference year. Therefor one day is selected which has the tenth most radiation of that theoretic year. So, we allow temperature override of a small percentage of the year. The representative day turned out to be the twenty-first of July, with a daily radiation of 7024 Wh/m$^2$.

To make comparison graphs between the different parameters, the standard settings for the parameters are:

| | |
|---|---|
| Dimensions | 30 x 30 x 15m |
| STF | 0.25 |
| Internal heat (8.00 to 18.00h) | 8000 W |
| U-value external façade | 1.0 W/m$^2$K |
| U-value internal/adjacent façade | 0.33 W/m$^2$K |
| Temperature adjacent building | 21 ∘C |
| Air inlet/outlet | 30 m$^2$<br>(3.3% of area roof) |
| Height difference in- and outlet air | 12.5 m |
| Weight mass atrium (stone + windows), 60 mm active in calculation | 1600 kg/m$^3$<br>(±300.000 kg for the baseline model) |



*Figure/table 6.12: Baseline model of theoretical atrium with standard test settings*

Assumptions made for the calculation are:

- No active climate control, only (passive) stack ventilation;
- A uniform temperature distribution in the atrium.

## 6.3.2 Results

Parameters for the inside temperature calculation are researched with the model. In figure 6.13 you can see the visual feedback you get. Each yellow circle represents an hour of sunlight. The most important results of the parameter study are presented below; the remaining results can be found in Appendix IV: calculation model test results.

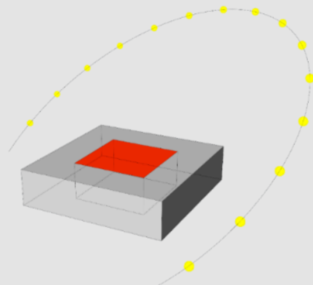


*figure 6.13: analysis model visual from Rhinoceros.*

*Ventilation area and height*

Ventilation has considerable influence on the internal temperature of the space. This is the only significant cooling load (the other is heat transmission through the facades, but has much less influence especially in summer). This baseline test is done for a roof of 900 m$^2$. Calculations give: to get a maximum temperature of 23 $^{o}$C, there should be approximately 50 m$^2$ effective ventilation area (5,5% of the total roof). The top and bottom need sufficient height difference to create the stack effect. From tests is concluded that it should not be less 9 to 10 meters, otherwise the stack effect does not work appropriately (figure 6.16).

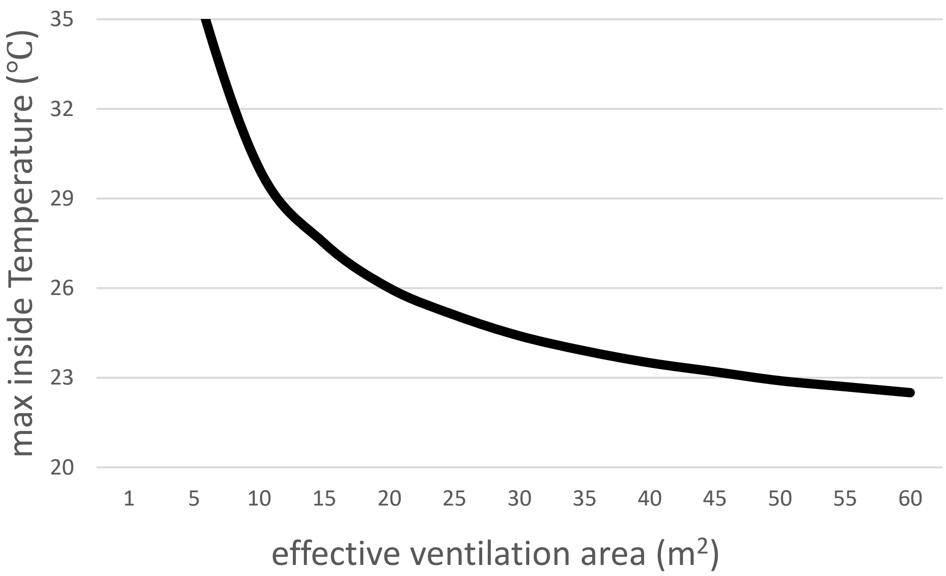



*figure 6.14: effect of effective ventilation area on the max temperature on the reference summer day (baseline model).*

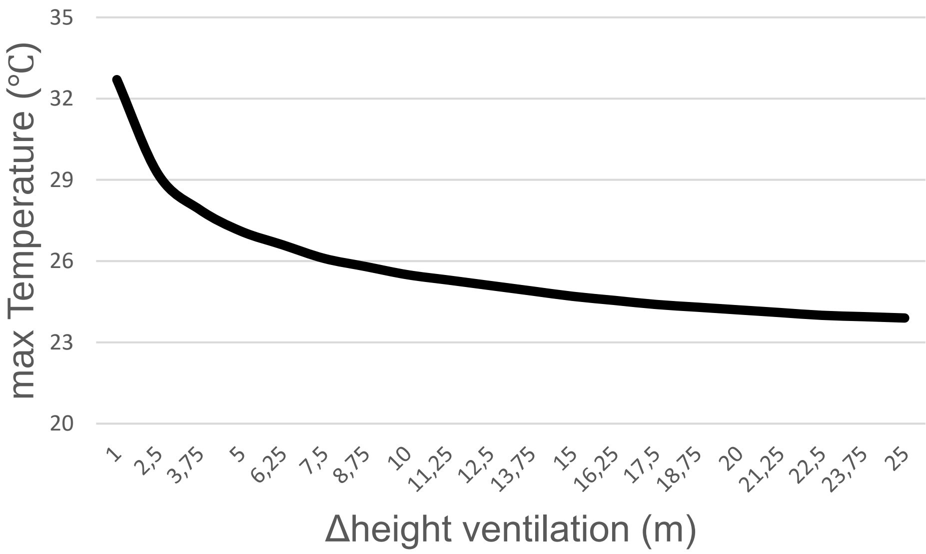



*figure 6.16: height difference ventilations openings top and bottom (baseline model).*

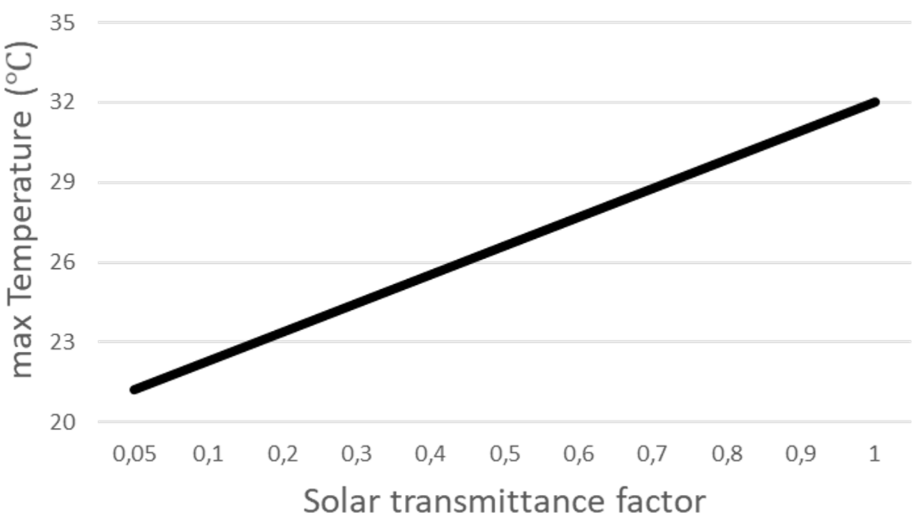



*figure 6.15: increase of STF leads to increase of max temperature (baseline model).*

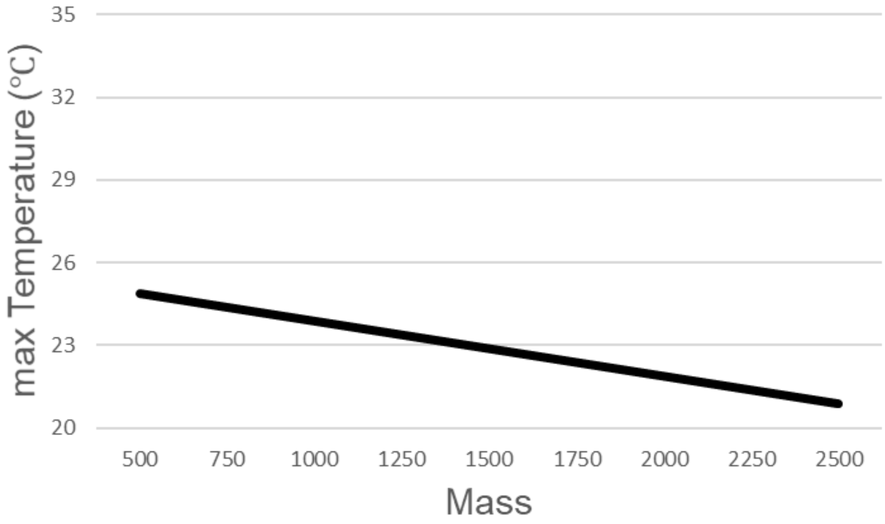



*figure 6.17: mass in kg/m$^3$. Only 60mm in the depth of the adjacent walls is considered to be thermal 'active' (baseline model).*

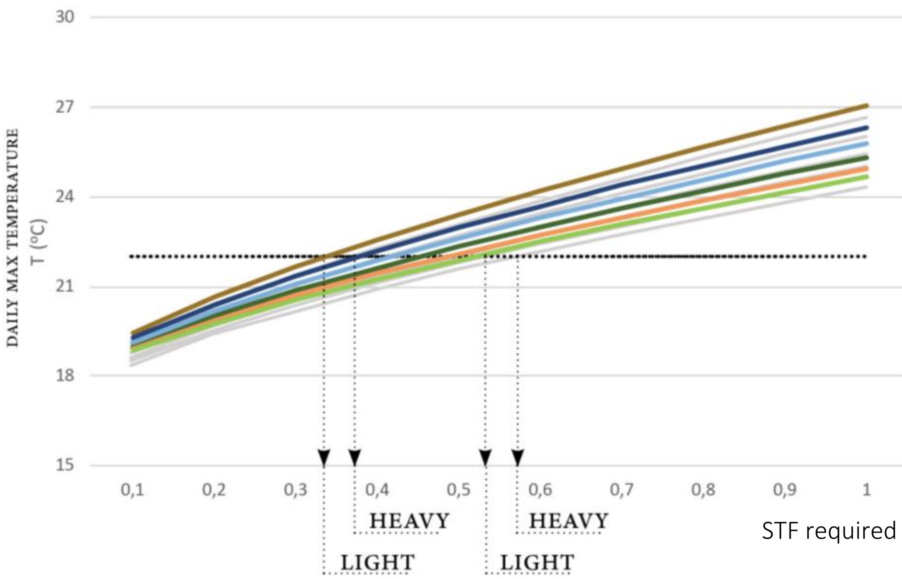



*figure 6.19: test for required STF: between "heavy" and "light" building (600 kg/m$^3$ vs. 1600kg/m$^3$). For a light building, approximately 5% lower STF is required than a heavy one (for a maximum temperature of 22 °C, on the representative summer day).*

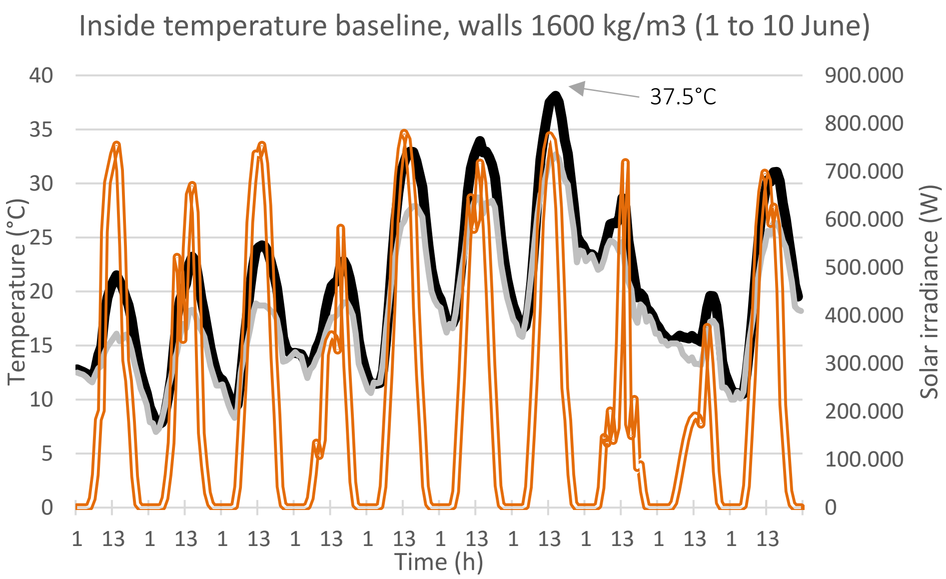



*figure 6.18: Temperature calculation over ten days for the baseline model (900m$^2$ transparent roof).*

*Mass of building*

Analysis is done for the different dimension atria; with different area with thermal mass of the adjacent walls. For six different atria with 1600 kg/m$^3$ (e.g. a brick wall), the results are calculated. The same atria are analyzed, but then with 600 kg/m$^3$. These twelve results are plotted together in (figure 6.19). As a conclusion, we can say that in general, a heavy or light internal façade of a glazed space can make a difference of approximately 5% of the STF. So, less solar shading is needed with a building with high thermal mass due to its thermal buffering effect. Also, the possible effect of heat accumulation over a number of following 'hot' days is researched (figure 6.18). You can see an increased temperature. However, this temperature rise is close to similar to the outside air temperature. From this analysis we can conclude that ratio mass / volume in this analysis example is not sufficient to have a accumulating effect. In a smaller space, with higher mass / volume ratio it is expected that this effect can be found.

*Solar transmittance factor*

The solar transmittance factor has a linear connection to the maximum temperature (figure 6.15). For this baseline model, the STF to get 23 $^o$C inside is rather low. It is advisable first to try to bring the maximum temperature down with the other parameters. Especially with low STF's, the LTF also goes down. (The solar energy spectrum is approximately 50% visible light and 50% invisible, near infrared. See figure 4.3)

*Transparent surface area*

Obviously, when the surface area of the glazed space increases, the needed solar transmission reduction increases. The area of the roof is directly connected with the inside temperature, according to ISO 1379:2008 (see page 41). When the area of the roof increases exponentially, the solar irradiance increase with the same ratio. The graph below can be used as an indication for designers which STF they should aim for.

## 6.4 Conclusion

Concluding, with this tool the following aspects can be analyzed:

- Solar radiation on (freeform) geometry;

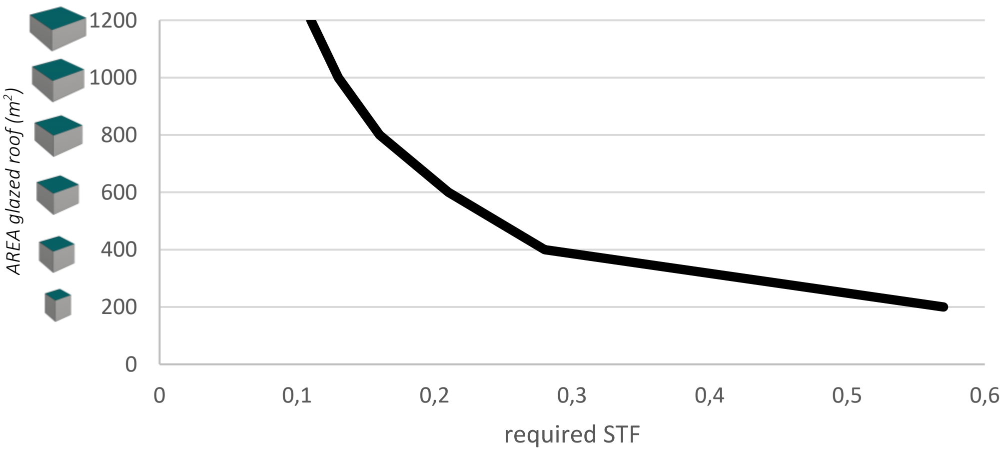



*figure 6.20: influence of area of a glazed roof on the solar transmittance factor for a daily maximum temperature of 22 $^o$C on a summer day.*

- Inside temperature with the (dynamic) calculation model;
- Yield of photovoltaic layout.

So, after analysis the required STF is known. Then, you can adjust the PV layout and technology on this. If you know the percentage of solar radiation your PV transmits, you can calculate the STF (see Appendix III: STF with integrated PV), and see if it is sufficient as shading. In addition, it is investigated if it is possible cool the space with the energy that is produced at the same moment. It is found that this is not possible. Only because there is efficiency loss of 80 to 90% of energy by solar energy conversion, it is smarter to shade to prevent solar heat gain. Obviously, this approach had also disadvantages. For example, the limitations the PV calculation tool has for new technologies. Also, the model can be optimized in the way that it takes rather some manual effort to interpret the results and plot them into graphs.

Points of improvement

- Take light reflections into account from object and context;
- Do total year analysis to see better effect of mass;
- Add dye-sensitized test data to model.

Additionally, the maximum summer day temperature is set on 22/23 °C. This can differ per situation. Furthermore, statistical analysis should be done to pick the ‘actual representative’ summer day for calculations. So, the results of these analyses should not be taken too literally, but mainly to see the connection between different models.

The temperature outcome works with iterative calculations. This means that the calculations are repeated over and over again until the result does not change significantly anymore (in this case it is set to 0.01 K. ultimately, it means that the model calculates the daily results as if it there is the same day (radiation levels and outside temperature) for the number of iterations that is needed. For instance 100 days. In reality this will never occur, obviously. For example, in summer days will get colder and radiation levels will go down relative to this representative summer day that is used for calculation. It was expected that the dampening effect of mass is more significant than it appears to be in the calculation results because of this calculation method. However, this effect is found to be rather small in a hourly calculation for a whole year (figure 6.18).

*Reflection on results*
Ultimately, together with the grasshopper model and test results we can conclude how a designer can influence the thermal behaviour of a glazed space. Most important is the area of the transparent façade and accompanying STF. Furthermore, passive stack ventilation should be enhanced by sufficient area of ventilation openings and height difference. Lastly, extra thermal mass makes the temperature drop. However, this is more significant in a space with a high ratio of adjacent façade area / glass space.

# 7 Application analysis tool

## 7.1 Introduction

This chapter elaborates on the way sun radiates geometries. How does the sun insolate, and from which direction? Also, what is the influence of contextual objects? Where on the geometry are the maximal and where the minimal radiated parts? The parametric model that is developed is tested on some buildings of different types. The goal is to know where it's best to shade and so, place PV cells.

