Solar panels reduce the urban heat island

Research into the optimization of a flat roof mounted photovoltaic installation system design as mitigation strategy for the urban heat island effect.

Research outline and literature study
Contents
I Literature study ........................................................................................................................................ 4
1 Urban Heat Island effect .................................................................................................................. 4
  1.1 Definition ...................................................................................................................................... 4
  1.2 Types ............................................................................................................................................ 4
  1.3 Causes intensifying the Urban heat islands ............................................................................. 4
  1.4 Consequences ............................................................................................................................ 5
  1.5 Rooftop mitigation strategies ..................................................................................................... 6
2 Poly crystalline photovoltaic (PV) solar roof panels .................................................................. 7
  2.1 Physical properties poly crystalline PV solar panels ............................................................... 7
  2.3 Existing conversion efficiency architectural design guidelines ................................ .......... 8
4 Urban energy Balance .................................................................................................................... 12
  4.1 Urban surface energy balance .................................................................................................. 13
  4.2 Energy balance of the photovoltaic roof ................................................................................. 14
  4.3 Most important parameters (QSWsky, Epv and H) for architectural design ....................... 15
II Design study .................................................................................................................................... 16
5 Case study: The Edge ..................................................................................................................... 16
6 Modeling methods .......................................................................................................................... 18
  6.1 Inputs: parameters and variables ............................................................................................. 18
  6.2 TRNSYS ....................................................................................................................................... 18
  6.3 TRISCO (VOLTRA) .................................................................................................................. 18
7 Model validation ............................................................................................................................. 18
  7.1 Measurement setup .................................................................................................................... 18
  7.2 Data collection .......................................................................................................................... 18
  7.3 Validation .................................................................................................................................... 18
8 PV roof design ................................................................................................................................ 18
9 Conclusions ..................................................................................................................................... 18
  9.1 Conclusion .................................................................................................................................... 18
  9.2 Discussion ..................................................................................................................................... 18
  9.3 Recommendation ....................................................................................................................... 18
Bibliography ...................................................................................................................................... 18
Figure/ table references ..................................................................................................................... 20
Appendix A ........................................................................................................................................ 21
Appendix B ........................................................................................................................................ 32
This report contains the research outline and literature study for the graduation as required for the P2 go-no-go presentation. Little attention is given to the page layout as it is a raw version of the data. In this early phase of the research, the literature study is written as short as possible. Therefore occasionally an introduction and conclusion is missing or the text of a chapter is not completed yet. Further in the graduation process an final literature study and elaborated layout will be presented. (Also as my English improves during the graduation process some text parts will be revised.)

First mentor: Prof. dr. G.J. Hordijk 
Second mentor: Prof. dr. M.M.E. Pijpers-van Esch
External mentor: ir. G. de Nijs,
I Literature study

1 Urban Heat Island effect

1.1 Definition

The weather data of countries across the world are showing considerably lower temperatures in the rural areas compared to the downtown urban areas. This emerging effect is called the Urban heat island (UHI) and it assumes that cities accumulate heat and are consequently (day and night) warmer than their surrounding rural area (Oke, 1982). Due to heat storage of the city’s building materials the UHI intensity will be at its maximum level during the night (Tan et al., 2010).

1.2 Types

Urban Heat Islands could be observed at the surface, we call them ‘Surface Heat Islands’ (SHI). But they could also be observed in the atmosphere in and above the city. These are called Atmospheric Heat Islands (AHI). The AHI’s in the city can be sub-divided into Canopy-Layer Heat Islands (CLHI) and Boundary-Layer Heat Islands (BLHI). The different types vary from each other in intensity, momentary behaviour, spatial form and degree of homogeneity.

The Surface Heat Island (SHI) effect can be observed when the temperature of urban surfaces is higher than that of the surrounding rural (mostly natural) surfaces. This type of heat island is commonly found where the dry impenetrable surfaces of the city are surrounded by moisty soil or vegetated areas. The urban SHI’s are the largest during daytime, especially in sunny conditions with little wind, and are generally at night. Therefor the SHI effect is most intense during the summer period, because of more sunny days with little wind than in wintertime.

The Atmospheric Heat Islands (AHI) effects are small or absent during the day and most intense during the night or just before dawn. Thereby the intensity of the AHI’s is higher during the winter period, because there is a higher temperature difference between the urban- and rural area.

The Canopy-Layer Heat Island (CLHI) is observed in the layer of air just above the surface in cities. The boundary is approximately extending upwards about the average (mean) building height. It is typically observed at night in stable atmospheric conditions with little or no cloud and/ or wind. The CLHI effect is weaker or non-existent during the day time. The Boundary-Layer Heat Island (BLHI) forms a dome of warmer air that extends downwind of the city. It may be one kilometre or more in thickness by day and shrinking to hundreds of metres or less at night. Wind often changes the BLHI to a plume shaped dome (Erell, Pearlmutter, & Williamson, 2011).

