SMART ENERGY BUILDINGS

Development of a photovoltaic thermal system configuration
with additional envelope-integration into a multi-family building

Allard Huitema

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Delft University of Technology

Graduation thesis

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> Our goal here is to fundamentally change the way the world uses energy.

Elon Musk

ABSTRACT

The problem that needs to be resolved is the fact that there is too little knowledge about the energetically optimal application of photovoltaic thermal collectors (PVT) in an energy system configuration as well as its integration in a building envelope. A solution for this problem could eventually entail an optimisation in the use and storage of solar energy.

The technology of PVT is very promising in relation to the current energy transition, most certainly as an incentive to foster the use of renewable energy sources and technologies. That is why the development of a PVT system configuration with additional envelope-integration is treated in this thesis.

The main purpose of this thesis is to expound the energy concept of PVT, its role in the system configuration and its facade-integrational aspects, all this in relation to the application of PVT on a multi-family case study building. The accompanying research question is: *How can an energy concept with PVT be optimised or maximised in terms of renewable energy and be integrated in the envelope of a multi-family building?*

In order to give an unambiguous answer to this question, the energy concept of PVT and other relevant technologies will be explained in a literature and background study upfront. This is followed by the description of the case study building. After that, the development of the PVT output types, configurations and the development of the system configuration and operation modes are discussed. The energy requirements of the multi-family building together with the energy output of the PVT collector results in an energy balance. Finally, the facade-integration aspects of PVT are described, where the amount of collectors on the roof and in the facade are determined by the energy balance.

It was shown that a PVT collector that is glazed on the top and insulated at the back is the most effective type in the light of this thesis, that is to say in combination with this specific multi-family building. In addition to this, several collectors in series will lead to an effective configuration. Besides, for an efficient utilisation of the (collected) energy, it is wise to apply low-temperature heating as well as an energy storage in the system configuration. For the integration of PVT into a multi-family building, it is first of all recommended to design a proper layout for the in- and outcoming distribution pipes. Finally, in order to improve the integrational flexibility, it is advised to introduce multiple dimensions of PVT collectors in the future.

PREFACE

Dear reader,

In front of you lies the graduation thesis as part of Sustainable Design Graduation (AR3B025). This report covers the research and design process of a photovoltaic thermal collector, its system configuration and its building-integration. The main purpose of this report is to substantiate the proposed concept by giving an insight in the exact working and mutual collaboration between various elements of the concept, all this with a view to foster the use of renewable energy technologies.

I hope you enjoy reading.

Allard Huitema

Delft, 10 April 2018

NOMENCLATURE

General	
ATES	aquifer thermal energy storage
BA	building-added
BAPVT	building-added photovoltaic thermal collector
BI	building-integrated
BIPVT	building-integrated photovoltaic thermal collector
BRE	building-related energy
CI	covered-insulated
COP	coefficient of performance
DHW	domestic hot water
DSSC	dye-sensitised solar cell
DWHR	drain water heat recovery
EPC	energy performance coefficient
FGM	functionally graded material
GJ	gigajoule
HTC	high-temperature cooling
ICSSWH	integrated collector storage solar water heater
kW(h)	kilowatt(hour)
LTH	low-temperature heat(ing)
MJ	megajoule
MRE	material-related energy
NOS	Nederlandse Omroep Stichting
OPV	organic photovoltaic/solar cell
PC	polycarbonate
PJ	petajoule
PV	photovoltaic
PVT	photovoltaic thermal
RVO	Rijksdienst voor Ondernemend Nederland
SPF	seasonal performance factor
ST	solar thermal
STES	seasonal thermal energy storage
TESPI	thermal electric solar panel integration
UI	uncovered-insulated
URE	user-related energy
UU	uncovered-uninsulated
W	watt
Wp	watt-peak
WWR	window-to-wall ratio