## 7.2 Sunlight and radiation case analyses

Distribution of yearly insolation on a theoretical globe is illustrated by figure 7.1. Obviously, the south size receives by far the most radiation in total. An altitude between 50 and 60$^o$, and azimuth between 140 and 220 is radiated the most. Two thirds of the total annual radiation is diffuse light. Diffuse light has lower light levels, but is less dependent on orientation. For not optimal directions, nano-PV, like OPV and DSSC, are better applicable than conventional PV.

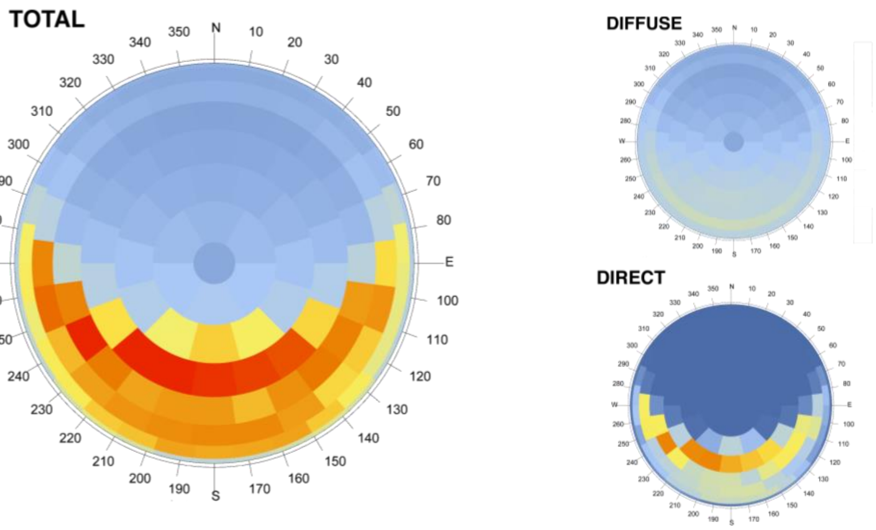



*figure 7.1: annual distribution of solar irradiance in Amsterdam. l: cumulative result of radiation distribution of sky dome. r, top: distribution of direct sunlight, approximately 1/3 of total yearly insolation. r, bottom: distribution of diffuse sunlight, approximately 2/3 of total yearly insolation.*

### 7.2.1 Case – Centre court of British museum in London

*figure 7.2: grid shell roof over the great court of the British museum in London by Foster + Partners (2000); (http://www.fosterandpartners.com/projects/great-court-at-the-british-museum/;)*

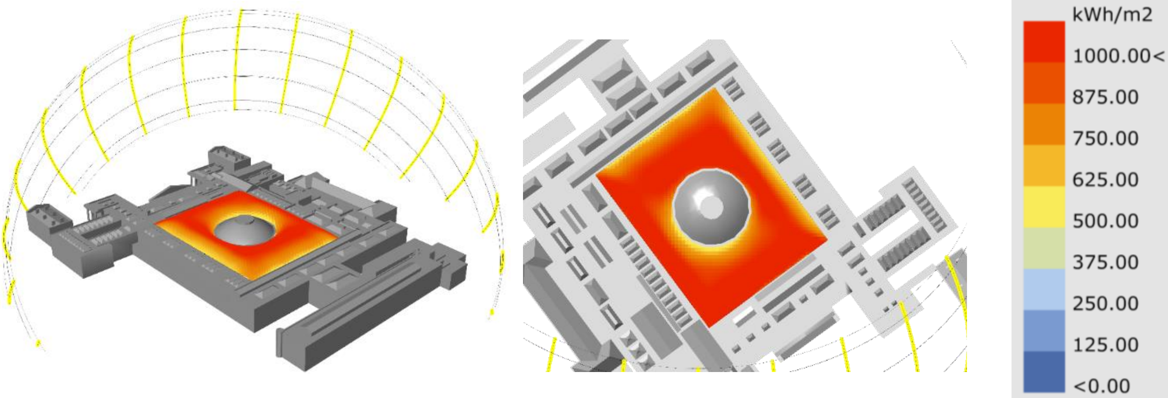



*figure 7.3: radiation analysis over one year, average 921 kWh/m$^2$. l: view from the north; r: top view (north is up); (http://workflow.arts.ac.uk/artefact/file/download.php?file=458886&view=66288)*

The British museum in London has a roof which covers the centre court of the building. It is a large atrium with dimensions of roughly 75 by 100m. The type of the roof is bent.

This analysis considered how much, and where, this roof receives radiation. The roof is practically not shaded since it is at the top of the building, and there are no high buildings close. From figure 7.3 it appears that the middle tower shades the roof. In fact, this is not the case. This local reduction of radiation is due to the curvature of the roof, since it is at the south side of the tower. The north side has a similar effect from the curvature: when it curves down, the geometry is oriented at the north. So, there is a reduction of radiation. Because of the relative smooth, flat curvature, the roof does not shade itself locally a lot. The lack of contextual local shading result in an average of 921 kWh/m$^2$ on a yearly basis. With a yearly radiation of 1010 kWh/m$^2$ in London, the geometry of this roof still receives 91% of the total possible.

### 7.2.2 Case – The Bubble in Eindhoven

*figure 7.4: "the Bubble" in the center of Eindhoven (2013) Photo's: Octatube*

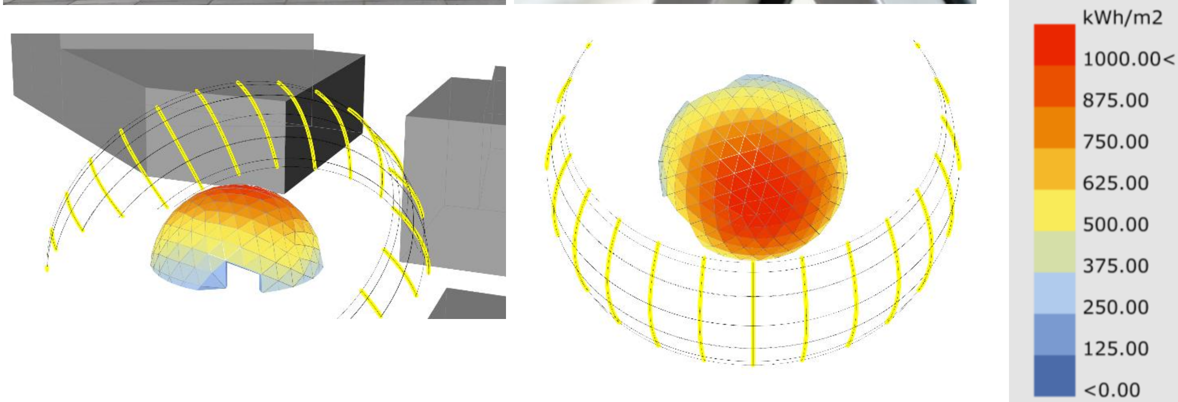
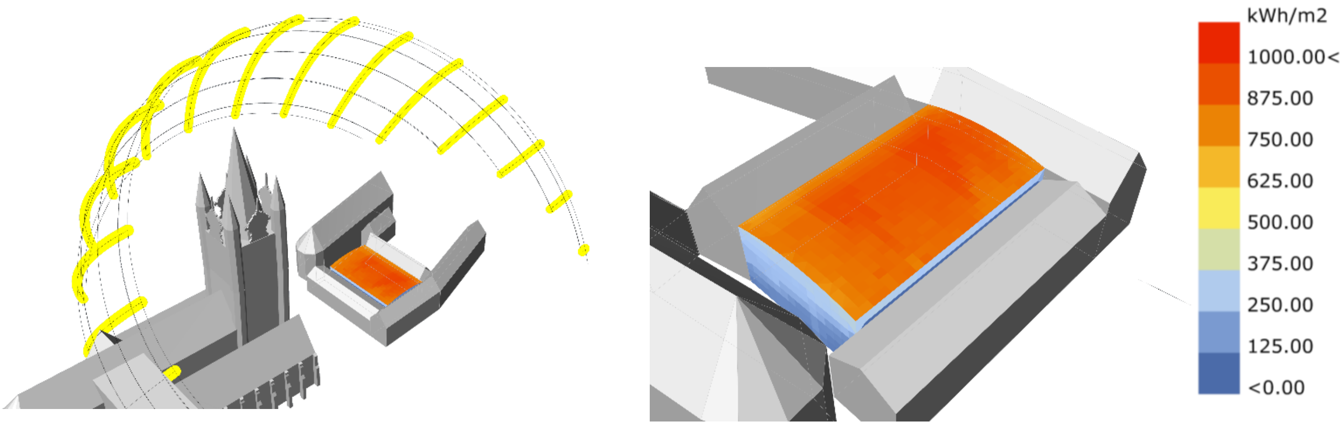



*figure 7.5: radiation analysis over one year, average 617 kWh/m². l: view from the north; r: top view (north is up)*

The Bubble is a geodesic, self-supporting dome in the centre of Eindhoven by Tarra Architecture and engineered by Octatube. It is eight meters high and has a diameter of 18 meter. This analysis shows how the sun radiates the surface of the dome throughout the year. Since it is a typical dome, the distribution of the solar irradiation is like you would expect. There is a big, red portion, which is most strongly radiated, and a big part is yellow or blue. The latter represents the approximately the half and less of the conceivable insolation. The façade of the building receives on average 617 kWh/m². The maximum insolation on this location is 985 kWh/m², so the surface gets 63% of the possible radiation (climate data is from Beek, 60km from Eindhoven. This is the closest available source). This relatively low average insolation value is partially explained by the strong curvature this geometry has. Furthermore, the context has a big impact on this value. There are buildings around this building, and some of them are two or three times higher as the Bubble. These buildings shade the dome, especially when the sun is at a low angle (in the east and west). Concluding, the strong curvature and the context make the average insolation low. Especially compared to the British museum, which receives 91% due to its gentle curvature and lack of shade by surrounding buildings.



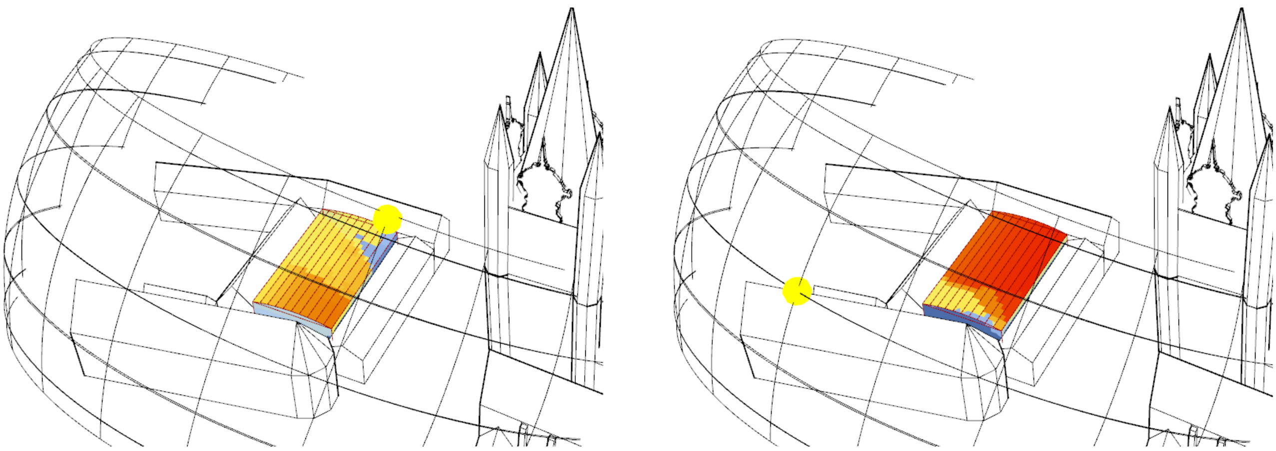



*figure 7.8: covered courtyard of the Prinsenhof in Delft (1997) Photo: Octatube*

*figure 7.8: radiation analysis over one year, average 688 kWh/m². l: view from the north; r: top view (north is up)*

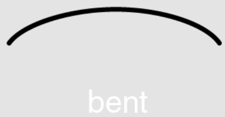
*figure 7.8: l: position of the sun at 10 'o clock in the begin of July, you can clearly see the shade of the old church on the roof; r: position of the sun in the middle of the day in march 21 (equinox), the "Waalse kerk" shade the south side of the glass roof.*

### 7.2.3 Case – Prinsenhof in Delft

The Prinsenhof in Delft is a museum which has a glass volume enclosed on three sides. On the last side, the courtyard is ‘closed by the “Waalse kerk”. In 1997, when the building was constructed, the glass coatings were not as good as there are available nowadays. Partially due to that, the atrium has problems with overheating, in summer. Today, the roof is covered with a highly reflective, translucent canvas during summer to prevent excessive heat (figure 7.9). The façade of the building receives on average 688kWh/m$^2$. The maximum insolation on this location is 983 kWh/m$^2$, so the surface gets 70% of the possible radiation (climate data is from Amsterdam, 55km from Delft. This is the closest available source).

*figure 7.9: translucent/reflective summer cover of the Prinsenhof to prevent excessive heat. Photo: Octatube*

There is a clear distinction between (horizontal) roof and the (vertical) façade (figure 7.8). This is mainly because of the surrounding buildings. On a yearly basis, the insolation is rather uniformly distributed on the roof. In fact, when you zoom in on one day, you see that there is shading on several moments of year (figure 7.8). In winter, when the altitude of the sun is low, the roof is shaded a lot due to the adjacent buildings.




It stands out that the differences in radiation zones are mainly in the longitudinal direction. To prevent partial shading of PV, when you consider applying PV cells, you would place strings (cells in series) in the width of the roof. Either mutual connected with bypass diodes or parallel. Also, it would be wise to keep of the very edges, especially on the longitudinal ones since they are also shaded in morning, afternoon and winter in general.

## 7.2.4 Case – Złote Tarasy in Warsaw

*figure 7.10: Złote Tarasy (Golden Terraces) in Warsaw (2007)*

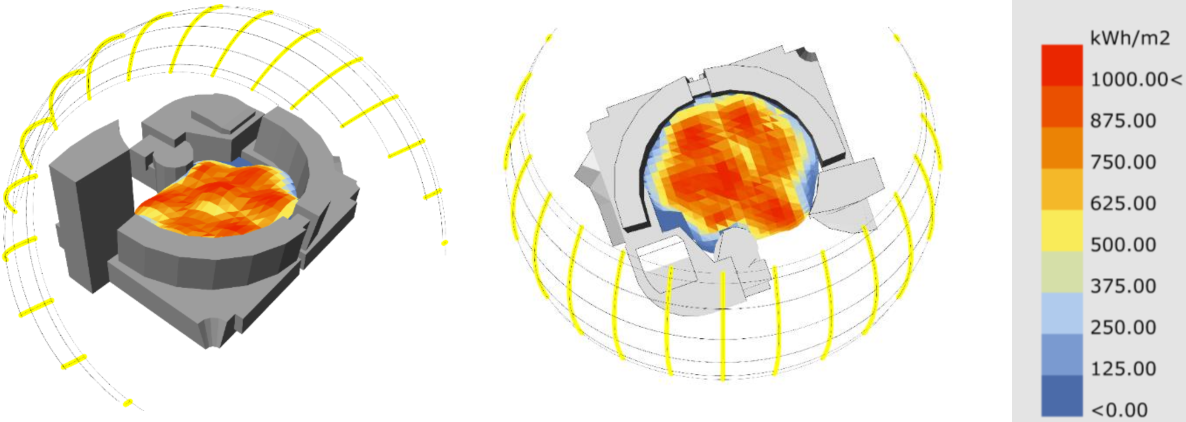
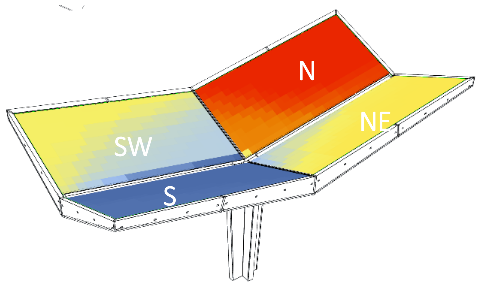



*figure 7.11: radiation analysis over one year, average 492 kWh/m$^2$. l: view from the 'back'; r: top view (north is up)*

Złote Tarasy is a large shopping mall in Warsaw, with 205000 square meters for offices, shops and restaurants. The transparent entrance "blob" in the middle is made of glass and steel. This freeform centre of the complex is approximately 130 by 110 meter and more than 40 meters high. The façade of the building receives on average 492 kWh/m$^2$. The maximum insolation on this location (Warsaw) is 999 kWh/m$^2$, so the surface receives only 49% of the possible radiation. The average is relatively very low. This can be explained by the adjacent building which shades the geometry. Especially the edges are shaded heavily like you can see in figure 7.11. Furthermore, the geometry shades itself as well. There are some spots behind the several domes which receive only half of the yearly solar irradiance. If this building has problems with overheating, it is very clear now where it is most efficient to shade; on the tops and south side of the domes. Obviously, to the question where to place PV cells, the same applies.

## 7.3 PV yield validation – Fastned station



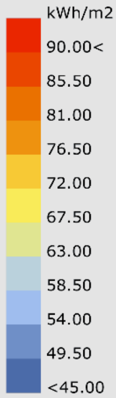




*figure 7.12: l: Fastned charge station for cars in The Hague, Photo: Octatube; r: radiation analysis in analysis period (December – February)*

*PV cell yield validation*

To validate the grasshopper/ladybug tool to estimate a PV layout, it is tested on a case with a PV layout. The geometry is put into the model which gives a result. This analysis is done on the months December to February, since only these results of this station are available. The analysis period was sunnier than the normalized year the model works with. Weather statistics from the KNMI show that the monthly sun hours were higher than ‘normal’ (except for February).

| | sun hours actual | sun hours normal | |
|---|---|---|---|
| dec-16 | 87 | 69 | +26% |
| jan-17 | 72 | 49 | +47% |
| feb-17 | 71 | 85 | -16% |

The output of the station in the analysis period is 214 kWh. The estimation from the parametric model is 237 kWh. For the total year, this would be 3556 kWh. Since the test months were slightly sunnier than ‘normal’, the estimation from the model is probably somewhat optimistic. Still, this model gives a realistic estimate, within circa 15% of the actual yield.