1.3 Causes intensifying the Urban heat islands

The UHI effect has the following causes (Oke, 1987, 1995; Santamouris & Asimakopoulos, 2001), which is summarized and illustrated by Pijpers-van Esch et al., (2015):

1. Absorption of short-wave radiation from the sun in low albedo and high emissivity of materials. The absorption is even more stimulated by multiple reflections between buildings and street surface.
2. Decreased long-wave radiation heat loss from street canyons, caused by obstruction of the sky by buildings, trees and other objects (smaller sky view factor). The heat is intercepted by the obstructing surfaces and absorbed or radiated back to the Urban Canopy-layer (UBL).
3. Absorption and re-emission of long-wave radiation by air pollution in the urban atmosphere.
4. The release of anthropogenic heat by combustion processes, such as traffic, space heating and industry processes.
5. Decreased turbulent heat transport from within streets caused by a reduction of wind speed.
6. Increased heat storage by building materials with large thermal admittance. Cities have a larger surface area compared to rural areas and therefore store more heat.
7. Decreased evaporation from urban areas because of less permeable materials (waterproofed surfaces) and less vegetation compared to rural areas. As a consequence, more energy is put into sensible heat and less into latent heat.
A more extensive explanation of these causes can be found in the book ‘Urban microclimate: designing the spaces between buildings of Ereill, et al. (2011), chapter 3.

The weather (particular wind and cloud cover) affects the intensity of heat islands. The magnitudes of heat island effects are largest under calm and clear weather conditions. Strong winds mix up the air and theretofor breakdown the heat island. The wind-effect can be noticed during day and night time. Cloud cover reduces radiative cooling to the atmosphere at night.

The geographic location determines the regional climate and topography of the area in which the city is situated. Regional and local weather influences (local wind systems) may impact heat islands. For example the Hague may experience reduced heat island magnitudes compared to Eindhoven due to lower sea surface temperatures than the land surface temperatures, whereby wind is cooling by convection (Erell et al., 2011).

1.4 Consequences
The most direct effect of an urban heat island is increased air temperatures in urban areas. Increased air temperature in these areas during day and night time result in a number of relevant consequences.

Heat related morbidity & mortality
As temperatures in the city increase, so does the possibilities of heat related illness. Exposure to extreme and prolonged heat is associated with cramps, fainting, heat exhaustion and heatstroke, with heatstroke being the most common cause of heat related death. Regardless of the cause, heat mortality tends to occur 1 or 2 days after the peak temperature of a heat wave. The increased thermal storage of cities, which leads to increased overnight temperatures, can deprive the urban citizens of their night time relief and worsen heat related health problems.

Higher energy consumption
Increased urban air temperatures causes an increase in the energy used to cool buildings. Although there is a slight urban heat island (UHI) benefit in the winter, this benefit is generally small compared to the penalty incurred during the winter season. Also in the Netherlands office buildings have to switch on their conditioning system when the outdoor temperature rises above 12-15 degrees Celsius (Kleerekoper, 2009).

Poor air quality
....[To be continued]

Economic impact
All of the above UHI consequences also have an economic impact. The societal cost of smog and increased demand for healthcare should certainly be considered, but is also hard to calculate. Fortunately, the cost of increased energy consumption is slightly easier to quantify.
1.5 Rooftop mitigation strategies

Recent studies revealed that the large-scale deployment of solar photovoltaic (PV) roof systems in the urban environment can be beneficial to mitigate some of the causes of the urban heat island (UHI) effect. In addition to the longer known indirect reduction effect of greenhouse emission gases and combustion of fossil fuels. Recent investigations have documented a reduction of the annual cooling load of a building (Dominguez, Kleissl, & Luvall, 2011) and the cooling of regional outdoor near-surface temperature as a consequence of the deployment of solar PV roof systems. In combination with the direct effect of harvesting free local energy, these recent discoveries show huge potential for cities becoming more resilient and more comfortable during heat waves. Within this research we will only address the outdoor urban microclimate, there for the rest of the chapter will focus more on the various studies conducted to compare the reduction effect of solar PV panels on the near-surface temperature.

A meteorological model of the metropolitan area of Los Angeles was built to simulate the large-scale deployment of solar PV panels, which showed a reduction up to 0.2 °C for the regional outdoor near-surface temperature (Taha, 2013). Other researchers have modelled more detailed results. Scherba et al. (2011) modelled the rooftop energy balance for different types of rooftop. He discovered the deployment of a conventional density of solar PV panels is capable of reducing (on average) the daily sensible heat flux into the urban environment by 11%. Masson et al. (2014) concluded solar (PV and thermal) panels can reduce the near-surface air temperature of Paris up to 0.2 °C during the day and 0.3 °C during night time.