SI and non-SI units

A	absorber area of collector	[m^2]
a	absorption coefficient of collector	[-]
c_w	heat capacity	[J/kg K]
d	thickness	[m]
d_{col}	collector depth	[m]
E	electricity output	[Wh]
E_{aux}	auxiliary energy	[J]
E_F	final energy use	[J]
$E_{EPus;\,el}$	electricity use	[J]
E_P	primary energy demand	[J]
η	general efficiency	[%]
η_B	exergy efficiency	[%]
η_{el}	electrical efficiency	[%]
η_E	energy efficiency	[%]
η_{th}	thermal efficiency	[%]
η_{tot}	total efficiency	[%]
ΔT	temperature difference	[°C]
ΔT_e	temperature progression from the water to the outside	[°C]
ΔT_i	temperature progression from the water to the inside	[°C]
ΔT_n	temperature progression along layer *n*	[°C]
λ	thermal conductivity	[W/m K]
m	mass of a substance	[kg]
$\dot{m}$	mass flow rate	[kg/s]
Q_{coll}	thermal output of collector	[W]
Q_h	heat	[W]
Q_{sun}	heat provided by the sun	[W]
Q_{trans}	heat lost through transmission	[W]
Q_{nd}	heat demand	[J]
q_{sun}	solar irradiation	[W/m^2]
PR	performance ratio	[-]
R_e	resistance to the outside	[m^{2}K/W]
R_i	resistance to the inside	[m^{2}K/W]
R_l	thermal resistance of the whole construction	[m^{2}K/W]
R_n	thermal resistance along layer *n*	[m^{2}K/W]
$R_{tot;\,e}$	thermal resistance from the water to the outside	[m^{2}K/W]
$R_{tot;\,i}$	thermal resistance from the water to the inside	[m^{2}K/W]
r	PV panel yield	[%]
r_e	transition resistance to the outside	[m^{2}K/W]
r_i	transition resistance to the inside	[m^{2}K/W]
$T_{e;\,max}$	average maximum outside temperature	[°C]
T_i	inside temperature, or temperature underneath collector	[°C]
T_{in}	incoming temperature of the water	[°C]
T_m	mean inside water temperature	[°C]
T_{out}	outcoming temperature of the water	[°C]
t	transmission coefficient of cover	[-]
v	flow velocity	[l/h]
W	work	[J]

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1. INTRODUCTION

1.1 Background

At this moment, we are in the middle of a global energy transition. It is scientifically proven that various familiar energy sources like natural gas and oil are causing climate change. This endorses a switch-over to renewable energy sources like solar and wind energy. According to the Paris Agreement, the global warming has to be limited to a maximum of one and a half degree by 2050. This asks for serious and complex measures to be taken - both for the short and the long run - which consolidate more and more in the future.

There are numerous renewable energy harvesting techniques possible nowadays. On a building scale, one can think of the application of photovoltaic (PV) panels, solar thermal (ST) collectors and (small) wind turbines. A relatively new technique is the so-called photovoltaic thermal (PVT) collector, which basically is a combination of a PV panel and an ST collector, thus generating both electrical and thermal energy. Having a higher energy yield per square meter than two separate PV panels and ST collectors, PVT collectors are deemed to be a very auspicious renewable energy source.

A direct-use of the energy that is generated by a PVT collector requires an auxiliary distribution system in which one or more heat pumps and boilers/buffer tanks are essential elements.
In addition to using the energy for various practical purposes, there is also a possibility to (temporary) store it in case it is undesired to use the energy immediately. The reason for this is that the yield and availability of solar energy is the highest during the warmer periods of the year, particularly when the need of energy is the lowest. By contrast, the energy demand is higher in the winter, but the available solar energy is significantly less. This means that a time span of a couple of months - the energy mismatch - has to be bridged, which can be done by gaining energy during summer, storing it, and utilising it in wintertime.

Finally, renewable energy techniques are applied on different scales in the built environment. One of these scales are multi-family residences: apartment buildings with multiple storeys and a relatively small roof surface compared to, for example, a single-family dwelling. These multi-family buildings are especially attractive for PVT collectors, for they perform optimally in such a situation. It could even be better to integrate those modules into a building envelope or a building addition, not least because the energy yield can be increased if the possibilities of placing PVT collectors become more. In that case, this is referred as a building-integrated PVT module or BIPVT.