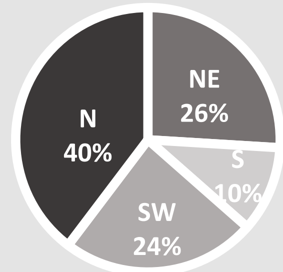



*figure 7.13: electric yield winter*

*Geometry*

In the insolation analysis, you can already see that not all panels are optimally orientated to gain the highest insolation. One panel is less than 50% insolated compared to the maximal radiated. The ‘worst orientated’ panel even shades the others, which leads to partial shading and can cause the bypass diodes to work (thus switch out the panel). However, figure 7.12 (r) exaggerates this effect since this analysis is covers only three winter months. In these months, the altitude of the sun is low. An analysis period over that covers a full year, shows that even the ‘bad’ orientated panel produces approximately 70% of the kWh’s compared to the best orientated one. The other two panels (yellow/blue in figure 7.12 (r)) have an output of 85-90% relative to the best panel.

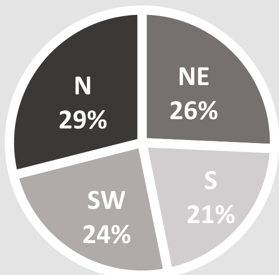



*figure 7.14: annual electric yield*

## 7.4 Conclusion

A large part of the total radiation is diffuse light, relatively smoothly distributed in all directions. The more curved, the higher the standard deviation is. When the curvature of a geometry is heavy, it shades itself. You can see in figure 7.15 that the standard deviation is the highest, on the geometry with the lowest average insolation. The energy production calculation works relatively good. Especially on longer analysis periods, it will be closer to the actual yield. More verifying should be done, but for now we can say that the tool has an error margin of about 15%.

The added value of this tool is that you have a quick first visual impression on how much insolation is where and when. Later you can interpret the values for temperature an energy production calculations.

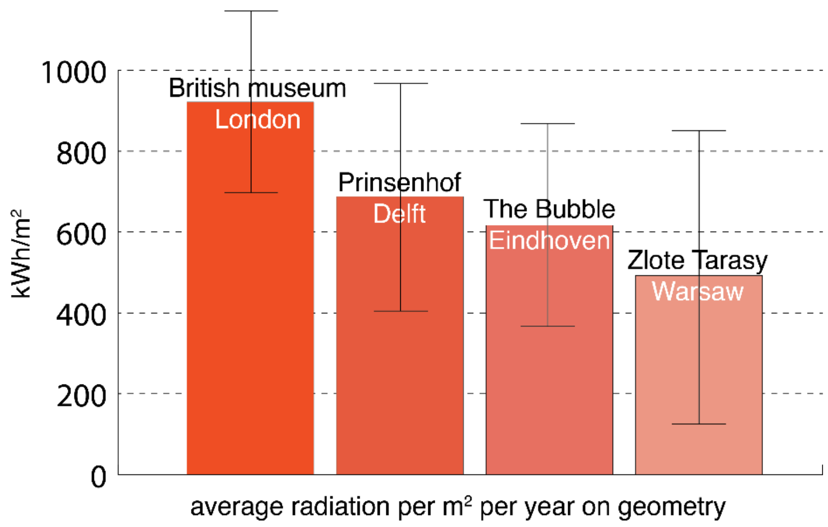
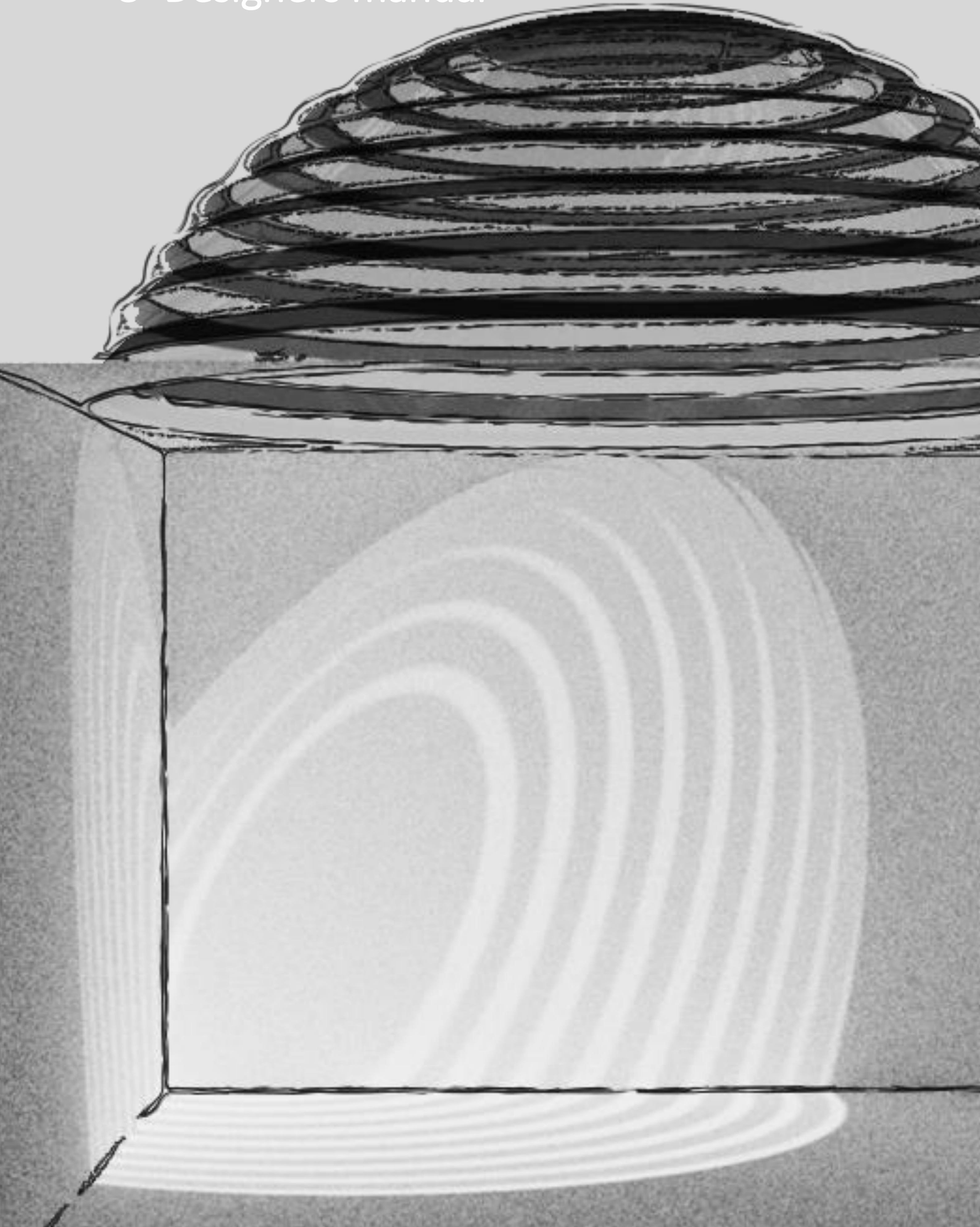



*figure 7.15: average radiation and standard deviation of the four analyzed cases.*

# Part C – design

This part describes what can be done with the knowledge provided by the previous parts: literature and analyses. What are the options for a designer and what are the consequences?

# 8 Designers manual



## 8.1 Introduction

With all the previous knowledge and analysis results, conclusions can be drawn. What can you do with this information as a designer or architect? The next morphological overview gives insight in which options are there and on what grounds to decide. Throughout the process, from big to small scale, it provides grip to make choices. Options are labelled to give insight on the consequences of the choices. It helps a designer to design a roof of a glazed space from a climate and energetic point of view. A possible path is illustrated in figure 8.2.

To design towards an energy effective glazed space, you must strive for the following goals:

- No additional shading needed;
- Retain sufficient daylight;
- Retain sufficient transparency (quality of daylight);
- Effective use of PV installation;
- The system should function throughout all seasons.

First, this chapter informs about the consequences of choices in the morphological overview on each scale. Then, the design tool (analysis & design manual) is used for three designs. Two would currently be possible to build, the third is to show the possibilities there are in the near future.

## 8.2 Morphological design overview

The design manual can be used in different phases or approaches. You can start from scratch and start from the macro scale to select the type of atrium. Also, you can start with the wish to apply solar cells (micro scale), for instance. Then you can use this design overview to learn what else you can do on the other scales to enhance the thermal comfort and get most out of the solar cells. Often, the design process cannot be defined as linear but more randomly (figure 8.1). This design manual can be used to take the first, rough, design steps. Later, the analysis tool can be used to see, whether your design works or not in a more detailed way.

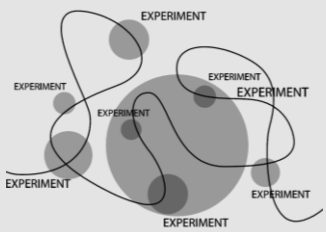


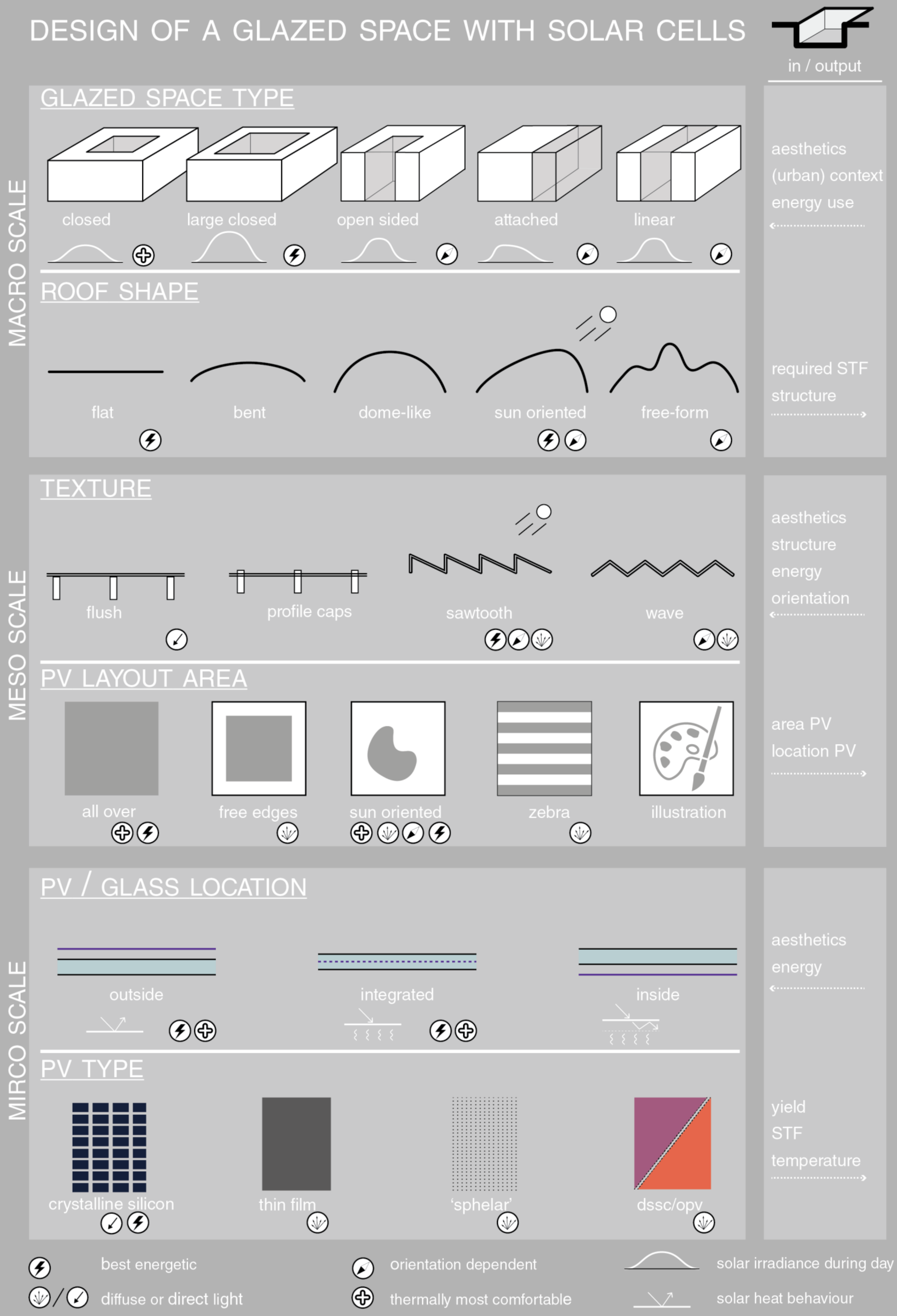

*figure 8.1: often, a design process is not linear but goes through all scales and aspects, all the time. (van der Linden, 2011; van Dooren, Boshuizen, van Merriënboer, Asselbergs, & van Dorst, 2014)*

### 8.2.1 Macro scale

The macro scale is about the general shape and dimensions of the space. With the size and the type of the glazed space, already you can get a rough idea of the required STF (see paragraph 6.3). Furthermore, for the open sided and linear glazed space, direction does matter. An analysis can be run with the developed analysis tool.

The shape of the roof matters for the distribution of shaded and radiated zones. In general, the more curvature, the higher the standard deviation is. In the case of shaded zones, you can choose to assign PV to the radiated zones and no PV to the shaded zones. In the shaded zones, you will choose for glass with a high light transmittance factor.

# DESIGN OF A GLAZED SPACE WITH SOLAR CELLS



### 8.2.2 Meso scale

The meso scale is about the level of the skin of the roof. This scale has a big influence on (local) shading. Added texture can provide shaded and unshaded zones, which determines how the PV layout will be designed. For instance, the wave or sawtooth texture goes hand in hand with the zebra layout. PV where there is much sunlight, and no PV in the parts that are shaded.

### 8.2.3 Micro scale

On the smallest scale, you must choose which PV technology you use and where to place it. This thesis only considers the PV -in-glass location, but inside and outside the skin is also possible. Paragraph 4.4.4 explains the difference. The characteristics of the different technologies are explained in chapter 5.

## 8.3 Design options – application of the tool

### 8.3.1 Design 1 – dome-like, wave, thin film

This concept design to shows how you could make a dome-like roof which makes best use of all seasons. The decision path is illustrated by figure 8.3. In summer, with an overload of heat, sun is prevented to get in by thin film PV. In winter when heat is needed inside, the sun stands lower in the sky and is ‘allowed’ in to heat the space (figure 8.5).

*figure 8.2 (l): morphological overview to design a glazed roof.*

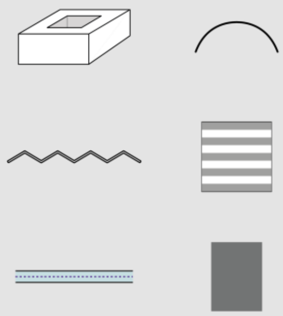


*figure 8.3: choices for design 1*

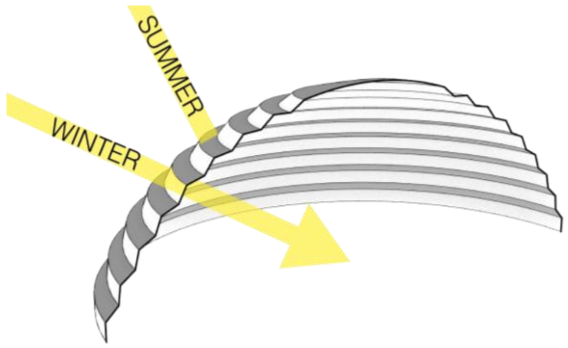



*figure 8.4 (l): wave texture concept: block summer sun with thin film PV and allow winter heat gain.*

An analysis is run to see the impact of this design on radiation levels, inside temperature and PV yield (figure 8.5 and figure 8.6). Clearly, a big part of the summer sun is blocked and winter sun is let through. On the other hand, a large part of the solar irradiance is diffuse light (annually ±2/3). Even more effective would be to totally block sun from the

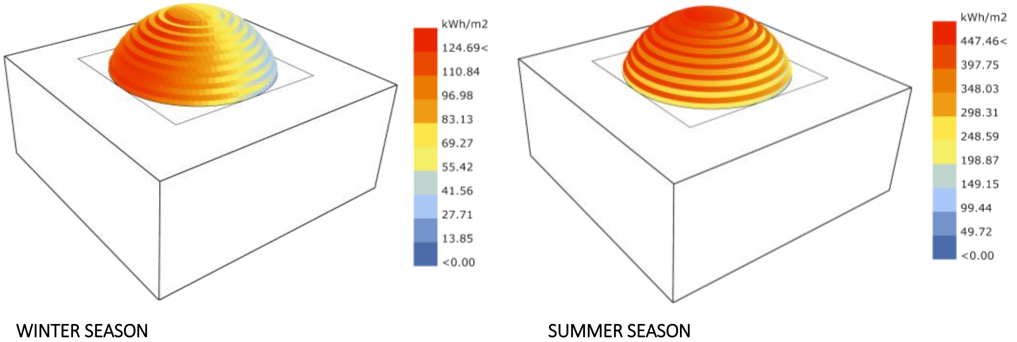



*figure 8.5: summer and winter season analysis (summer: June to August, winter: December to February)*

south. However, the result for this size glass dome (radius of 14m) is rather good, temperature and energy wise (figure 8.6). The temperature drops with almost 3 °C on a summer day, compared to a flush design without PV. There is a temperature difference of 0.7 °C between a flush and wave design, both with PV. The difference throughout the day can be seen in Appendix VI: analysis of design. The concept of figure 8.4 to block summer sun works, but not to a significantly large extent. The winter situation, the wave concept has an advantage since it gains solar heat. The yield from the PV layout of the flush and wave design are comparable, both produce electricity for approximately five average households. The flush design produces slightly more. Apparently, the overall orientation of the solar cells is better.

Visually, the zebra application on a glass dome, with accompanying shadows, creates an interesting image (figure 8.7).