In April Salamanca et al. (2016) published their research on mitigation strategies for the two major USA cities of Arizona: Phoenix and Tucson. They characterized the diurnal cycle of near-surface air temperature in these cities. A brief overview can be found in the table below. To provide a more extensive explanation, the research results are described more extensive.

<table>
<thead>
<tr>
<th>Modelled scenario</th>
<th>Day time (°C)</th>
<th>Night time (°C)</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV rooftops (100%)</td>
<td>0.2 - 0.4</td>
<td>0.4 - 0.8</td>
<td>69%</td>
</tr>
<tr>
<td>Solar PV rooftops (75%)</td>
<td>0.1 - 0.3</td>
<td>0.1 - 0.3 or 0.1 - 0.4</td>
<td>61%</td>
</tr>
<tr>
<td>Solar PV rooftops (25%, 50%)</td>
<td>0.1 - 0.3</td>
<td>0 or 0.1 - 0.4</td>
<td>58%</td>
</tr>
<tr>
<td>Cooling rooftop surfaces</td>
<td>0.4 - 0.8</td>
<td>0.1 - 0.4</td>
<td>71%</td>
</tr>
</tbody>
</table>

Table 1: summary of modelled near-air temperature research results.

For the maximum coverage rate scenario of solar PV rooftops (100%), lowered near-surface temperatures results were found of 0.2-0.4 °C during daytime and 0.4-0.8 °C during the night. For Maximum coverage rate scenario of cooling rooftop surfaces results were found of 0.4-0.8 °C during the day and 0.1-0.4 °C during the night. With a high coverage rate scenario of solar PV rooftops (75%) still significant results are found. During the day the modelled lowered near-surface temperatures are 0.1-0.3 °C. During the night the lowered near-surface temperatures of 0.1-0.3 °C in Phoenix and 0.1-0.4 °C in Tucson are found. For a low coverage rate scenario of solar PV rooftops (25 or 50%) the panels reduced the near-surface temperatures by 0.1-0.3 °C during the day. During the night the panels did not demonstrate a significant impact for phoenix, but displayed cooling for Tucson between 0.1-0.4 °C. Finally, the researchers estimated the resilience of their simulations by calculating the number of times (showed as a frequency in %) near-surface air temperature difference was in a particular range. As a result, near-surface temperature cooling occurred 69% of the time during the diurnal cycle, which illustrates enough confidence for the mitigation strategy being capable of reducing near-surface temperatures. On the other hand, the least aggressive solar PV panels deployment (25%) reduced near-surface temperatures cooling occurred only 58% of the time and is therefore less capable of reducing the UHI effect.

For several decades now research has been conducted into the use of cool/green roof (high solar reflective or high “albedo” value) technologies both for direct building energy savings and urban heat island mitigation. The results from recent studies indicate solar PV rooftop systems can also be deployed as mitigation strategy for reducing the UHI effect. The cool/ green rooftops perform better in reducing the daytime UHI, on the other hand the solar PV rooftops are performing better in reducing the night time UHI. Although these mitigation strategies sound very promising, there are certain negative effects to consider as well. A consequence of the large deployment of rooftop mitigation strategies is the reduction of the Planetary Boundary-Layer (PBL), which causes a reduced capability for the lower atmosphere to effectively mix pollutants vertically. The result could be potentially negative effects for the air quality of the urban environment (Li, Georgescu, Mahalov, Moustaoui, & Hyde, 2015). The analysis of the negative effects are complex and beyond the scope of this research.
2 Poly crystalline photovoltaic (PV) solar roof panels

2.1 Physical properties poly crystalline PV solar panels

Within this research we will only take the properties of the photovoltaic solar panel module components in account, which are horizontally placed in an open system above a flat roof. Most of the other components of a PV system are mostly found inside of a building and are therefore not relevant during this research.

2.1.1 PV solar panel components overview

A poly crystalline PV solar panel exists out of 50 or 60 PV-cells of 150x150 mm, which are placed between a glass plate on the front site and plastic foil on the back side. The plastic foil is composed of multiple layers. The most common substance for the plastic foil layers are polyester and Tedlar. The polyester layer takes care of the electrical isolation. The Tedlar layer ensures the protection of the polyester layer against outdoor weather conditions. Tedlar is a trade mark for polyvinylfluoride (PVF). The PV-cells are embedded in ethylvinylacetate (EVA), before they are placed between a glass plate and the plates foil. The combination of glass, EVA, PV-cells and plastic foil is laminated under pressure and high temperatures into one integral component. The integral component is called PV-laminate. The PV-laminate will be placed in an aluminium because of weather conditions and the desire to keep the PV solar panel as light as possible (Amerongen, 2016). An overview of the previous described components can be found in figure 2.