The application of PVT collectors on multi-family buildings - all in combination with the storage of energy - can thus play a significant role in the global energy transition, ultimately resulting in an environment with locally harvested renewable thermal and electrical energy. The next paragraph will present a framework out of which a subsequent research will arise.

1.2 Research framework

This paragraph describes the methodology that leads to a specified and substantiated implementation of the further research. We start with the problem background, followed by the problem statement, research context and limitations, after which the research questions will be formulated. Finally, the research objectives, the research methodology and the planning will be discussed.

1.2.1 Problem background

> In our closed system, everything is connected with each other: nothing operates on its own. Moreover, all of the physical is finite. But which intangible sources do we have to our disposal? Can we make the finite infinite with them? (Rau & Oberhuber, 2016, p. 51)

The above mentioned quote is derived from the book *Material Matters* by architect Thomas Rau and Sabine Oberhuber. Although the message of the book is about a circular economy with a different perspective on the ownership of materials, another theme of the book is the continuous use of finite resources. That is also a guiding principle in this research.

The problem background consists of the large-scale use of non-renewable energy sources nowadays. It is therefore necessary to ensure a complete restructuring of the energy sector by phasing out the use of natural gas and other fossil fuels, fostering the use of electricity and other renewable energy sources, with a continuous reduction of the CO_2 emission. To contribute to the solution of this problem, the application possibilities of renewable energy sources have to be researched properly.

One of those application possibilities is the use of photovoltaic thermal (PVT) collectors, as mentioned in the previous paragraph. This technology is promising for it to be applied on multi-family buildings, together with an accompanying system configuration that provides for an adequate energy distribution and storage. Besides that, building-integration options can be investigated to increase the application possibilities of PVT modules even more. It is not yet known what the effect of PVT collectors will be on the scale of a multi-family building. Additionally, it is not exactly known yet in which way PVT collectors or a PVT system can be integrated in a building skin.

1.2.2 Problem statement

The problem that needs to be resolved is the fact that there is too little knowledge about the energetically optimal application of PVT in an energy system configuration as well as its integration in a building envelope. A solution for this problem could eventually entail an optimisation in the use and storage of solar energy.

1.2.3 Research context and limitations

In order to ensure a proper conduct of this research, a research context is defined together with several limitations beforehand. These limitations will eventually lead to a main research question together with a couple of sub-questions.

PVT

With PVT being the main topic of this research, this report begins with describing the motives for using renewable energy technologies, after which some renewable energy systems are briefly discussed. Then, an in-depth explanation on the basis of the current developments, compositions and efficiencies regarding PVT, followed by an enumeration of other relevant energy technologies, is provided.

System configuration analysis and optimisation
PVT collectors are meaningless if the complete energy system behind it is not configured in a proper way. That means that it is of great importance to find out which PVT system configuration is not only efficient, but also effective. Therefore, a case study is discussed in which a couple of system configuration possibilities are explained. Yet PVT plays a minor role in this case study. Additionally, various configuration elements will be discussed, resulting in a final configuration. All this is going to be substantiated with either reference examples, calculations and simulation programs.

Multi-family building
The integration of PVT will be based on a building envelope design of a recently completed multi-family building in the city of Amsterdam, but may also be applicable to comparable buildings which are to be built in the (near) future. The reason why there is chosen for new buildings has to do with the fact that PVT collectors are currently in development when it comes to their building-integration. That is to say that it is wise to integrate any renewable energy-related techniques into the building upfront, which invites to take a closer look at the performance of building-integrated PVT modules.

1.2.4 Research questions
Now that the problem statement, the research layout and boundary conditions are defined, this means that the research questions can be formulated. This graduation project will try to answer one main research question together with five corresponding sub-questions.

The main research question is the following:

> ***How can an energy concept with PVT be optimised or maximised in terms of renewable energy and be integrated in the envelope of a multi-family building?***

There are four additional sub-questions:

> *What is the current situation regarding PVT?*
>
> *How can the energy output for PVT be calculated for different situations?*
>
> *What is a common multi-family typology that can be used as a reference case for this study?*
>
> *How can a PVT system configuration be optimised or maximised for renewable energy use?*
>
> *What does this multi-family typology offer when it comes to PVT building-integration possibilities?*

1.2.5 Research objectives
The research objective of this thesis is to transfer knowledge on how to design an optimal PVT energy system configuration and how to integrate this system in a multi-family building in such a way that this can be implemented in (real-life) future projects.