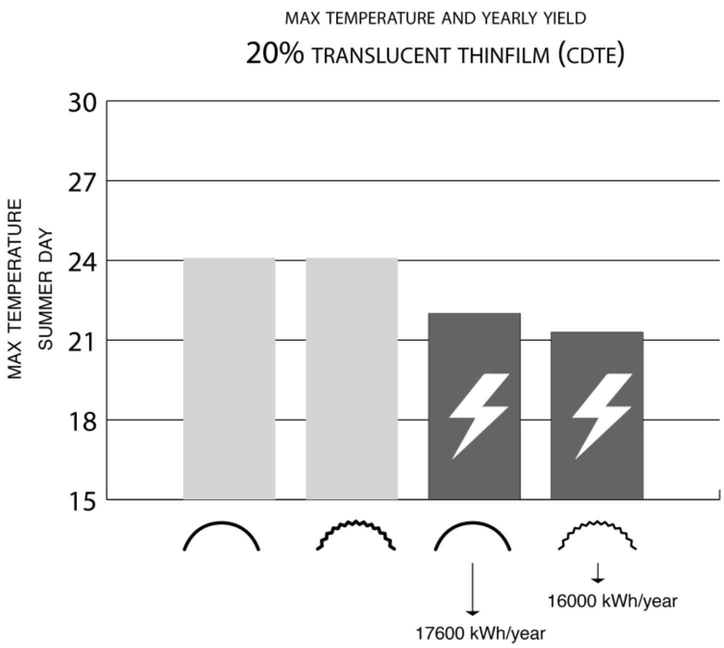



*figure 8.6: solar radiation analysis result of a total year. Comparison between flush or wave texture and with or without PV cells.*

*a-SI thin film with 20% transparency and 11% conversion efficiency is used.*

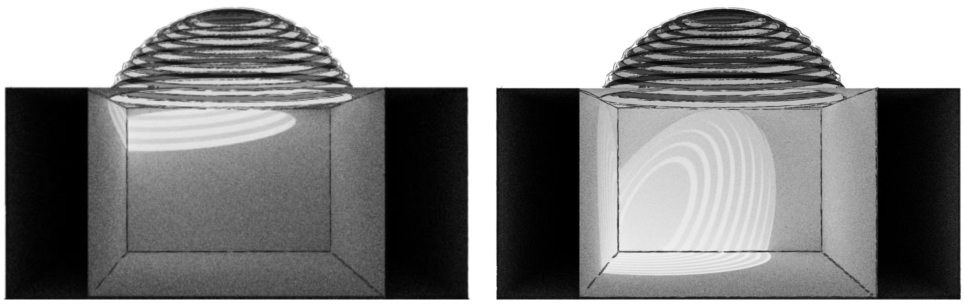



*figure 8.7: image of zebra thin film PV on a glass dome on a winter and summer day.*

### 8.3.2 Design 2 – flat, sawtooth, mono c-Si

A sawtooth roof is an old, proved concept, which is often used in for example factory's. The vertical north side of the saw tooth are transparent and let diffuse light in. The oblique part is closed. What if this oblique part of the roof is covered with 50% c-Si solar cells? The result of the insolation analysis is shown in figure 8.9. A clear and obvious difference is seen between the oblique and vertical roof components.

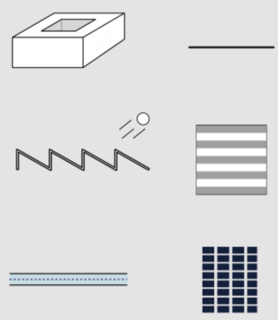


*figure 8.8: choices for design 2*

The temperature difference with no PV between flush and sawtooth is calculated to be 1.4 °C (figure 8.10). Although there is a slight increase of radiated area, this outcome is estimated to be too high, considering only direct radiation. However, in figure 7.1 you can see that a large part of the solar irradiance is from diffuse radiation. So, from a 'diffuse light' point of view, the area has increase significantly. This explains the temperature rise.

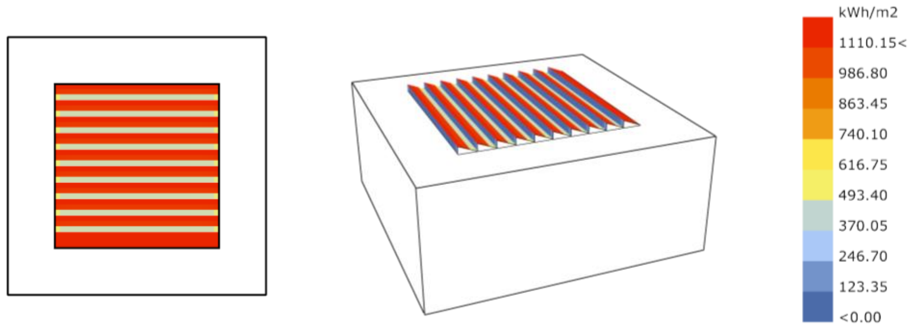



*figure 8.9 (l): year analysis insolation; l: top view (north is up), r: perspective view*

A temperature difference of 1.8 °C is calculated between the sawtooth and flat design with PV, with the sawtooth with PV is the 'coolest' option. Also, the orientation dependence of mono c-Si is very clear. The flat roof produces 38% less electricity over the year, compared to the better orientated sawtooth (figure 8.10). The 80000 kWh that would be produced covers the annual energy use of approximately 24 average households.

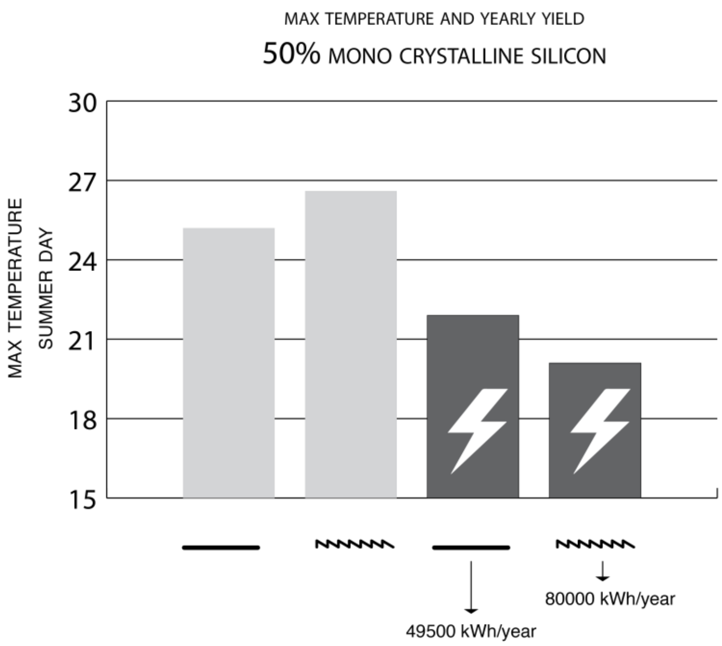



*figure 8.10: solar radiation analysis result of a total year. Comparison between flush or sawtooth texture and with or without PV cells.*

*Mono crystalline silicon cells, spaced so it has 50% transparency and 21% conversion efficiency is used.*

### 8.3.3 Design 3 - future vision

To show what an architect can do with the knowledge of this thesis, a design proposal is made. How could this roof look like, with the focus on climate and energy production? This is a redesign of the atrium roof of the museum of history of nature in Leeuwarden, has covered their courtyard with a glazed roof, in 2004. This was designed by Jelle de Jong and engineered by Octatube. The current design has a flat roof, with a flush texture. The roof is constructed with cables, which makes an efficient structure. The goal of the following design is to show the added value DSSCs can have both architecturally as in an energetic way.

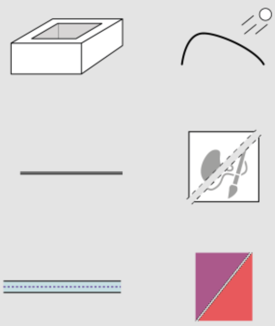


*figure 8.11: choices for design 3*


*figure 8.12: top view (Google maps)*

*figure 8.13 (l): internal view atrium (Google maps)*

*Macro*

This case is a large close atrium. The area of the roof is about 900 $m^2$, so we know that the atrium needs approximately an STF of 0.2 or less, which is fairly low (figure 6.20). For this case the geometry is dome-like/sun oriented, in a way that it receives as much sun as possible (figure 8.14). On the other hand, the north side of this geometry is almost not directly radiated. In this way, diffuse northern light can enter. The radiation analysis is presented below (figure 8.15). The average radiation level is 864 kWh/$m^2$. This is rather high for a curved geomertry. It can be explained by the lack of adjacent buildings (no shade).

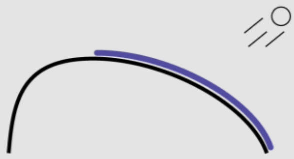


*figure 8.14: sun oriented geometry, PV layout intensified on south side.*

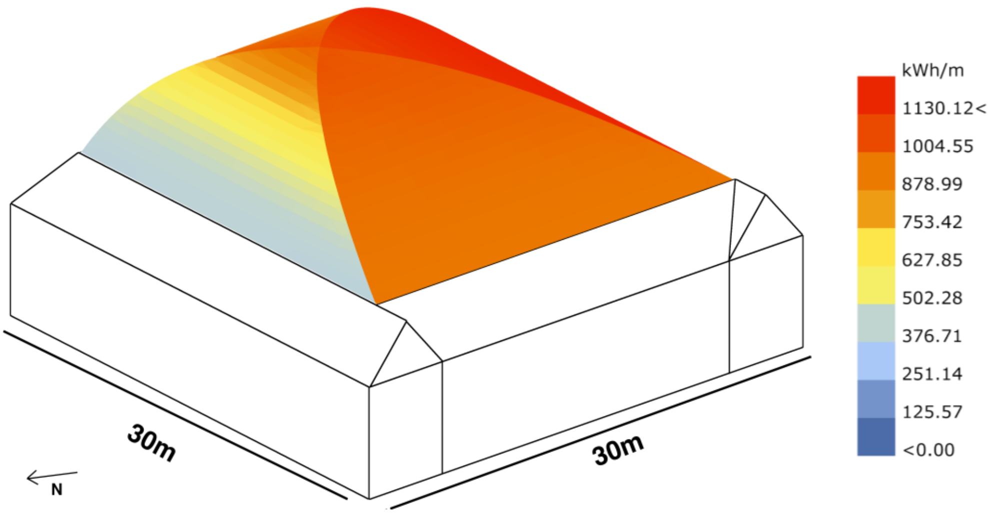



*figure 8.15: annual radiation distribution analysis.*

*Meso*

For the meso scale, a flush texture is chosen. This will need less construction materials and time. Also, you would choose another texture, like sawtooth, to add shaded parts for diffuse light to enter. In this design, the macro shape of the roof already achieves this. The PV layout will illustrate leaves of a tree. To meet the low STF, but still have sufficient daylight and view, the PV print is most dense on the south side and top. Just like the solar irradiation, to shade maximal, and to gain the highest energy yield.. On the north side, the 'leaf cover' opens up to allow for daylight and view. The

*Micro*

The DSSCs is integrated in the interlayer of the outer two glass panes, with a screen printing technique (figure 8.16 and figure 8.18). The detail is developed considering some boundaries. The layout should not be shade by itself, so a flush texture on panel level is required. This also enhances the image of the total print from the outside. Furthermore, cables from the PV cells should be kept out of sight. On the other hand, there should be easy access to the cables for maintenance. The detail (see next page), is based on the structural glazing system of Raico. An extra steel profile is bolted on the steel structure for the cables. Holes are made in the top for cables and every 400mm there is an oval gap in the side of the profile (figure 8.19). The connection wire which comes out the panel is attached before the silicon seal. For maintenance in this part, the silicon seal should be cut out locally.

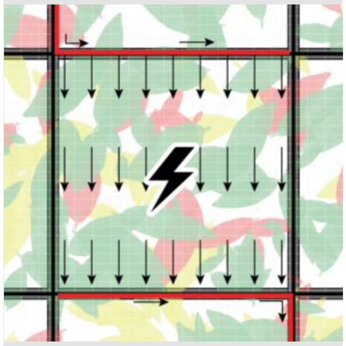


*figure 8.16: close-up roof structure; current flow and cables through DSSCs glass.*

See next pages for details and impressions of this design.

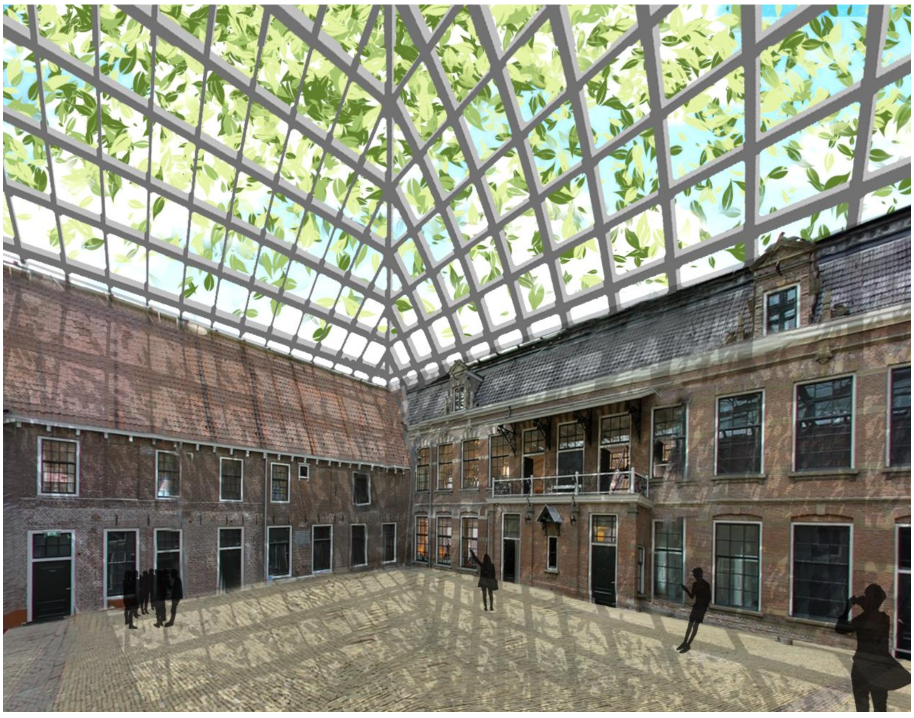
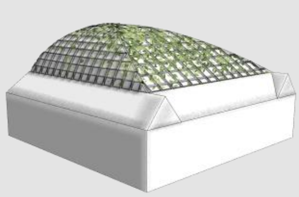


*figure 8.17: 'natural' screen print of DSSCs with three different shades of green.*



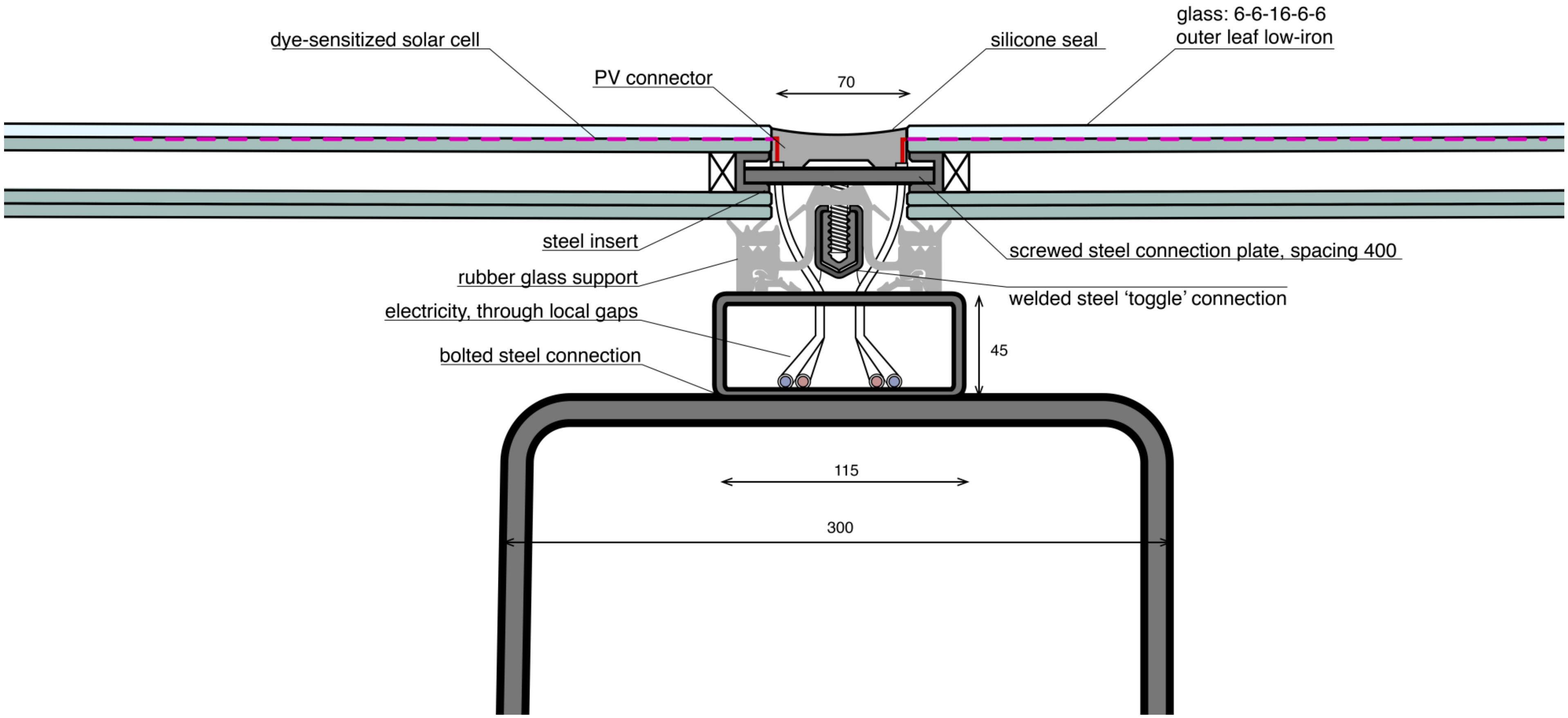



*figure 8.18: detail of glass panels with integrated solar cells, connected to the structure.*