![Figure 2: components overview poly crystalline solar panel](image)

2.1.3 Material properties

Certain values of material properties will be important for calculations later in the process, therefore this section will provide an overview of these values. The Albedo is a measure of the reflectivity of a surface. The Albedo of PV solar panels typically varies from 11% to 16%. When the panel is favourably oriented and tilted to the sun, the albedo is in the low range, and equal to about 11%. The emissivity of a surface is its ability to emit thermal energy. The emissivity of the PV solar panel is equal to 0.93. (Masson, Bonhomme, Salagnac, Briottet, & Lemonsu, 2014)

2.1.4 Material innovation

In October 2014, CSEM has unveiled a white or coloured module technology. CSEM is a private, non-profit Swiss research and technology organization focused on generating value for a sustainable world. The technology is developed to serve the architects constant demand for new solutions to customize the colour of PV panels, which could blend them into the building skin.

As shown in figure [...] the developed technology relies on various elements. First the coloured film scattering filter is able to reflect and spread the visible spectrum, while transmitting infrared light. The transmitted infrared light is absorbed by the poly crystalline silicon solar cells, which have been proven to be the best choice. The conversion efficiency of the technology is calculated to be 11.4%, where traditional proven reference technology reaches a 19.1% conversion efficiency.
Figure 3: Schematic principle of the white PV module (left) and white PV modules fabricated at CSEM (right)

At the beginning of 2015, a startup company Solaxess was founded with the goal to manufacture and commercialize the coloured PV technology developed by CSEM. The challenges are a demonstration of the reliability of this new technology and the upscaling of the scatter filter fabrication at an acceptable production cost for the solar panel market.

An important side effect of the new technology is the potential for heat reduction inside and outside the building, whereas the positive effect are most likely comparable with the mitigation effect of cool roofing during daytime (Escarré et al., 2015).

2.3 Existing conversion efficiency architectural design guidelines

2.2. Flat roof assembly methods

There are multiple PV solar panels assembly methods for flat roofs. The PV solar panels will always be an addition to the flat roof construction. As an example the PV solar panels can never be used to replace the traditional roof surface. A distinction between three different methods will be made (Amerongen, 2016).

Assembly method 1
The PV solar panels will be mechanically attached to or on the external separation construction. The moister barrier will still be supported by the underlying construction. The panels are mounted horizontal or with an angle to the roof.

Assembly method 2
The PV solar panels are placed movable on flat roofs. Some are supported with extra weight (concrete tiles), which keeps the panels in place. The moister barrier will also be supported by the underlying construction.

Assembly method 3
The PV solar panels are directly placed on the roofing surface. The moister barrier is still supported by the underlying construction.

All assembly methods should meet the building regulations, which can be categorized in following themes: permanent load, extra wind load (wind resistance), extra snow load, accessibility, roof sloping and fire safety. Influence by extra wind load can be reduced, when the PV solar panels are attached to each other.

There are different proven systems to mount panels on a flat roof. The most common method is to mount the panels on an aluminium frame, due to the minimal natural weight of the material. Other used systems are plastic trays and concrete bears. The aluminium frames are used in three different configurations: solar sconce, triangular support or flat support. The solar sconce supports multiple PV solar panels, which reduces the loading of the roof substructure even more and can be placed must faster (see figure 3). The triangular supports are the most frequently used methods and they can be placed after each other with space in between (south orientation) or mirrored without space in between (west- and east orientation). The solar sconce and triangular supports can be extended with wind protection plates, which reduce the required loading by concrete tiles or fixed mounting (see figure ..).
Figure 4: example aluminium solar sconce (left) and aluminium triangular support with wind protection sheets.

The flat supports are material efficient and less extra load is needed, since less wind is able to flow under the solar panels (see figure 4).

Figure 5: example aluminium flat support system

The plastic trays can be placed free on the roof and extra weight will be added with gravel. The trays are assembled easy, however due to the closed trays the solar panels will heat up and the efficiency will be reduced (see figure…). With concrete bears the extra load is combined with the sub support construction, which is a very efficient solution if the building construction is strong enough.

Figure 6: example plast trays (left) and concrete bears (right).

The support construction could be adjust in height to catch more or less wind, which potentially cools the panels.

More extensive reference details of the flat roof solar panel can be found in Appendix A.

**Tilt and Orientation**

To catch as much available short wave sun radiation as possible the PV panels are placed under a local favourable tilt and orientation. The orientation is defined as the position of the perpendicular upper alignment to referenced with the wind directions. The tilt angle is defined as the angle between the panel and the horizontal surface (see figure 6).
60\% of the received energy by the PV panel is transported by diffuse radiation. Therefore the orientation and tilt angle of the panel has less influence than most people might suspect.

Figure 7: Illustration definition tilt angle and orientation solar PV panel.