Throughout this report, a number of PVT systems, system configurations and integration possibilities will be discussed and proposed, together with all kinds of climate- and facade-related aspects. It has to be noted that for all of these aspects, both non-renewable and renewable solutions could be suggested. For the sake of the objective of this research, only renewable proposals and solutions will be given.

1.2.6 Research methodology
The first important aspect is to explain the current energy transition and the government's view on it. The energy transition serves as a motive that fosters renewable energy technologies, which are therefore briefly described. The next step is to define what the PVT technology means. What are

the basics of PVT? Are there different types of PVT collectors and if so, which type offers the best energy outputs in combination with the application possibilities? What is the precise advantage of a PVT collector over a photovoltaic panel or a solar thermal collector? The third step is to give a more thorough explanation of renewable energy systems - both for distribution and storage purposes - that could be part of the PVT system configuration. After that, the building-integration possibilities of PVT are discussed. What typical building envelope-related aspects need to be taken into account that lead to an aesthetical element integration in a most reasonable way?

Then, a case study example is presented, where renewable energy technologies are assessed into practice. The next subject consists of the definition of the multi-family building in the scope of this research. There are a lot of multi-family buildings - both existing and new, large and small - which makes it important to know which building will be used in the end. Thus, which typology is the most suitable to use as a reference for this research, and why?

After this, PVT energy outputs are calculated for different situations, such as the time of year, the mean temperature of the water and the composition of the PVT module. After this is done, there is taken a look at which systems and equipments can possibly be combined with PVT in order to configure an optimal network in order to supply or store the collected energy in a most efficient and effective way.

The final step is to determine the amount of PVT collectors that are needed for an energy balance in combination with the multi-family building. This energy balance will result in an optimal amount of modules that can be placed on the roof and integrated in the facade of the building. Together with this, integration details and distribution drawings and schemes are presented.

Figure 1 explains the research methodology step by step.

1.2.7 Research planning
The programme of the Sustainable Design Graduation consist of five progress review presentations. In order to give a structured layout of the further development of this programme, a research planning is set up from the first progress review (P1) op to the last one (P5). Figure 2 shows this planning in the form of a Gantt chart.

Between P1 and P2, the complete research design is made together with a preconceived literature and reference study. What is done mainly in this period is to make clear what a PVT collector exactly does and to discuss the types and configurations of a PVT module. Besides this, an introduction will be given in both the PVT system configuration and the integration possibilities.

After the P2, the research will be more focused on personal findings and ideas - like the definition of the multi-family typology - simulations with various programs, the integration of PVT into the building envelope and additional calculations. This means that several PVT system configurations are tested, examined and substantiated on their feasibility and effectiveness. Prior to the integration, the multi-family residence will be defined to make clear which integration possibilities are relevant. P3 is an intermediate review of this process.

The P4 is to all appearances the most important progress review, where the simulation and integration study together with all of the calculations should be finished: a preliminary graduation report needs to be (nearly) completed by then. Finally, the time between the P4 and the P5 can be used to optimise the report and to add any aspects that were missing before.