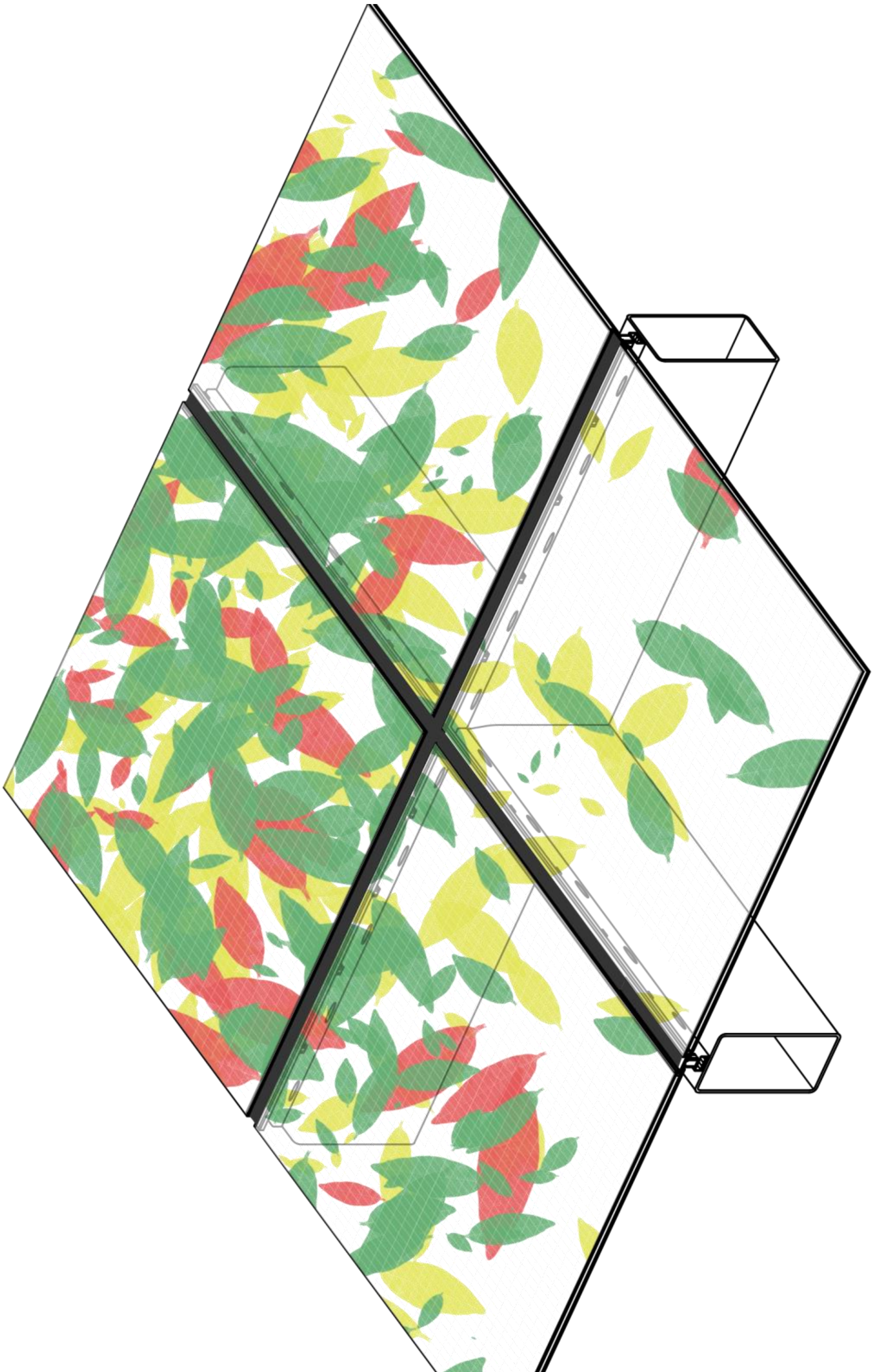


*figure 8.19: 3d view - part of structure, with screenprint of DSSCs in different colours*

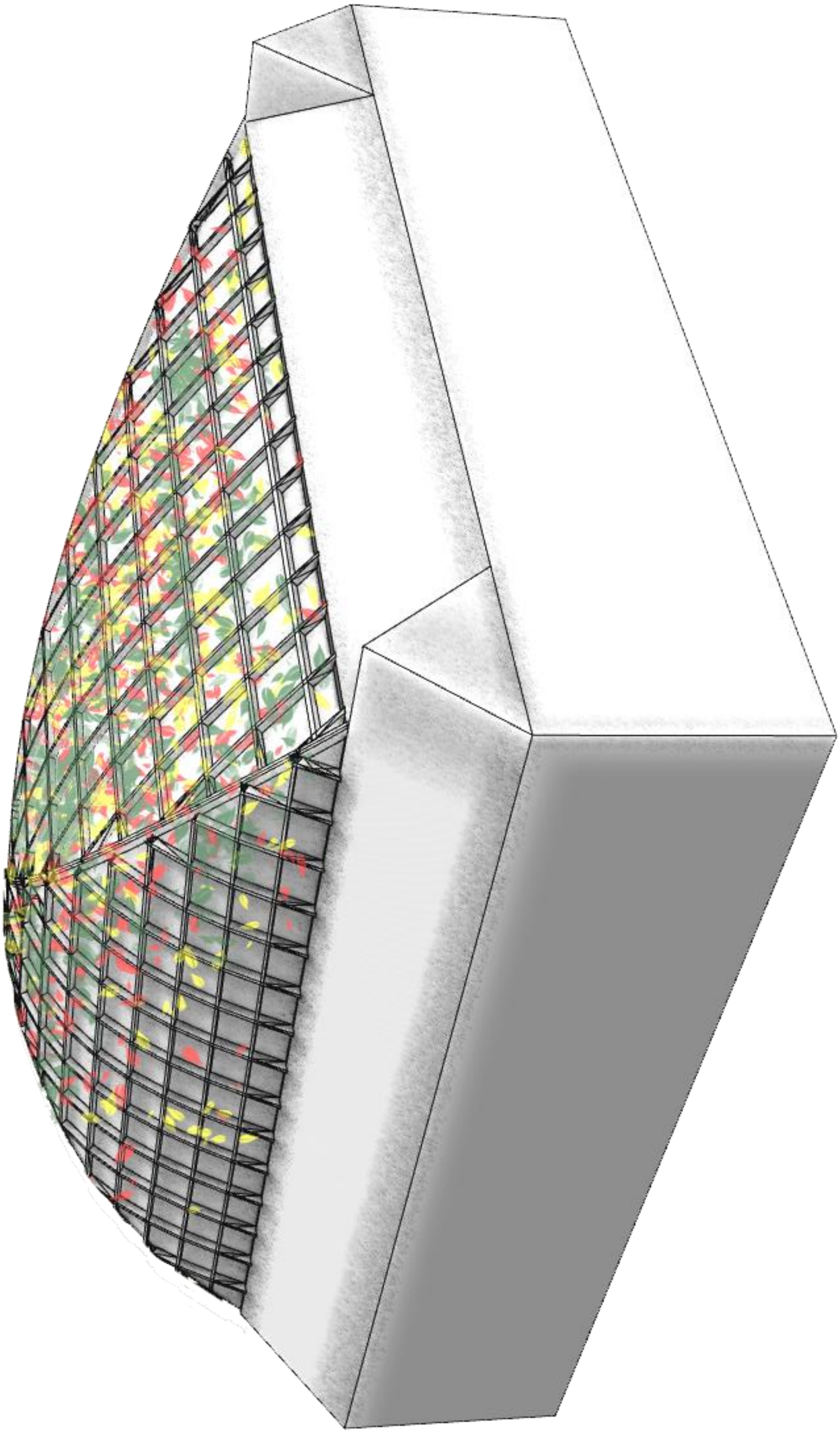


*figure 8.20: outside view*

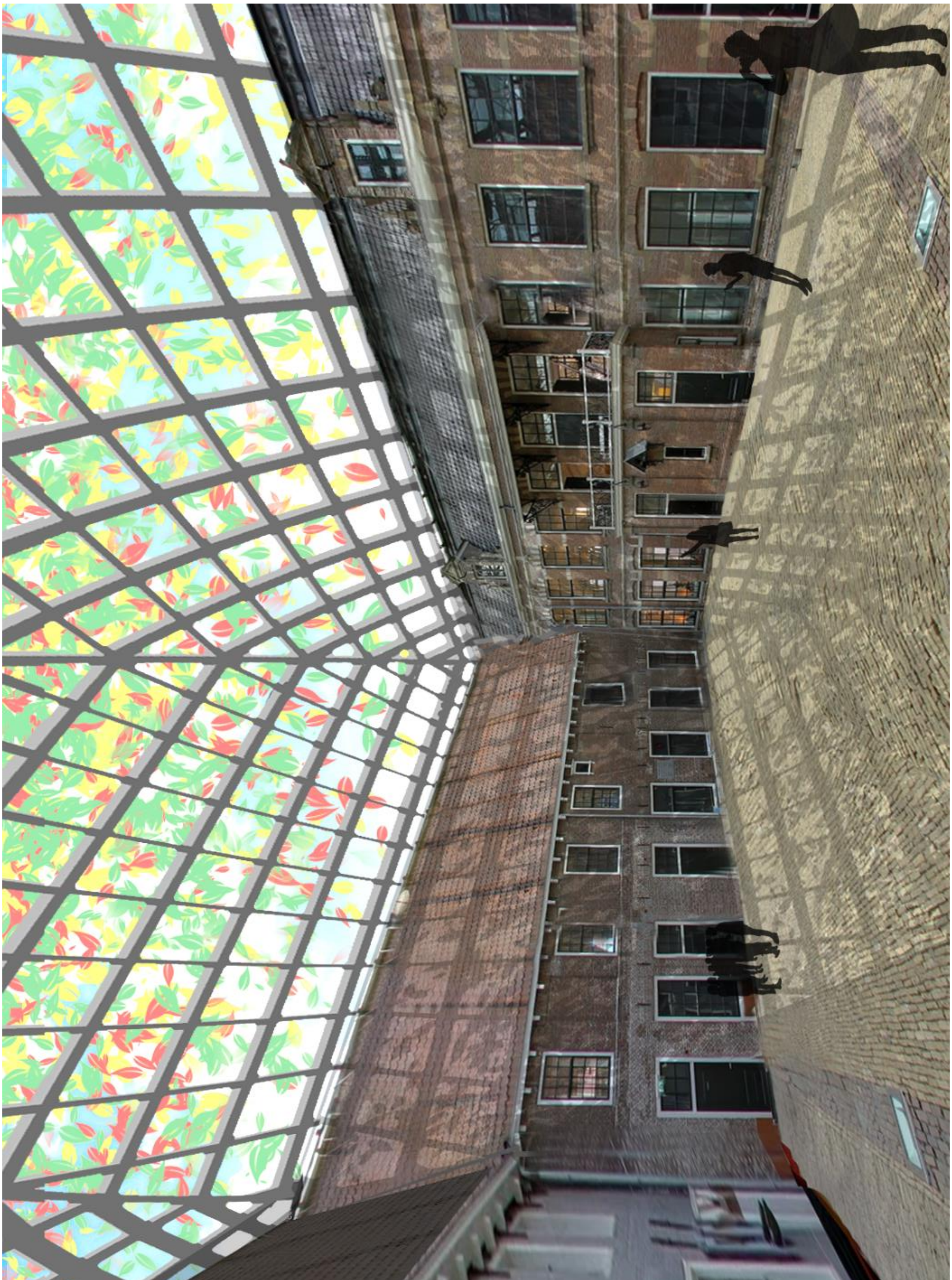


*figure 8.21: inside perspective*

## 8.4 Conclusion

A design of a glazed roof can be made with the presented morphological overview. A designer can use this as a guideline through the process. Choices can be made on ground of energy, but also input from aesthetics or structural behaviour can determine the choice. Roof shape and texture add shaded zones to the roof. PV layout can be fit to these zones and leave place where diffuse light can enter. The analysis tool gives first input in the design process for the morphological overview. When all decisions in the manual are made, the analysis tool can be used again to calculate the final values. In this way, design decisions can be adjusted throughout the process based on visual and numerical feedback.

The first design is a dome-like roof with a waved texture. Alternating per layer, thin film PV is applied. This design has a reduction of 3 $^{o}$C on the representative summer day. Heat gain in winter is helped because sun with a small altitude can enter since the STF of the vertical façade panels is higher. The second design is a typical sawtooth roof. But this time, the surfaces directed to the sun are covered with 50% mono c-Si. The temperature calculated between sawtooth and flush without PV is too high. To drop the maximum temperature, PV applied on the oblique parts of the roof is very effective.

In the future, glazed structures can be printed on with DSSCs in various shapes and colours. In the redesign of the museum of history of nature in Leeuwarden, the translucency of the PV is minimized on the place where most solar heat enters the atrium. On the other places, diffuse light can enter. This new type of PV can add architectural value, besides production of energy.

A design for large glazed spaces will always be a trade-off between quantitative values like PV yield and maximum internal temperature on the one hand, and qualitative values like aesthetics and quality of daylight/view, on the other hand. For instance, for the energy production it would be best to make a complete closed roof with c-Si cell oriented and tilted to the south. But for other, architectural reasons, you want to have daylight. So, there is no ‘one best option’.

# Part D – conclusions & reflections

This part reflects and concludes on the total thesis. How is the research question answered and what could be researched in following studies? Also, did the chosen method work and do the results have added value?

# 9 Conclusions

To answer the research question, *"In what way, can the integration of solar cells in the skin of large glazed spaces be applied effectively and contribute positively to the internal thermal comfort?"* the following conclusions are drawn:

The starting point of this thesis is sustainability, with the focus on energy. To reduce the energy use of non-renewable resources, to increase the thermal comfort and production are most relevant in large glazed spaces. To produce energy in large glazed space, photovoltaic cells are most convenient to use. At the same time, these can function as shading and enhance the thermal comfort (cooling load reduction). Spaces like these are built for the extra architectural quality they offer, but go hand in hand with climate problems. Solar control is one of the major challenges, especially in 'bigger' large glazed spaces. The temperature model uses standard ISO 1379:2008 for dynamic hourly temperatures. The solar transmittance factor (STF) is the most important parameter, in regard of this type of buildings. Also, ventilation is a very important one, as concluded by the parameter study. Furthermore, a heavy or light building can differ the required STF for approximately 5%. Considering shading with PV, solar heat reduction-wise, external shading is the most efficient. However, integrated PV in glass is favourable since it easier to manufacture/build and requires less maintenance. Also, it has comparable solar heat reduction properties with external shading. Engineering the climate of a large glazed structure is a delicate practise. Many parameters are should considered for temperature calculation.

For optimal performance of the PV layout, (local) shading should be considered in a design. New PV technologies like thin films and DSSCs have (potentially) lower production costs and energy use. However, conversion efficiency is often lower than mono c-Si. New printing techniques and the use of colour, especially for DSSCs are very promising and give more freedom to design with.

*The parametric analysis tool*

For direct feedback during the design phase, a parametric model is developed to present radiation levels and calculate the accessory internal temperature. Together, the yield of the photovoltaic layout is calculated. Now, not all types of PV cells can be calculated with. The model is limited to input of systems that are on the market. Also, the model can be automatized further since to interpret the results, still manual effort is done to plot it into graphs. A large part of the total radiation is diffuse light, relatively smoothly distributed in all directions. The more curved, the higher the standard deviation is. When the curvature of a geometry is heavy, it shades itself. The energy production calculation works relatively good. Especially on longer analysis periods, it will be closer to the actual yield. More verifying should be done, but for now we can say that the tool has an error margin of about 15%. The added value of this tool is the first quick visual impression on how much insolation is where and when. Later, the values for temperature and energy production calculations can be interpreted.

*The design manual*

With the morphological overview, a design of a glazed roof can be made. One of the input parameters for decisions is energy. However, structure and aesthetics are often also decisive parameters, for instance. Roof shape and texture add shaded zones to the roof. PV layout can be fit to these zones and leave place where diffuse light can enter. The analysis tool gives first input in the design process for the morphological overview. When the path through the design manual passed, the analysis tool can be used again to calculate the final values. In this way, design decisions can be adjusted throughout the process based on visual and numerical feedback. With two design examples made with the design manual, the effect of applying PV to the yield and the internal temperature is clarified. In the future, glazed structures can be printed on with DSSCs in various shapes and colours. In the redesign of the museum of history of nature in Leeuwarden, the translucency of the PV is minimized on the place where most solar heat enters the atrium. On the other places, diffuse light can enter. This new PV type can besides production of energy, add architectural value.

A design for large glazed spaces will always be a trade-off between quantitative values like PV yield and maximum internal temperature on the one hand, and qualitative values like aesthetics and quality of daylight/view, on the other hand. For instance, for the energy production it would be best to make a complete closed roof with c-Si cell oriented and tilted to the south. But for other, architectural reasons, you want to have daylight. So, there is no 'one best option'.

*Concluding*

Orientation of PV cells is important to get a maximum yield. However, this does not mean that a designer should determine geometry of a building only on orientation. The negative effect of badly orientated solar cells is not that significant in most cases. Also, new technologies like thin film, OPV and DSSCs, perform good even in not optimal orientations. The new technologies also have less embodied energy and are potentially cheap. So, it will be easier than it used to be to have a short energetic and economic payback time. More freedom in design is achieved and designs can be optimized with the morphological design overview and the parametric analysis tool.

So, solar cells can be applied effectively to enhance the thermal comfort of large glazed spaces. A design can be made with the morphological design overview and optimized with the parametric analysis tool.

# General Reflection

*Method*

The chosen method (literature, analyses, design) worked out well. With this methodology, I have touched all scales of the research question; from theory to design. The results I got from the analyses part, give justified input for the design. Because of this process, I would describe the graduation ‘design by research’ since all decisions until now are based on the output from the parametric model.


*Graduation is characterized as design by research*

During the process, I learned software I had not a lot of experience with. I did not use the parametric software Grasshopper too much before and especially the plugins honeybee and ladybug took me quite some time to learn. Now, this effort payed off, and the research method worked in that sense. I got substantiated conclusions from the calculation models, and I made visual what the impact of geometry and context is on the local radiation level of a surface. What is new, is the link between the energy weather data, parametric design and climate calculations. However, I expected that it would take less time and wonder if this is the most effective method to make these calculations. The temperature calculations should be validated. Now, the results can only be used for reciprocal comparison. Also, the PV yield calculation should have an extra validation with another project, over a longer time.

The morphological design overview is a good way to give insight in the choices that you need to make, designing a large glazed space with PV cell. However, I think that there are more options to add in the overview. Also, numerical consequences of choices could be attached.

*Social context and relation graduation lab theme*

In general, the world needs ‘clean’ energy sources (without greenhouse gas emissions). Most people agree that humans emit too much greenhouse gasses, especially carbon dioxide, and that it leads to climate change. This climate change threatens the way people live today. Buildings use a significant portion of world’s energy consumption. With new and cheaper becoming technologies like photovoltaic cells, decentralized energy production emerges as a promising option for energy production on buildings. The theme of this graduation lab is sustainability. The starting point of my thesis is focused on the energy part of sustainability; reduction and production. So, one specific theme in sustainability is considered. Reduction of use of energy from non-renewable resources is the aim throughout the thesis. However, sustainable aspect could be worked out further. For instance, what is the lifetime of an atrium or how does such a space influence human wellness?