Figure 8: Relatively, yearly mean solar insulation for different orientations and tilt angles for north/west Europe.

Figure 9: Relatively, yearly mean solar insulation for different orientations and tilt angles for the Netherlands.
Wind load
The wind load on flat roofs depends on the obstructed wind flow influenced by the building. The obstructed wind flow is causing pressure and draft forces on the surface of the flat roof. Derived under pressure creates wind suction above the flat roof. A conical formed vortex will be formed above the flat roof if the wind direction is between 30° and 60° compared to the building. The vortex will start in the corner and extend along both roof edges. The vortex will put strong fluctuating and extreme forces on the flat roof surface. These forces determine the load in the corners, which are defined by corner zones. The wind will be guided over the edges of the building, when the wind direction is rectangular positioned compared to the building. Behind the roof surface edge, the wind flow will be released and declines before the other edge, where again higher wind suction will be formed (see figure ).

Banks (2013) concluded that the most critical loads on roof mounted solar PV panels are consistently observed for wind directions that form corner vortices. Another important observation he mentioned, was that load patterns of tilted roof mounted solar PV panels demonstrate considerable asymmetry. Finally, the presence of the roof-mounted PV’s will enhance the strength of these vortices.

To predict the acquired wind effect on the mounted PV panels a CFD simulation model is required, since this type of modelling is a time consuming process it is not likely to be performed within this research. We need to look for less complex methods of predicting the wind effect or ignore it for the time being, since there is not much wind to consider during a heat wave. The program ‘Autodesk Flow design’ is a virtual wind tunnel testing tool and could provide a solution to get a better understanding of the air flow around the mounted PV panels. The creators claim the program is user friendly and give rapid results (see figure ).

Shadow
PV panels should encounter as little shadow as possible during daytime. We can distinguish temporary shadow in two types. Shadow caused by its environment (buildings, trees, chimneys etc.) or natural shadow (own shadow) when PV panels are placed in rows after one another. Sun simulations can calculate and visualize the amount of shadow hitting the designed PV roof system.
Table 2: relatively, yearly yield, at south-orientation, as function of the tilt angle and in between distance of conventional row modules.

**Modularity**
Due to their standard dimensions, the design of a solar PV energy installation system is limited to a multiplication of standard dimensions (see figure).

**Urban energy Balance**
To understand how the causes and mitigation strategies of the urban heat island (UHI) are effecting the microclimate of the built environment, we should start with an analysis of differences in their surface energy balance (SEB). Most likely the positive outcomes are caused by the physical properties (higher albedo value of solar PV, their growing conversion energy efficiency, and low thermal heat storage capacity) of the solar PV panels compared to a traditional rooftop (black bitumen).
4.1 Urban surface energy balance

The first law of thermodynamics states that energy cannot be created nor destroyed. It is only possible to convert the energy from one form to another (Mills, 1999). Simplified in an equation:

\[ \text{Energy input} = \text{Energy output} + \text{change in stored energy} \]

The urban surface energy balance can be viewed as a local- or mesoscale phenomenon. Where the built environment is represented as a textured surface with a determent resolution. The built environment is characterized by its average properties (for example aerodynamic roughness or albedo). With a higher resolution the average properties will be more diverse and extensive. The energy transfer between this surface and the atmosphere is quantified by measuring or modelling fluxes above the urban canopy, at a height which is sufficient to ensure that these fluxes are representative of the overall urban terrain. For the above summarized qualifications, the general equation of the urban surface energy balance is illustrated in the figure below and can be written as (Erell et al., 2011):

\[
Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (3.1)
\]

- \( Q^* \) = net total radiation \([\text{Wm}^{-2}]\)
- \( Q_F \) = anthropogenic heat flux \([\text{Wm}^{-2}]\)
- \( Q_H \) = convective sensible heat flux \([\text{Wm}^{-2}]\)
- \( Q_E \) = latent heat flux \([\text{Wm}^{-2}]\)
- \( \Delta Q_S \) = net storage heat flux \([\text{Wm}^{-2}]\)
- \( \Delta Q_A \) = net horizontal heat advection \([\text{Wm}^{-2}]\)

![Figure 13: Schematic section showing urban Surface Energy Balance (SEB) components](image)

The effect of the urban heat island on the surface energy balance can be categorized in four main themes (Oke, 1995):

**Properties of urban materials**
- The lower overall albedo values are increasing the solar absorption.
- The higher overall thermal emissivity results in an increase storage of sensible heat.
- The less permeable materials (waterproofed surfaces) and less vegetation produces a decrease in evapotranspiration.
Urban geometry
- Bigger surface area and ‘trapping’ by multiple reflections of building also increasing the solar absorption.
- The smaller sky view factors, due to urban obstacles creates a decrease in net long-wave radiation loss.
- Reduction of the wind by increased wind shelter result in a decrease of the total turbulent heat transport.