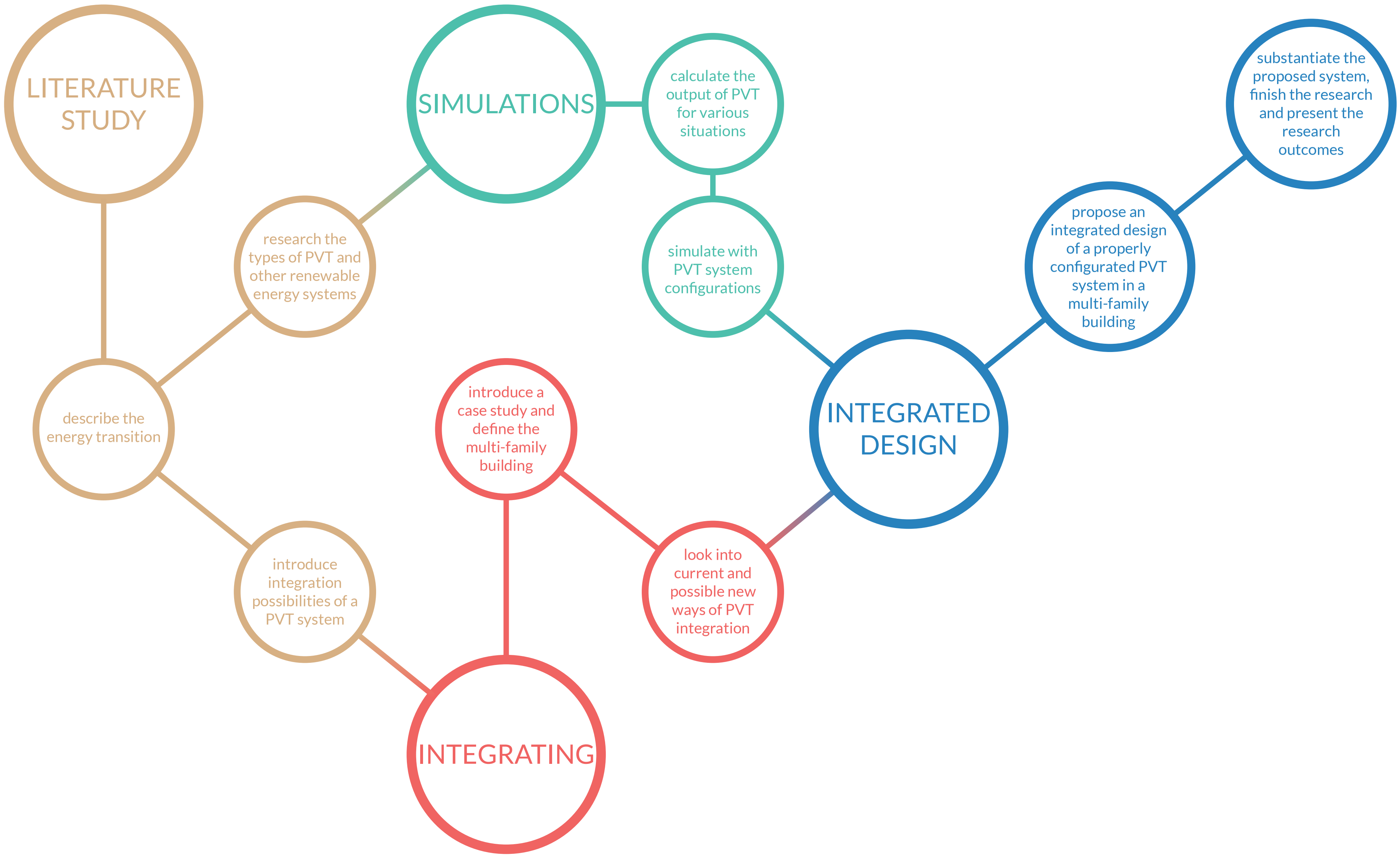


Figure 1. Detailed planning chart (Own illustration).