*Architectural value*

Architects tend to make more transparent building nowadays. However, overheating is a problem for large glazed spaces. Often, the coating to filter as much of the near-infrared part away, is not enough to meet the requirements. With the new PV cell technologies you can meet these requirements and use the solar energy instead. With the parametric model and design overview a designer 'knows what to do', without the need of extensive knowledge on the subject. With this insight, you can give solar shading something 'extra' in a design, and design with it instead of adjust the STF at the end.

## Reflection on sustainability

Large glazed spaces have several climate/comfort issues. Currently, the internal thermal comfort is one of the most important ones. On summer days, large glazed spaces tend to get overheated. Leading to low thermal comfort. Human wellbeing is an important aspect of sustainability. Also, if people do not feel comfortable in the space, it will be used less or demolished quicker (durability).

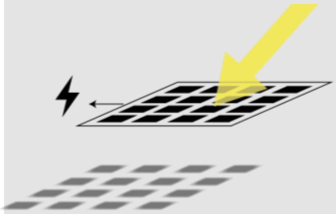


*figure 9.1: solar cells provide shading and electricity*

Operating buildings in general, is a large part of the global annual energy consumption. Adding to the thermal comfort reduces the probability that such a space is climatized actively. To affect the climate of large glazed spaces, much energy is needed. So, the probability that a space will be actively climatized should be brought to the minimum. The concept is to shade the space (adjust the STF) by applying solar cells. The focus of thesis considering sustainability is presented in figure 9.2.


people
wellbeing/comfort
aesthetics

planet
sustainable energy production
low embodied energy solar cells

profit
reduction energy bill
higher value building
reduction solar cell cost

*figure 9.2: focus of thesis regarding sustainability*

*Results*

The focus of this thesis is on thermal comfort in summer of large glazed spaces. With solar cells a double effect is achieved; increase of thermal comfort and production of sustainable energy. The most significant parameters to bring down the temperature in summer are the solar transmittance factor, the (passive) ventilation rate and the thermal mass.

There are several solar cell technologies that all have their own specific properties to select on. Cost and efficiency are the most well-known criteria. Also embodied energy (from production) is a very important factor, regarding sustainability. When you compare the embodied energy of a solar system, it is important to take into account the total "balance of system" (BoS). The second generation of PV cells already have a significant lower embodied energy (figure 9.3).

The new third (nano) generation of PV cells has some important advantages relative to first or second generation solar cells. For example, dye-sensitized solar cells, the embodied energy is much lower than regular crystalline and thin film solar cells. In production, you just need a maximum temperature of 500 °C instead of 1600 °C. Also, the light level threshold is low. So even with a little light, DSSC's produce energy. How much energy is saved per kWp relative to c-Si solar cells, is hard to say since there is no large scale, commercial production yet.

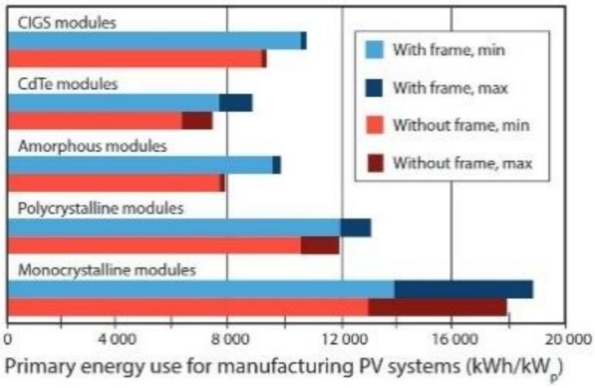



*figure 9.3: primary energy use for manufacturing different PV systems (kWh/kW$_p$); top to bottom: CIGS, CdTe, a-Si, poly c-Si, mono c-Si. The three thin films use about 30 to 50% less primary energy relative to crystalline silicon cells. (Smets et al., 2016, p. 346)*

The efficiency of these solar cells is typically lower. However, if the embodied energy per kWp is lower than for instance c-Si cells. Maybe you need more square meters per kWp, when it is cheap and you have plenty of surface area, it does not matter.

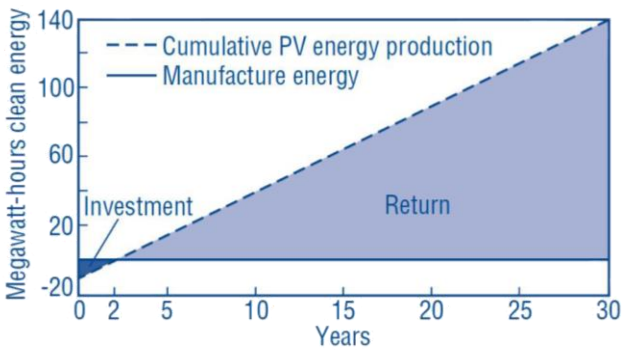



*figure 9.4: PV module (c-Si) energy payback time of 2 years; during expected lifetime of nearly 30 years, the module produces multiple times the invested energy (U.S. Department of Energy, 2004, p. 2)*

The application of solar cells to bring down the indoor temperature is studied before. James et al. (2009) concluded that "*with appropriate consideration of added value factors*" the use of semi-transparent solar cells in atria/large glazed spaces can be justified in terms

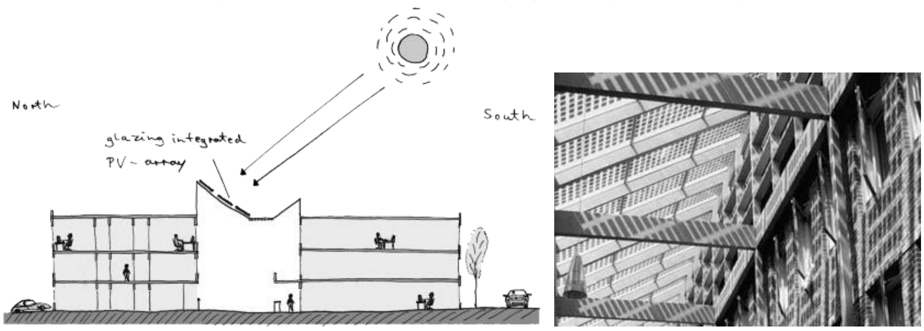



*figure 9.5: PV cells as a replacement for shading, placed on the most intensely radiated part of the roof (James, Jentsch, & Bahaj, 2009, p. 222)*

of both cost and carbon footprint (figure 9.5). Factors that should be considered to make it pay off are orientation, location, context, function of space and temperature demand, for example.

With the developed parametric model for this thesis you can calculate the added value of integrated PV cells (figure 9.6). Now, in an early design phase you can already test whether the concept ‘works’ like you have in mind. Based on results for the parametric model you can make design decisions. Before you had to experiment like the project in figure 9.5. Or in the best situation, the  design is calculated by a consultancy company. But this would always be after the first temporary design decisions are made.

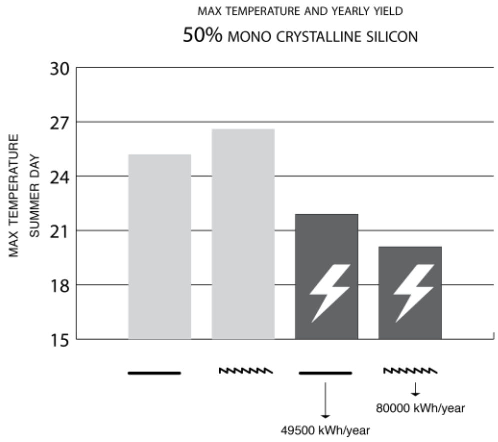



*figure 9.6: solar radiation analysis result of a total year. Comparison between flush or sawtooth texture and with or without PV cells.*

*Mono crystalline silicon cells, spaced so it has 50% transparency and 21% conversion efficiency is used.*

In the thesis, thermal comfort is only addressed as the maximum temperature in summer. However, it would be good if from the calculations the thermal comfort, per month e.g., would be rated. In that way, one would really see whether the double effect of integrated solar cells work or not.

## Recommendations for further research

- Exact values on the solar transmittance factor/absorption facto of the ‘new’ types of PV (for instance thin films, DSSC’s, OPV);
- Only a moderate climate is considered in this thesis. What would a different climate mean for the parameters and design decisions?
- Solar cells on a curved surface will receive a different level of insolation. This will cause the cells to wear off uneven. What is the relevance per solar cell technology; which one is more suitable to apply on a curved surface than a the other? Maybe half of the cells should be replaced for example after fifteen years, and the other half already after eight years;
- A daylight level study can be added to the parametric analysis tool;
- The parametric model can be optimized to make it user friendly/fool proof;
- Development of parametric tool, to make it possible to let the computer search for the best options (computational optimization)

# 10 References


[1] Baker, N. (2009). *The handbook of sustainable refurbishment: non-domestic buildings* (pp. 172).

[2] Biancardo, M., Taira, K., Kogo, N., Kikuchi, H., Kumagai, N., Kuratani, N., . . . Nakata, J. (2007). Characterization of microspherical semi-transparent solar cells and modules. *Solar Energy, 81*(6), 711-716.

[3] Blesgraaf, P., Ham E. R. van den, & Novem. (1996). *Grote glasoverkapte ruimten: atria, serres, passages* (1 ed.). Sittard: Nederlandse Onderneming voor Energie en Milieu.

[4] Bokel, R. (2014). [Equation Sheet AR1B025_D4_Thermal].

[5] Broersma, S. (2008). *De PV-wirefree zonwering: Een adaptief buitenzonweringsysteem met draadloos geïntegreerde zonnecellen.* (Master), TU Delft, Delft.

[6] Campbell, M. (2017). Supporting Methods and Tools. In A. Reinders, P. Verlinden, W. van Sark, & A. Freundlich (Eds.), *Photovoltaic solar energy : from fundamentals to applications*. Chichester, West Sussex, United Kingdom: John Wiley & Sons Ltd.

[7] Casini, M. (2016). *Smart buildings: advanced materials and nanotechnology to improve energy-efficiency and environmental performance* Woodhead Publishing series in civil and structural engineering, *Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance* (pp. 364).

[8] Chartered Institution of Building Services Engineers. (2000). Understanding building integrated photovoltaics. *25*.

[9] Cheng, S. (2009). *Curved photovoltaic surface optimization for BIPV: an evolutionary approach based on solar radiation simulation.* UCL (University College London).

[10] Crawley, D. B. (1998). Which weather data should you use for energy simulations of commercial buildings? *Ashrae Transactions, 104*, 498.

[11] van den Dobbelsteen, A. (2007). Energy, 11. Retrieved from http://www.urbangreenbluegrids.com/energy/ Accessed on 8 Mar 2017

[12] van den Dobbelsteen, A. (2008). *Towards closed cycles - New strategy steps inspired by the Cradle to Cradle approach*. Paper presented at the Conference on Passive and Low Energy Architecture, Dublin.

[13] van Dooren, E., Boshuizen, E., van Merriënboer, J., Asselbergs, T., & van Dorst, M. (2014). Making explicit in design education: generic elements in the design process. *International Journal of Technology and Design Education, 24*(1), 53-71.

[14] Elstner, M. (2008). Coated Architectural Glass. *International Symposium on the Application of Architectural Glass 2008, 2017*(3-1), 81 - 91.

[15] Ferrara, C., Wilson, H. R., & Sprenger, W. (2017). Building-integrated photovoltaics (BIPV). In N. Pearsall (Ed.), The Performance of Photovoltaic (PV) Systems (pp. 235-250): Woodhead Publishing.

[16] Gaglia, A. G., Lykoudis, S., Argiriou, A. A., Balaras, C. A., & Dialynas, E. (2017). Energy efficiency of PV panels under real outdoor conditions– An experimental assessment in Athens, Greece. *Renewable Energy, 101*, 236-243.

[17] Gevaerts, V. S. (2017). Organic PV Module Design and Manufracturing. In A. Reinders, P. Verlinden, W. van Sark, & A. Freundlich (Eds.), *Photovoltaic solar energy : from fundamentals to applications* (pp. 432 - 443). Chichester, West Sussex, United Kingdom: John Wiley & Sons Ltd.

[18] Gevorkian, P. (2008). *Solar Power in building design*. Chicago: McGraw-Hill.

[19] Grapperhaus, F., & Kesteloo, W. (2016). Changing the Perspective. Retrieved from http://www.physee.eu/ Accessed on 10 Feb 2017

[20] Groenewolt, A., Bakker, J., Hofer, J., Nagy, Z., & Schlüter, A. (2016). Methods for modelling and analysis of bendable photovoltaic modules on irregularly curved surfaces. *International Journal of Energy and Environmental Engineering, 7*(3), 261-271.

[21] Hagfeldt, A., Boschloo, G., Sun, L., Kloo, L., & Pettersson, H. (2010). Dye-Sensitized Solar Cells. *Chemical Reviews, 110*(11), 6595-6663.

[22] Herzog, T., Krippner, R., & Lang, W. (2004). *Facade Construction Manual* (S. Lenzen, C. Fritzenwallner, & S. Bender-Grotzeck Eds.). Basel: Birkhäuser.

[23] Honsberg, C., & Bowden, S. (2016). Absorption Coefficient. Retrieved from http://pveducation.org/pvcdrom/absorption-coefficient Accessed on 2 Apr 2017

[24] Huld, T., & Dunlop, E. D. (2017). Performance of grid-connected PV. Retrieved from http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php# Accessed on 12 Dec 2016

[25] James, P. A. B., Jentsch, M. F., & Bahaj, A. S. (2009). Quantifying the added value of BiPV as a shading solution in atria. *Solar Energy, 83*(2), 220-231.

[26] de Jong, M., Kesteloo, W., & van der Kolk, E. (2015). Deposition of luminescent NaCl:Tm2+ thin films with a Tm concentration gradient using RF magnetron sputtering. *Optical Materials, 46*, 149-153.

[27] Kaan, H. F., & Reijenga, T. H. (2002). Geïntegreerd PV-Zonweringsysteem.

[28] Kettle, J., Bristow, N., Sweet, T. K., Jenkins, N., dos Reis Benatto, G. A., Jørgensen, M., & Krebs, F. C. (2015). Three dimensional corrugated organic photovoltaics for building integration; improving the efficiency, oblique angle and diffuse performance of solar cells. *Energy & Environmental Science, 8*(11), 3266-3273.

[29] Lin, C.-F., Huang, W.-G., Chen, P.-H., & Kung, J.-H. (2015). *Lifetime study of Dye sensitized solar cells.* Paper presented at the Active-Matrix Flatpanel Displays and Devices (AM-FPD), 2015 22nd International Workshop on.

[30] van der Linden, A. C. (2011). *Bouwfysica* (7e dr. ed.). Amersfoort: ThiemeMeulenhoff.

[31] Mackey, C. C. W. (2015). *Pan climatic humans: shaping thermal habits in an unconditioned society.* Massachusetts Institute of Technology.

[32] Mark, L. (2012). What's new in Building Integrated PV (BIPV) at the RIBA. Retrieved from https://www.architectsjournal.co.uk/home/whats-new-in-building-integrated-pv-bipv-at-the-riba/8637389.article Accessed on 5 Jan 2017

[33] Nagy, Z., Svetozarevic, B., Jayathissa, P., Begle, M., Hofer, J., Lydon, G., . . . Schlueter, A. (2016). The Adaptive Solar Facade: From concept to prototypes. *Frontiers of Architectural Research, 5*(2), 143-156.

[34] Quaschning, V. (2005). *Understanding renewable energy systems*. Bath: Routledge.

[35] Reinders, A., Verlinden, P., van Sark, W., & Freundlich, A. (2017). *Photovoltaic solar energy : from fundamentals to applications*. Chichester, West Sussex, United Kingdom: John Wiley & Sons Ltd.

[36] Roberts, S., & Guariento, N. (2009). *Building integrated photovoltaics: a handbook*. Basel: Birkhäuser.

[37] Roudsari, M. S., Pak, M., & Smith, A. (2013). *Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design.* Paper presented at the Proceedings of the 13th International IBPSA Conference Held in Lyon, France Aug.

[38] Sampatakos, D. (2014). *Development of three dimensional PV structures as shading devices for a Decentralized Facade Unit of the Future.* (Master), TU Delft, Delft.

[39] Sánchez, E., & Izard, J. (2015). Performance of photovoltaics in non-optimal orientations: An experimental study. *Energy and Buildings, 87*, 211-219.

[40] Skandalos, N., & Karamanis, D. (2015). PV glazing technologies. *Renewable and Sustainable Energy Reviews, 49*, 306-322.

[41] Smets, A. H. M., Jäger, K., Isabella, O., Swaaij, R. A. v., & Zeman, M. (2016). *Solar energy : the physics and engineering of photovoltaic conversion, technologies and systems*. Cambridge, England: UIT Cambridge Ltd.

[42] Solar Edge. (2010). Bypass Diode Effects in Shaded Conditions. Retrieved from http://www.solaredge.com/sites/default/files/se_technical_bypass_diode_effect_in_shading.pdf Accessed on 8 Mar 2017

[43] Solaronix. (2017). Solaronix Solar cells, 4. Retrieved from https://www.solaronix.com/documents/solaronix_solar_cells.pdf Accessed on 30 Nov 2016

[44] U.S. Department of Energy. (2004). What is the energy payback for PV? *National Renewable Energy Laboratory*.

[45] U.S. Department of Energy. (2013). Solar Performance and Efficiency. Retrieved from https://energy.gov/eere/energybasics/articles/solar-performance-and-efficiency Accessed on 1 Apr 2017

[46] U.S. Department of Energy, Building Technologies Office, & National Renewable Energy Laboratory. (2016). Weather Data for Simulation. Retrieved from https://energyplus.net/weather/simulation Accessed on 20 Jan 2017

[47] Veitch, J., & Newsham, G. (1996). *Determinants of lighting quality I: State of the science.* Paper presented at the Annual Conference of the Illuminating Engineering Society of North America.

[48] Wurm, J. (2007). *Glass structures: design and construction of self-supporting skins*: Walter de Gruyter.

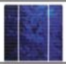
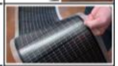
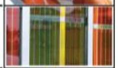
[49] Wyckmans, A. (2005). *Intelligent Building Envelopes.* Norwegian University of Science and Technology, Trondheim.

[50] Wyckmans, A., Aschehoug, Ø., & Hestnes, A. G. (2007). Intelligent Building Envelopes. In M. Crisinel, M. Eekhout, M. Haldimann, & R. Visser (Eds.), EU COST C13 Glass & Interactive Building Envelopes (Vol. 1, pp. 85 - 94). Amsterdam: IOS Press.

[51] Yang, T., & Athienitis, A. K. (2016). A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. *Renewable and Sustainable Energy Reviews, 66*, 886-912.