Anthropogenic heat
- Due to the exhaust of human activities (industry, households, traffic) more anthropogenic heat will be released.

Air quality
- Air pollution increases infrared absorption and re-mission and therefor there will be an increased long-wave radiation from the sky.

The energy balance equation given above is of value in understanding the overall thermal transfers, but it tells very little about the urban microclimate surrounding the photovoltaic roof system. To understand what makes the photovoltaic roof system urban microclimate different from other types of roof systems, we need to go in more detail of an energy balance of a photovoltaic roof (Erell et al., 2011; Mills, 1999; Santamouris & Asimakopoulos, 2001).

4.2 Energy balance of the photovoltaic roof
The energy balance for an open poly crystalline photovoltaic roof system, where the solar panels are horizontal to avoid unnecessary complexity and details of individual buildings (Masson et al., 2014; Salamanca, Mahalov, Moustaoui, Georgescu, & Martilli, 2016).

![Figure 14: Schematic diagram of the energy balance of the solar PV panel.](image-url)

The equation (see figure) can be written as:

\[
(1 - \alpha_{pv})Q_{SW,sky} + Q_{LW,sky} - Q_{LW,panel} - Q_{LW,roof} + Q_{LW,roof} = E_{pv} + H
\]  

\[
\begin{align*}
\alpha_{pv} &= \text{Albedo of the upward face of the solar photovoltaic panels} \\
Q_{SW,sky} &= \text{Incoming Short-Wave radiation from the sun. It can be diffuse or direct} \\
Q_{LW,sky} &= \text{Incoming Long-Wave radiation from the atmosphere, which is diffuse} \\
Q_{LW,panel} &= \text{Long-Wave radiation emitted (and reflected) by the solar panel to the sky} \\
Q_{LW,roof} &= \text{Long-Wave radiation emitted (and reflected) by the solar panel to the roof} \\
Q_{LW,roof} &= \text{Long-Wave radiation coming up from the roof, being intercepted by the solar panel} \\
E_{pv} &= \text{Energy produced by the panel} \\
H &= \text{Sensible heat flux from the solar panel to the atmosphere}
\end{align*}
\]
Some of the terms require more explanation:

\( \alpha_{\mathit{pp}} \) According to Taha (2013) the albedo consist of the summarization of reflectivity and solar conversion efficiency. A representative value for the solar conversion efficiency could be between 5% to 19% (Taha, 2013). The value will raise in the future as the solar conversion efficiency would reach up to 30% by the year 2100 (Nemet, 2009).

\( Q_{\mathit{LW_{\text{panel}}}} \) The magnitude dependents on the surface temperature of the photovoltaic solar panel. The temperature can be estimated following the ISPRA centre method:

\[
T_{\text{panel}} = T_{\text{air}} + kTIRR
\]

\( T_{\text{air}} \) air temperature [K]

\( k \) constant coefficient equal to 0.05 K/ Wm\(^{-2}\)

\( IRR \) irradia\( \_\text{nce} \) received by the solar panel (see energy production pv panel) [Wm\(^{-2}\)]

Now the upward long-wave radiation from the solar panel can be written:

\[
Q_{LW_{\text{panel}}} = \epsilon_{\text{panel}}\sigma T_{\text{panel}}^4 + (1 - \epsilon_{\text{panel}}) Q_{LW_{\text{sky}}} \]

\( \epsilon_{\text{panel}} \) emissivity of the photovoltaic solar panel equal to 0.93 (Masson et al., 2014)

\( \sigma \) Stefan-Boltzmann constant equal to 5.670367(13)\( \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\)

\( Q_{LW_{\text{panel}}} \) Due to time some assumption should be made. The downward face of the solar panel is every moment in time approximately equal to the air temperature. Given the uncertainties, the dependency in emissivity for this face of the panel will also be neglect. Which gives:

\[
Q_{LW_{\text{panel}}} = \sigma T_{\text{air}}^4
\]

\( E_{\mathit{pv}} \) The energy produced by photovoltaic solar panels can be parameterized as:

\[
E_{\mathit{pv}} = Ef_{\mathit{pp}} x FT x Q_{SW_{\mathit{sky}}} x \min \{ 1; 1 - 0.005 x \left( T_{\mathit{air}} + kTFT x Q_{SW_{\mathit{sky}}} - 298.15 \right) \}
\]

\( Ef_{\mathit{pp}} \) the conversion efficiency of the photovoltaic solar panel.