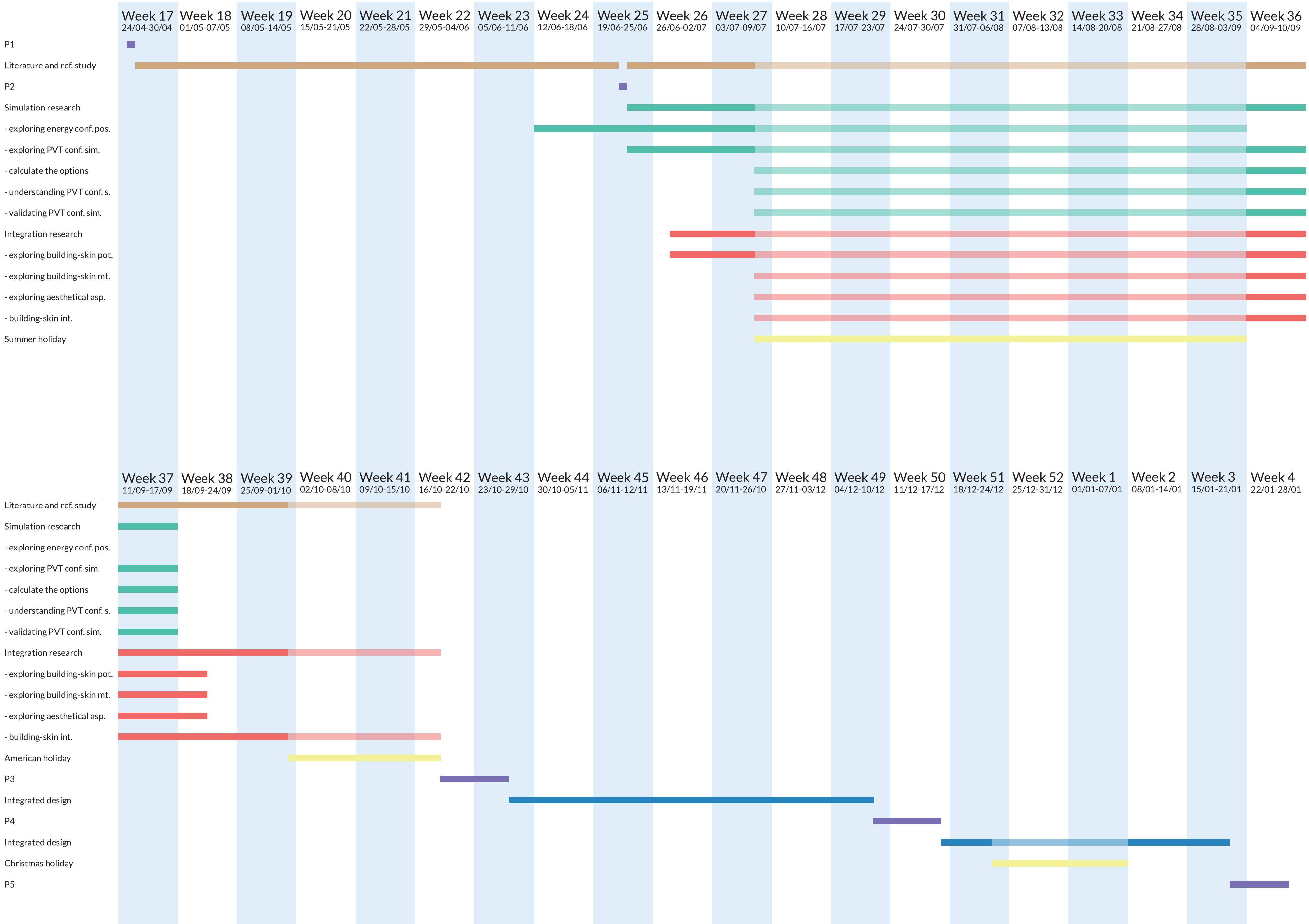


Figure 2. Gantt chart planning (Own illustration).

2. LITERATURE AND BACKGROUND STUDY

In order to get a basic understanding of the motives and incentives regarding the switch-over from fossil fuels to renewable energy, this chapter starts with a description of the energy transition, the government's view on it and energy consumption data of residences. The rest of this chapter focuses on four kinds of renewable energy categories, the PVT technology, other renewable technologies, the building-integrational aspects of PVT and finally a case study description.

2.1 The energy transition

In December 2016, the Dutch government presented their own future-oriented energy policy in the Energieagenda (Ministerie van Economische Zaken, 2016). With the Energieagenda, the government aims, among other things, at a sustainable production of electricity, at buildings heated primarily with electricity and geothermal energy and at the intent to cook without natural gas. Furthermore, future-oriented tasks are proposed, which are based on four so-called 'functionalities': power & light, high-temperature heat, low-temperature heat and transport. This paragraph will describe the details of only two of those functionalities: power & light and low-temperature heat. The functionalities 'high-temperature heat' and 'transport' are considered not applicable within the reach of this research, since the built environment as considered within the scope of this research is not a user of both of those functionalities.

By 2050, the government goes after its primary goal: to decrease the CO_2 emission by 95%. There are a lot of visionary and concrete proposals the government wants to put into practice. Energy reduction as well as the investments in renewable energy are two of those (pp. 5-9).