# Appendices

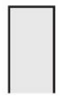
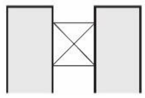
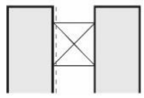
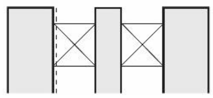
# Appendix I – overview PV technologies

| | | efficiency module (lab) | visual transparency | $W_{peak}/m^{2}$* | technique | low light performamnce/ angle sensitivity | thickness / flexibility | state of commercialisation | notably | appearance |
|---|---|---|---|---|---|---|---|---|---|---|
| CRYSTALLINE SILICON | monocrystalline silicon (mono C-Si) | 15 - 24% (25.6%) | 0%<br>50% (spacing)*<br>70% (spacing)* | 200<br>100<br>60 | glass-glass module | low / high | 160 - 240 µm / brittle | mature, large scale production | |  |
| | polycrystalline silicon (poly C-Si) | 13 -18% (21.3%) | 0%<br>50% (spacing)*<br>70% (spacing)* | 160<br>80<br>48 | glass-glass module | low / high | 160 - 240 µm / brittle | mature, large scale production | different colours possible |  |
| THIN FILM | amorphous silicon (a-Si) | 5 - 10% (14.0%) | 10%<br>20% | 50<br>40 | on flexible substrate (eg. PET), or glass | medium / low | 0.01 - 2 µm / flexible** | mature, large scale production | non-toxic |  |
| | copper indium gallium selenide (CI(G)S) | 7-12% (22.6%) | 0%<br>50% (spacing)<br>70% (spacing) | 95<br>48<br>29 | on flexible substrate (eg. PET), or glass | medium / medium | 0.01 - 2 µm / flexible | early, medium scale production | toxic |  |
| | cadmium telluride (CdTe) | 8 - 11% (21.1%) | 0%<br>50% (spacing)<br>70% (spacing) | 95<br>48<br>29 | on flexible substrate (eg. PET), or glass | medium / medium | 0.01 - 2 µm / flexible | early, medium scale production | |  |
| | Copper, zinc, tin, sulfide (CZTS) | 10% (12.6%) | 0%<br>50% (spacing)<br>70% (spacing) | 100<br>50<br>30 | on flexible substrate (eg. PET), or glass | medium / medium | 0.01 - 2 µm / flexible | fundamental research phase | abundant materials / non-toxic | |
| NANO | Organic solar cell (OPV) | 1 - 10%<br>4.5%<br>(11.5%) | 0%<br>70% | 55<br>45 | on flexible substrate (eg. PET), or glass | medium / medium | | research and development phase | vulnerable to degradation, organic, IR |  |
| | dye-sensitized solar cells (DSSC) | 1 - 10% (14.1%) | | 50 | organic dye, based on photosinthesis | | | early, first applications | (in)organic vulnerable to frost, increase eff. by temp increase, |  |
| | perovskite solar cells (PSC) | 10 - 15% (22.1%) | | | | | 0.1 - 0.6 µm / flexible | fundamental research phase | vulnerable to degradation,ran ge of colours |  |
| | gallium arsenide (GaAs) | 33% | | | on flexible substrate (eg. PET) | | µm / flexible | mainly space applications | |  |
| | quantum dots solar cells (QDSC) | (9.9%) | | | on flexible substrate (eg. PET) | | | fundamental research phase | | |
| | micro-crystalline silicon (µ C-Si) | (6.5%) | | | on flexible substrate (eg. PET) | | | research and development phase | option: 10% transp. visible spectrum, 5%ef |  |
| APPLIED | powerwindow | ~0.05%<br>~0.1%<br>(30W/m2) | ~90%<br>~70% | 0.5<br>1 | reflection in-plane by coating + CIGS | no | | product development, first applications | |  |
| | lumiduct | | diffuse | | concentrator / GaAs cels | no (tracks the sun) | | product development, first applications | |  |
| | glass prisms | | | | | | | | | |
| | sphelar | 15 - 24% (25.3%) | 50%<br>70%<br>80% | 100<br>60<br>40 | micro-spheres of mono C-Si, between glass | no | | product development phase | effective in all directions |  |
| | luminescent concentrators (LSC) | 0.1 - 2% (5.8%) | | | reflection in-plane | no | not flexible | | first results in IR part spectrum |  |
| | Belectric leaves | | | | integrated in glass, OPV | | | early, first applications | |  |

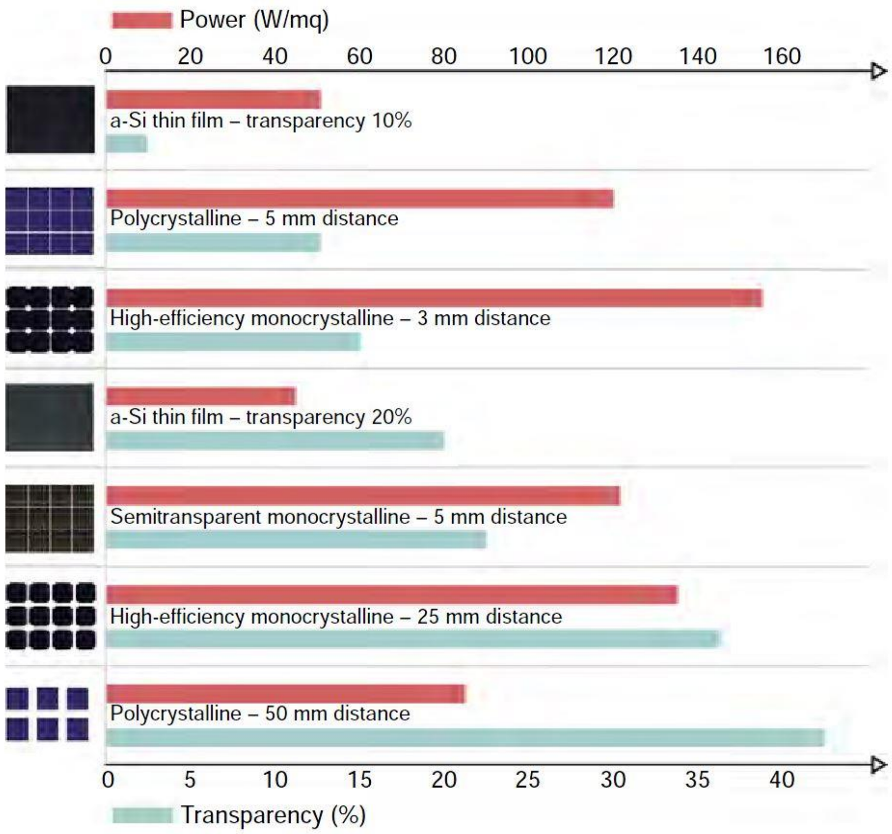
*$W_{peak}/m^{2}$ numbers are extrapolated from efficiency of the cells. The total module yield will be lower

**Flexibility highly dependent on substrate

# Appendix II – glass insulation and efficiency spacing mono c-Si

| | U-value ($m^2K/W$) | |
|---|---|---|
| Single glazing | 5 |  |
| Double glazing | 2 - 2.8 |  |
| Double glazing + low e | 1 - 1.8 |  |
| Triple glazing | 1 |  |

*range of U-values in glass (Guardian Sunguard)*




*comparison application of thin film and crystalline silicon PV in glass-glass modules (Casini, 2016, p. 330)*

# Appendix III: STF with integrated PV

Reduction factor for PV in glass (note that construction should also be considered as a reduction factor):

$$STF = g_{glass} \cdot \frac{A_{glass}}{A_{tot}} . STF_{pv} \cdot \frac{A_{pv}}{A_{tot}}$$

$$Q_{absorb} = Q_{sun} - P_{pv} - Q_{reflect} - Q_{trans} \quad \text{and} \quad Q_{absorb} = Q_{in} + Q_{out}$$

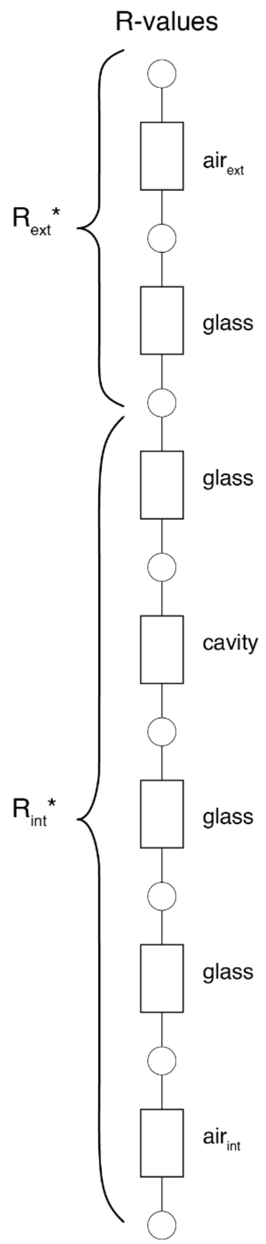
$$Y_{ext} = \frac{1}{R_{ext}*}$$

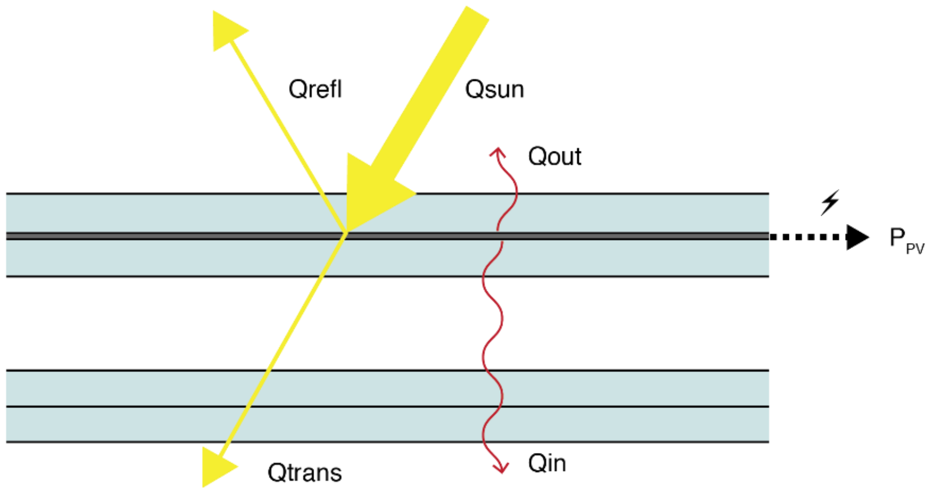
$$Y_{\text{int}} = \frac{1}{R_{\text{int}}*}$$

$$factor : Q_{\text{in}} = \frac{Y_{\text{int}}}{Y_{ext} + Y_{\text{int}}}$$

Goal= Qint

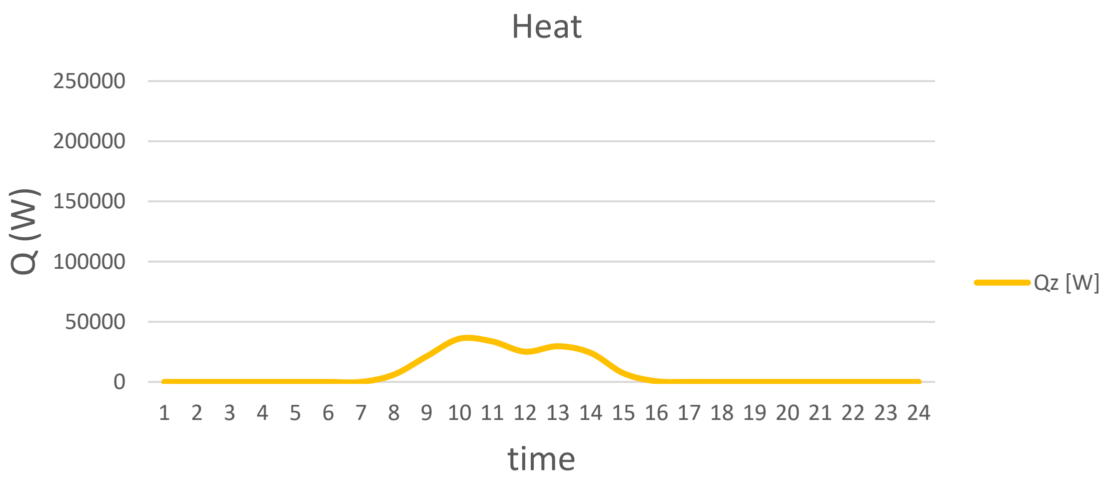
Qab = Qsun - Qrefl – Qtrans – Ppv



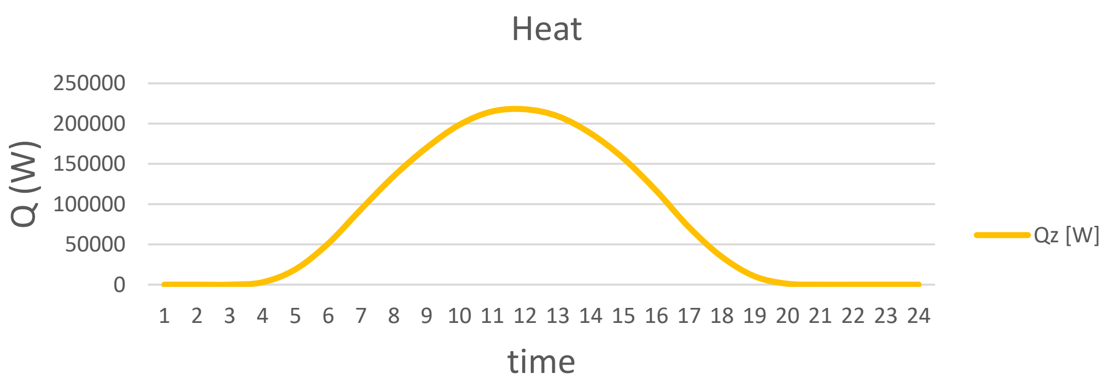



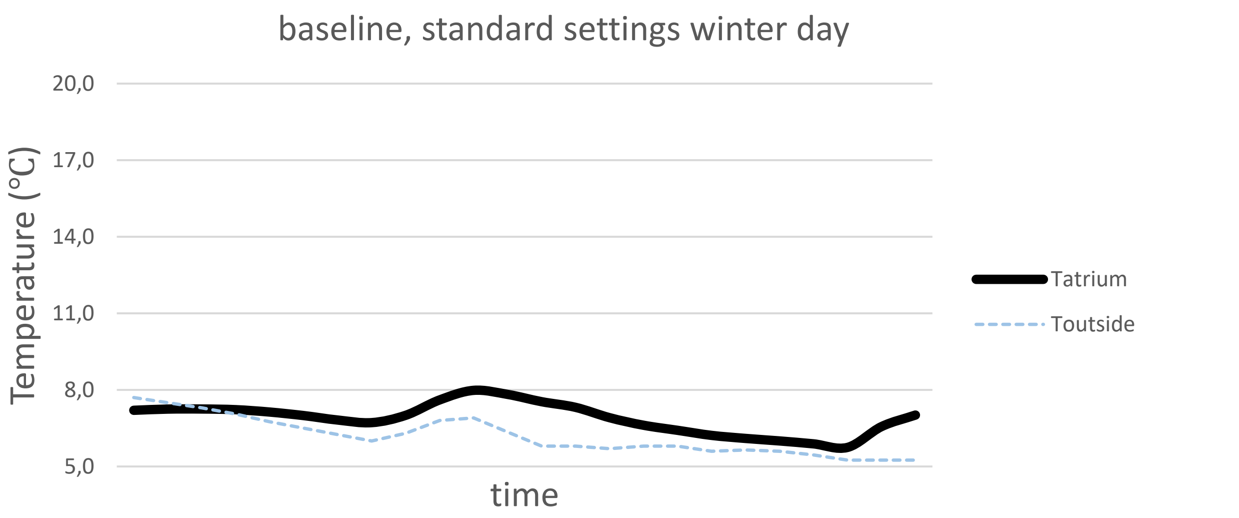
## Appendix IV: calculation model test results

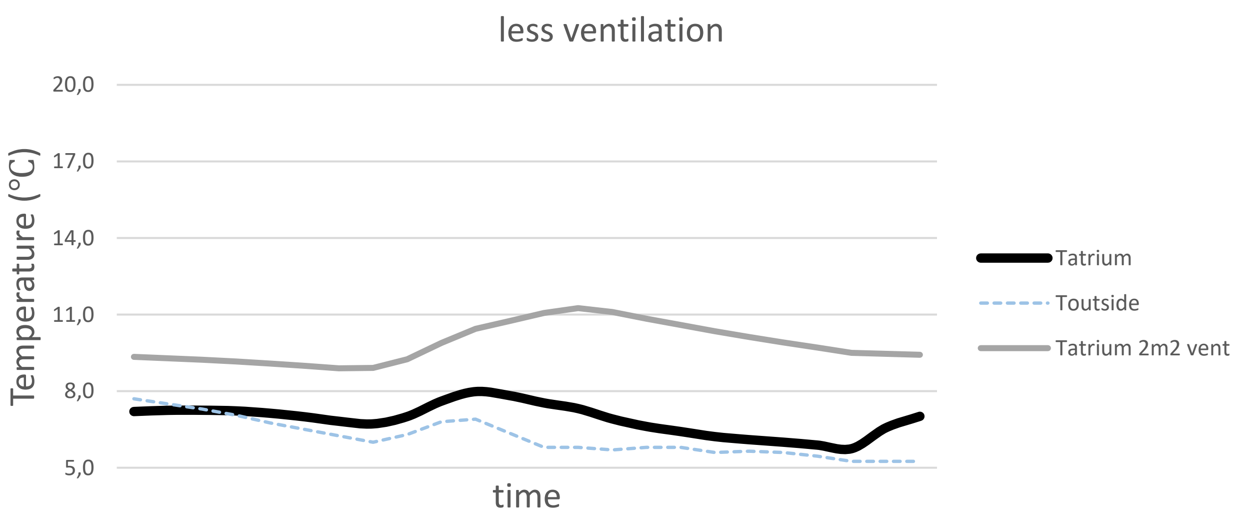
Winter solar irradiance results on reference day