\( FT \) correction factor, which is dependent on the tilt and orientation of the panel

\( R(T_{\text{panel}}) \) coefficient to reproduce the behaviour that photovoltaic solar panels are most efficient at 25 degrees Celsius and present a decrease in efficiency for warmer panel temperatures. Which can be written as:

\[
R(T_{\text{panel}}) = \min \{ 1; 1 - 0.005 x \left( T_{\mathit{air}} + kTFT x Q_{SW_{\mathit{sky}}} - 298.15 \right) \}
\]

\( H \) the assumption is made the poly crystalline solar panel is thin and has no significant thermal mass and hence is in quasi-equilibrium (almost balanced). Under this assumptions the sensible heat flux is taken to be equal to the residue of the solar panel energy budget.

4.3 Most important parameters \( (Q_{SW_{\mathit{sky}}} \) , \( E_{\mathit{pv}} \) and \( H \)) for architectural design

In coherence of the design guidelines of the previous chapter we can conclude the energy produced by solar PV panels \( (E_{\mathit{pv}}) \) and the sensible heat flux \( (H) \) are parameters we can influence by architectural design.
The sensible heat flux is the sum of convection and conduction, we could neglect the conduction due to the minimal construction. The convection is influenced by the convection coefficient and the wind speed. The wind is influenced by the amount of obstruction of the roof mounted solar PV panels.

The energy produced by solar PV panels is mostly influenced by the tilt angle and the orientation. Another parameter is the temperature of the PV cells, which could also be positively influenced by the wind speed.

II Design study

5 Case study: The Edge, Deloitte
6 Modeling methods
6.1 Inputs: parameters and variables
6.2 TRNSYS
The front end of TRNSYS is a simulation studio with drag and drop capabilities for components of systems. In this scenario, it could become necessary to modify the back-end of the standard components. According to an employee of Deerns, TRISCO is the preferred program for these modifications.

There are multiple standard PV components available in the TESS libraries distribution 17 for TRNSYS:

- TYPE 551: PHOTOVOLTAIC ARRAY SHADING
- TYPE 560: FIN-TUBE PV/T SOLAR COLLECTOR
- TYPE 562: SIMPLE GLAZED OR UNGLAZED PHOTOVOLTAIC PANEL
- TYPE 563: UNGLAZED FIN-TUBE PV/T SOLAR COLLECTOR
- TYPE 566: BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEM (INTERFACES WITH ZONE AIR TEMPERATURE)
- TYPE 567: BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEM (INTERFACES WITH TYPE56)
- TYPE 568: UN-GLAZED BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEM (INTERFACES WITH TYPE56)
- TYPE 569: UN-GLAZED BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEM (INTERFACES WITH ZONE AIR TEMPERATURE)

These PV components should be analysed to decided, which one or multiple component(s) can be used for further modification. Finally the calculations can be performed within the PV components using inputs from the selected weather data file and the TRISCO model.

6.3 TRISCO (VOLTRA)
TRISCO is a thermal analysis program for transient heat transfer in three-dimensional rectangular objects. VOLTRA is an extension for time-dependent boundary conditions of TRISCO, which is thermal analysis program for steady-state heat transfer.

7 Model validation
7.1 Measurement setup
7.2 Data collection
7.3 validation

8 PV roof design

9 Conclusions
9.1 Conclusion
9.2 Discussion
9.3 Recommendation

Bibliography


Figure/ Table references

Figure cover  Picture by Deerns

Figure 1  Pijpers-van Esch, M. M. E., Van Timmeren, A., & Hordijk, G. J. (2015). Designing the Urban Microclimate: A framework for a design-decision tool for the dissemination of knowledge on the urban microclimate to the urban design process. Retrieved from Item Resolution URL http://resolver.tudelft.nl/uuid:db37f8c4-c32d-42d7-8462-b2208a342184 WorldCat.org database.


Figure 4  https://www.zonnemarkt.nl/valk-quattro-zonneschans (left)
http://www.sun4ever.info/dakmontagesystemen.php (right)

Figure 5  https://www.schletter.eu/EN/solar-mount-system/flat-roof.html

Figure 6  http://www.sun4ever.info/dakmontagesystemen.php


Figure 11  http://autodesk.typepad.com/bpa/2014/02/cfd-for-revit-flow-design-project-falcon-building-performance-analysis.html

Figure 12  http://sunmetrix.com/solar-panel-size-for-residential-commercial-and-portable-applications/

Figure 13  Erell, E., Pearlmutter, D., & Williamson, T. J. (2011). Urban microclimate : designing the spaces between buildings Retrieved from WorldCat.org database Retrieved from Ebook Library

Figure 14  Own illustration

Figure 15 – 17  Picture by Deerns

Tabel 1  Own illustration

Appendix A

Architectural reference details of the flat roof mounted solar PV installation systems.