2.1.1 Power & light

According to the Energieagenda, the current power and light demand in the Netherlands consists practically only of electricity. The development of the Dutch electricity demand is two-fold. On the one hand, functionalities like low-temperature heat and transport are asking more and more electricity. On the other hand, there are investments in the reduction of electricity use - like LED lamps - which lower the electricity demand (p. 37). Energieonderzoek Centrum Nederland mentions in their *Nationale Energieverkenning 2016* that the total energy use will decline slightly until 2030, because of a "decreasing heat demand in the built environment". However, the electricity use until 2030 will slowly increase, for the heat generation and mobility will be more dependent on electricity (p. 68). In the Energieagenda it is said that the electricity use will increase with 3 to 7% between 2015 and 2030 (p. 37).

Besides the resoluteness of the government to put more money into the strengthening of the electricity grid, the previously mentioned aim to reduce the CO_2 emission is nevertheless applicable to the generation of electricity. Figure 3 shows a development regarding the CO_2 reduction for the power & light functionality up to 2050. Unfortunately, electricity generation with renewable energy sources like solar, wind, water and geothermal energy is at this moment more expensive than traditional energy from fossil fuels. However, it is predicted that the Energieakkoord (Dutch Energy Agreement of 2013) will cause an increase in the share of renewable electricity by approximately 41% in 2023, where it was only 15% in 2015 (pp. 37, 39). This could be an incentive to raise renewable electricity generation.

While the generation of wind energy in the North Sea proves to be successful according to the Dutch government, it is also important to foster local energy production by citizens and cooperations (pp. 41, 42), according to the Paris Agreement:

> *Agreeing* to uphold and promote regional and international cooperation in order to mobilize stronger and more ambitious climate action by all Parties and non-Party stakeholders, including civil society, the private sector, financial institutions, cities and other subnational authorities, local communities and indigenous peoples. (United Nations, 2015, p. 2)