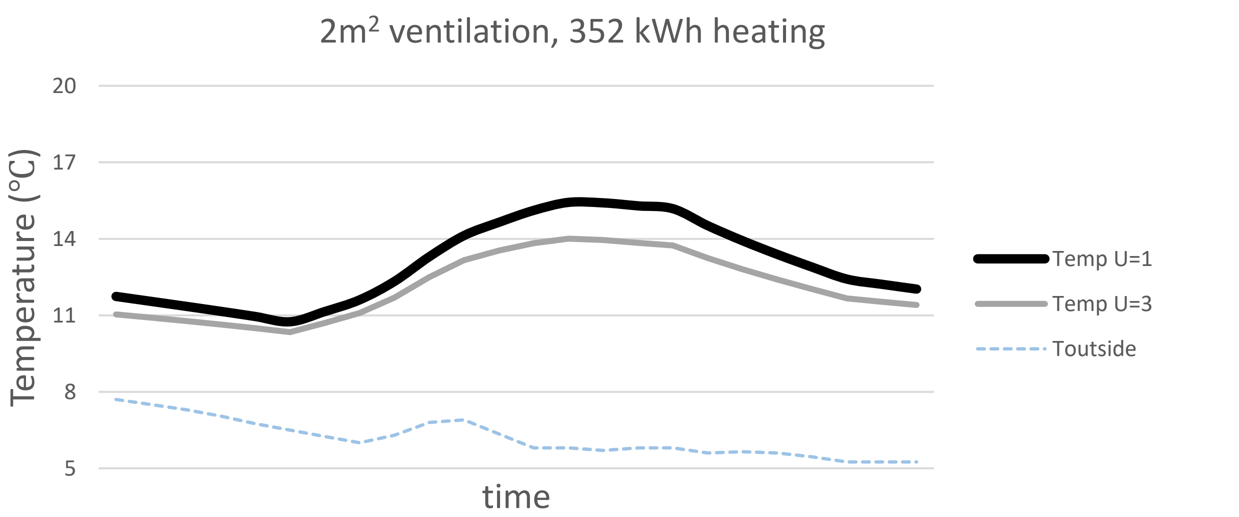


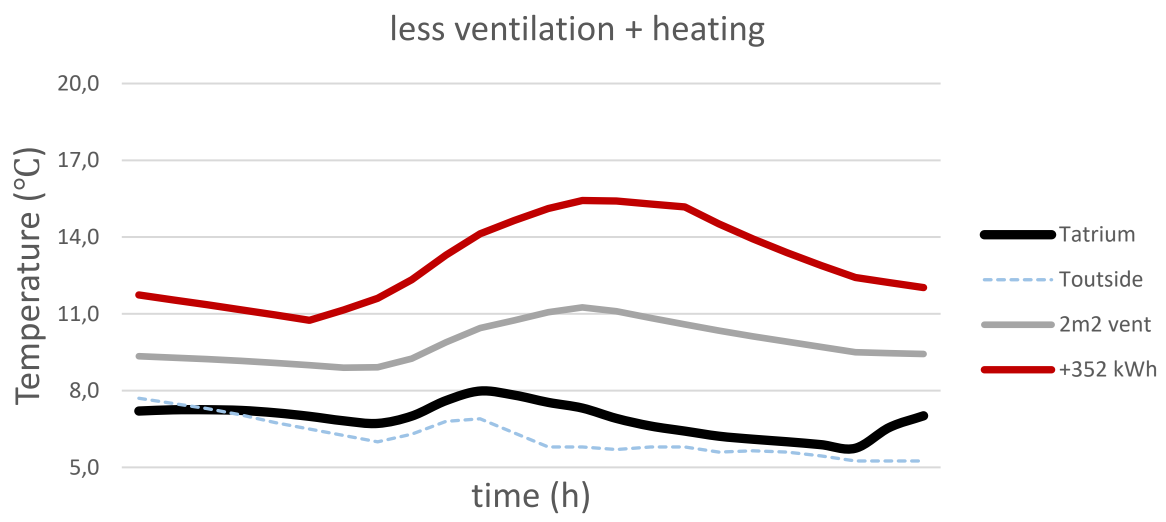

Summer solar irradiance results on reference day




baseline, standard settings winter day
20,0
17,0
14,0
11,0
8,0
5,0
Temperature (°C)
time
Tatrium
Toutside

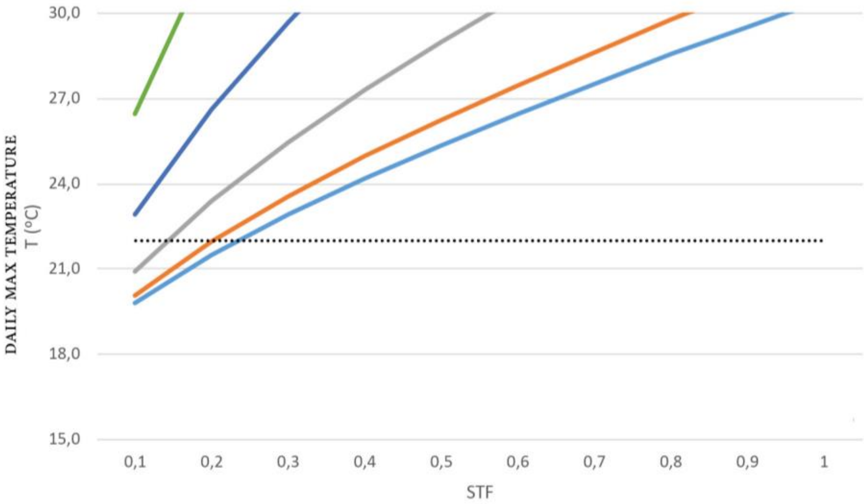

less ventilation
20,0
17,0
14,0
11,0
8,0
5,0
Temperature (°C)
time
Tatrium
Toutside
Tatrium 2m2 vent

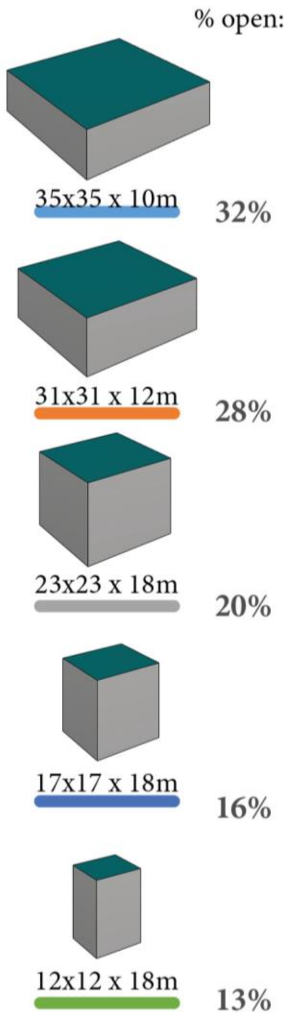

2m² ventilation, 352 kWh heating
20
17
14
11
8
5
Temperature (°C)
time
Temp U=1
Temp U=3
Toutside



less ventilation + heating
20,0
17,0
14,0
11,0
8,0
5,0
Temperature (°C)
time (h)
Tatrium
Toutside
2m2 vent
+352 kWh

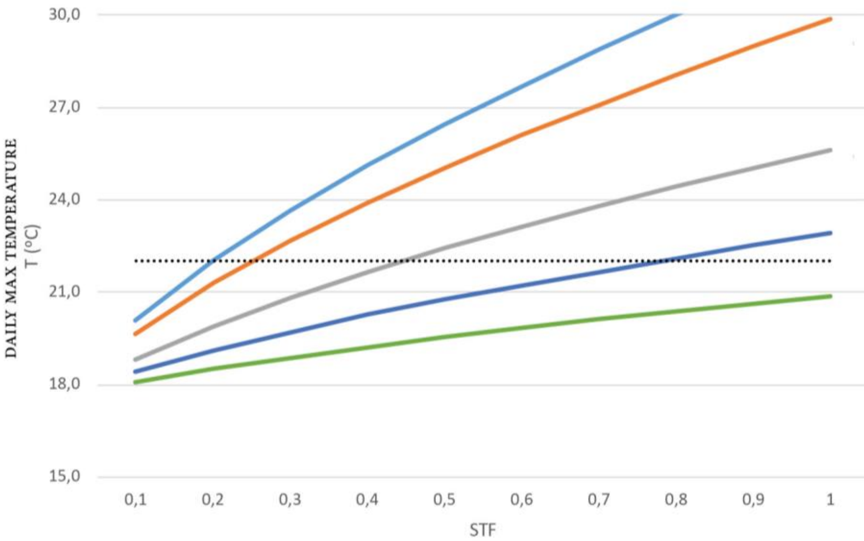
Appendix V: temperature results various atria



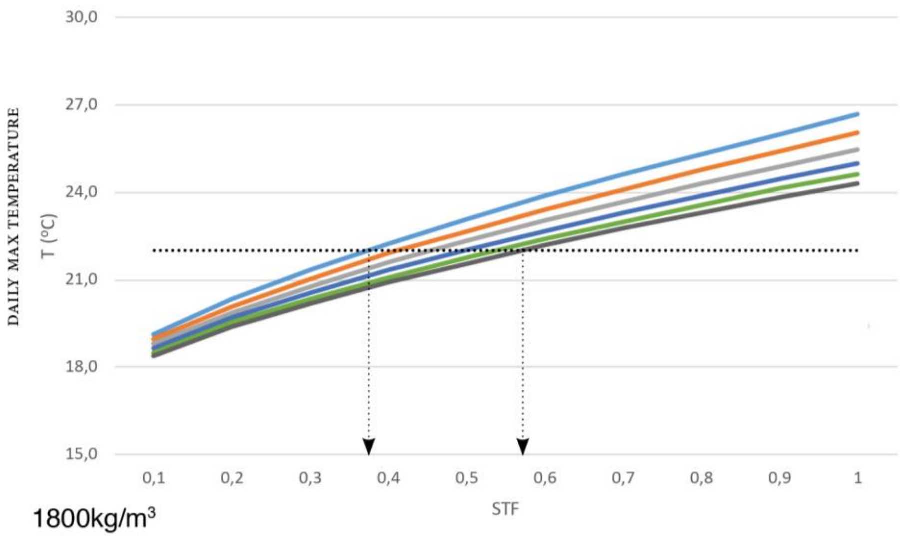

<u>variables:</u>
mass
area roof (insolation)
<u>ventilation area (3%)</u>
ventilation height
STF

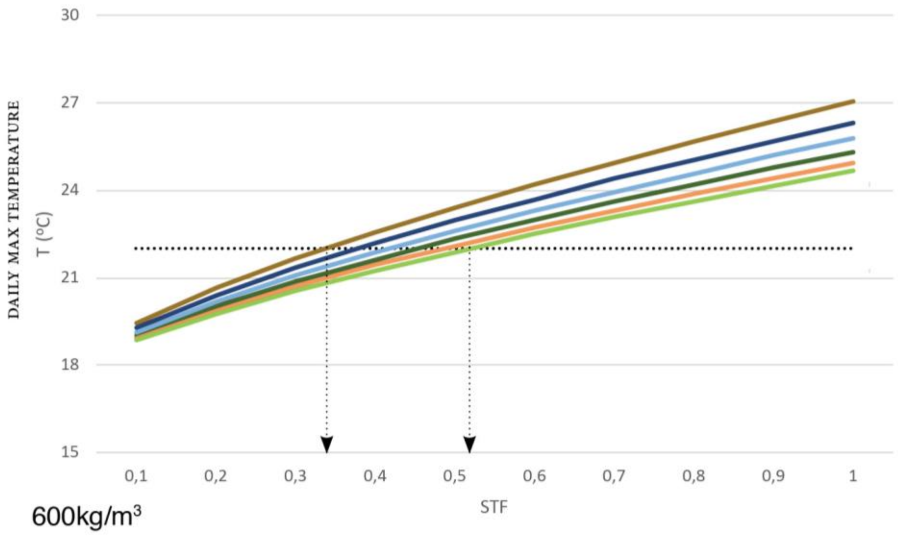
<u>constant:</u>
U-value
outside temp

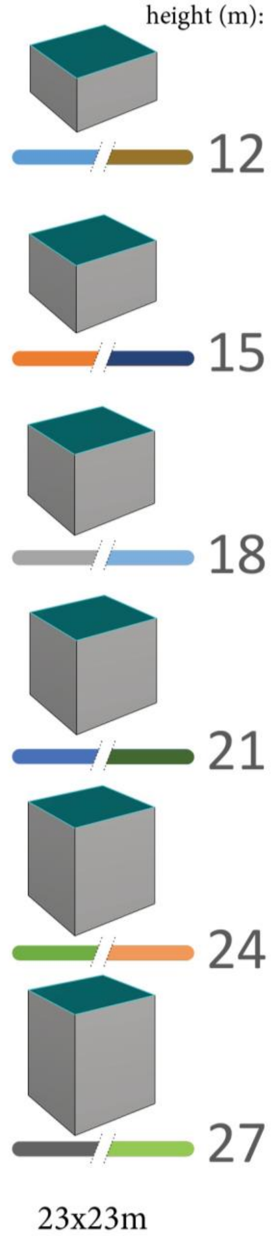


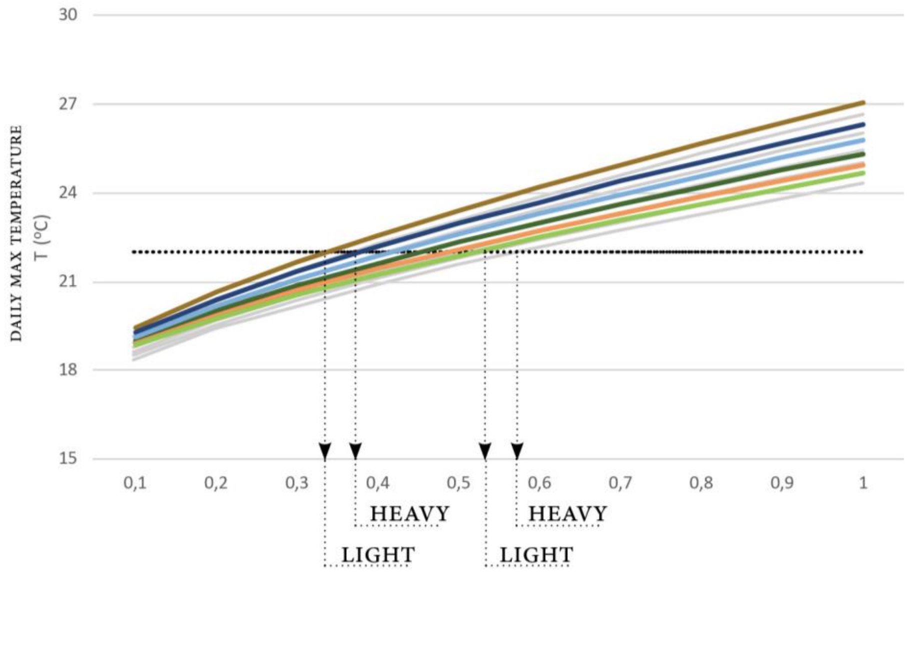

<u>variables:</u>
mass
ventilation height
area roof (insolation)
STF

<u>constant:</u>
<u>ventilation area</u>
U-value
outside temp



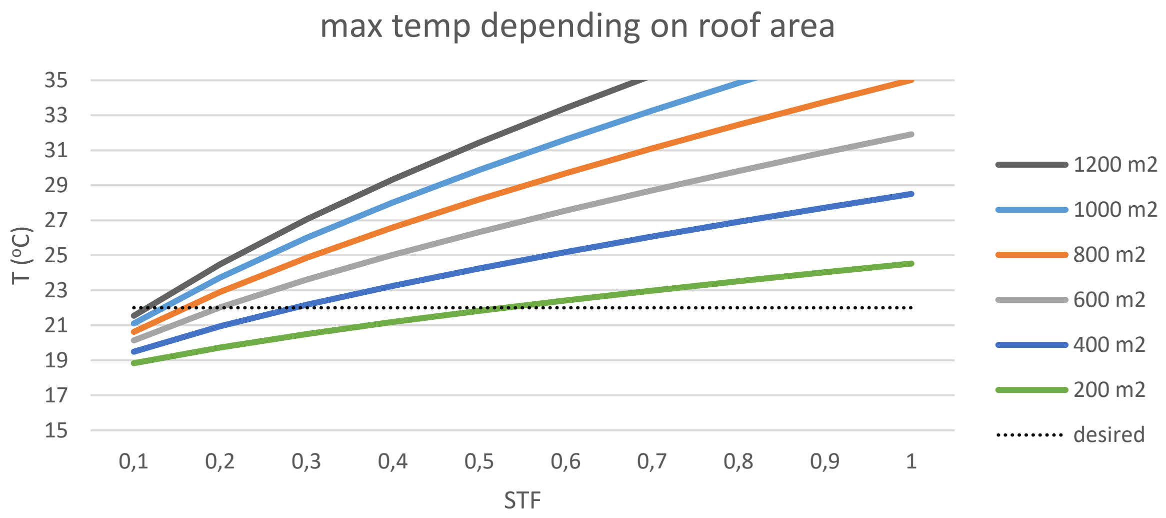



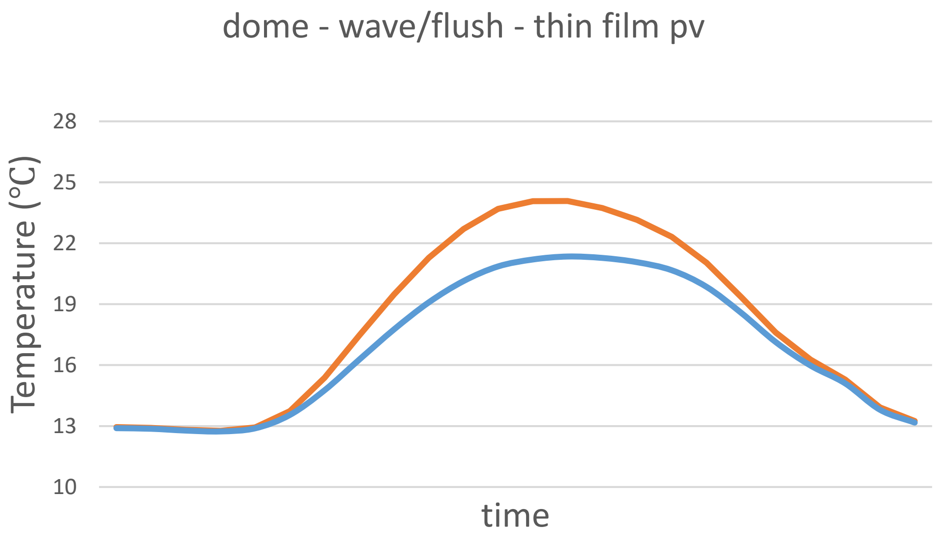




<u>constant:</u>
area roof (insolation)
ventilation area
U-value
outside temp

<u>variables:</u>
mass
ventilation height
STF




## Appendix VI: analysis of design




*Temperature during summer day with flush and wave textured dome with PV.*