Referentiedetails

Montageopzet: 2
Dakvorm: plat/helend
Omschrijving: lijnvormige bevestiging

-- Diagram --

Effectief afstand minimaal 10 mm
Dakbedekkingssysteem (begraaibaarheidsklasse R3 of R4)
Thermisch isolatie (begraaibaarheidsklasse C of D)
Dempemmer de laag onderconstructie
Schematisch Hoogteinstelling
RV5 schroef met RV5 volging en neopreen afscherming
Zelfkleverige zerkstraat, ronddig verbouwd
Neopreen afsluiting
Bovengordijn (thermisch onderscheid)

De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de bevestiging daarvan en de dakconstructie moet zijn aangetoond volgens de Eurocodes en NEN 7250.

Schaal 1:5
De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de bevestiging daarvan en de dakconstructie moet zijn aangetoond volgens de Eurocodes en NEN 7250.
De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de bevestiging daarvan en de dakconstructie moet zijn aangetoond volgens de Eurocodes en NEN-7250.
De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de bevestiging daarvan en de dakconstructie moet zijn aangetoond volgens de Eurocodes en NEN 7250.
De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de bevestiging daarvan en de dakconstructie moet zijn aangetoond volgens de Eurocodes en MHN 7250.
De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de bevestiging daarvan en de dakkonstruktie moet zijn aangetoond volgens de Eurocodes en NEN 7250.
Referentiedetails

Montagetype:
Dakvorm:
Oorsprong:

Het gebouwssysteem
dekconstructie

Dakbedekkingssysteem (begaanbaarheidsklasse R3 of R4)
thermische isolatie (begaanbaarheidsklasse C of D, compartimentering per 250 m²)
langsfractie laag
onderaardeuse

zonne-energiesysteem
effectief afhet minimaal D mm³

aluminium profiel

eventuele dikhuring/scheidingslaag
trekkabel

De weerstand tegen windbelasting en sneeuwbelasting van zowel het zonne-energiesysteem, de beleving daarvan en de dakconstructie moet zijn aangebonden volgens de Eurocodes en NEN 7250.
Referentiedetails

Materiaal:
2, 3 en 4
Dakvorm:
plat / holtop
Ondergang:
compatibilisering dakbedekkingconstructie

dakbedekkingssysteem (beghaarbaarheidsklasse P3 of R4)
thermische isolatie (beghaarbaarheidsklasse z of u)

werkwijze
De dampremmende laag of sluitlaag (hitmen) of bestaande dakbedekking
Op plaats van de ontwerper te bepalen plaats de thermische isolatie afsluiten met
een randstroken, breedte circa 500 mm. Deze randstrook volledig kleven op de
thermische isolatie (of eerste laag) en op de dampremmende laag of sluitlaag. Bij
dakranden en onderbrekingen deze randstrook waterdicht afsluiten
De toplaag aansluiten in het gewenste patroon volledig gekleefd op de
onderlagen
Referentiedetails

Merkwegtype: I en II
Dakvorm: plat
Omschrijving: retropolerings (geschikt voor klimaatklasse II en III)

Klimaatklasse II en III

Dakbedekkingsysteem (beslaanbaarheidsklasse R3 of R4)
Thermische isolatie (beslaanbaarheidsklasse c of d)
Dampremmerende laag
Onderconstruut

Aansluiting op
Dampremmerende laag
Met pakplaat (thermisch ondersproei)

Effectief afschot:
Minimaal 10 mm/m

Luchdtichte afsluiting

Afsluiting (beslaanbaarheid met PUR-aanhef)
Afgedekte laag met luchtische afsluiting

Schaal 1:5
Appendix B
The some worldwide reference projects are selected, to show the architectural opportunities of roof mounted PV installation system design.

Riedel recycling firm
Circa 1970, Riedel Recycling industry gets renovated by implementation of a new PV super power plant. Thin film PV cover the existing thin shell concrete roof and wall enclosure, covering the entire building solid opaque roof and facades envelope, more than 11 thousand modules in Cadmium Telluride (CdTe), manufactured by American industry First Solar, bring this mega energy plant to life. With a peak capacity of 837 kWP, this installation becomes the widest in Germany over an existing industrial facility. With optimal roof slope and southern exposure of the building’s design type and location conditions turn ideal for the installation of such a plant. The modules were not rigidly fixed so that an expected temperature change under expansion and contraction of the roof can be compensated in the future. The photovoltaic modules used are thin film modules from First Solar. Due to a very good low-light performance in combination with a low temperature coefficient. All electrical cables were laid below the modules. The total weight of the system together with a new roof is about 200 tons (Meekma, Valdes Cano, & Zhindon Andrade, 2015).

components
Cell type: Thin-Film
CIS modules (First Solar)

PV optimal tilt
Summer: 61.5°
Winter: 14.5°

Energy:
Cell Efficiency: 5-10%
Energy Production: 750,000 KWh/year

Figure 1: Riedel recycling firm overview pv roof only south side.
Figure 2: Riedel recycling firm detail

Bullitt building
Kaohsiung national stadium
Unwelt arena
Hofberg 6/7 residences

Sanyo solar ark