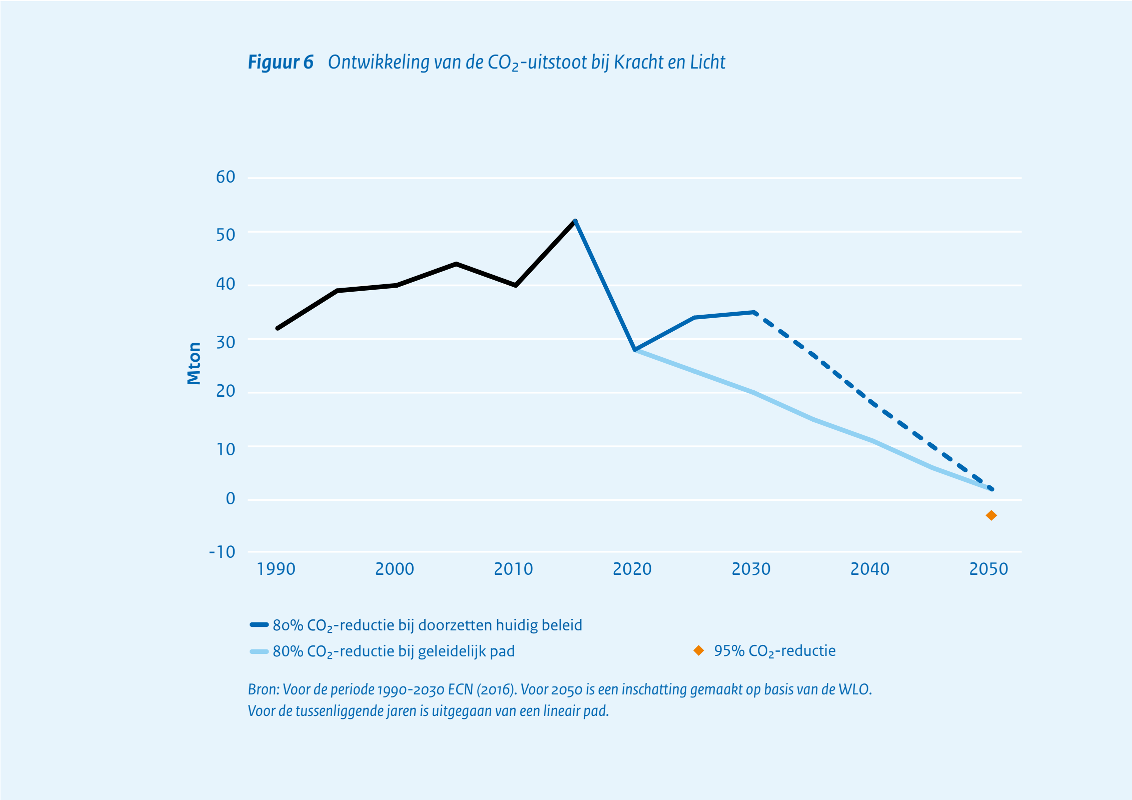


Figure 3. Development of the CO_2 reduction for power & light (Ministerie van Economische Zaken, 2016, p. 40).

Despite the fact that energy production on large scale still is cheaper than on local scale, the government continues to reduce the costs of renewable energy production and keeps supporting local initiatives, since it creates more awareness among civilians regarding the energy transition. One of these supports is the opportunity for small consumers to deduct their supplied electricity with the electricity they generate. This is called net metering and results in several tax benefits (p. 42). Goorden (2016) sees a problem here, because of the stability of the electricity grid. If citizens keep net metering, there is a danger that the grid will become overloaded, with all the consequences that will entail (p. 13). However, the so-called supply chain security of electricity is widely guaranteed for as long as 2035, a research of Frontier Economics shows. In addition to this, Dutch electricity company TenneT notices an increase of production capacity - which is not immediately useful - and will further look into this. Dutch grid operators have estimated that investments in the infrastructure, which are needed for the energy transition up to 2050, will be €21 to €70 billion. The lion's share will be for the electricity grid (pp. 43, 45). Anyhow, a reconsideration towards a complete different interpretation and structure of the electricity network may be the solution here, especially if civilians and their initiatives can produce and monitor their own electricity. What is the purpose of letting electricity companies provide electricity for their customers if those customers increasingly generate it themselves?

The (local) generation of electricity goes together with either a direct use of the electricity or the storage of it. The government realises that electricity storage will be an important matter for the near future. At this moment, the storage is relatively expensive and only possible for a short period. Seasonal electricity storage is therefore not (yet) possible. If this storage does happen in the future, the government assesses the levy of energy taxes in case a party other than the party that supplies the electricity, stores it. So for example, if citizens store the electricity that they receive from the energy company, they have to pay a tax (pp. 46, 47). However, it is unknown what happens if the party that stores electricity is the same that supplies or generates it.

2.1.2 Low-temperature heat

According to the Dutch government, more than 30% of the total energy use in the Netherlands is assigned to low-temperature heat. In addition to this, out of all dwellings, buildings and greenhouses in the Netherlands, approximately 90% is heated with natural gas. The government therefore targets on a reduction of the heat demand by energy savings through lowering the use of natural gas and fostering renewably-gained electricity and heat (p. 59).

There is no clear definition of 'low-temperature' in the Energieagenda. In literature, low-temperature has multiple definitions. Israëls & Stofberg (2017, pp. 165, 166) and Yanovshtchinsky, Huijbers & Van den Dobbelsteen (2013, pp. 87, 88) both define it as a water supply temperature of a maximum of 55°C and a water return temperature of not more than 45°C. They further mention two different low-temperature heating systems: radiator and convector heating with a maximum supply temperature of 55°C as well as floor and wall heating with a supply temperature between 25°C and 45°C. This means that it depends on the type of heating system which temperatures are used. Additionally, it has to be noted here that, according to Israëls & Stofberg (2017), the supply temperature of floor heating depends on the insulation measures: for a well-insulated building, 30°C is a feasible supply temperature (p. 171).

The Energieagenda tells us that the energy transition calls for a number of far-reaching measures that will have a large influence on the Dutch households, not to mention the obstacles that have to be surmounted. First, the energy capacity of natural gas is a lot more than its renewable alternatives. This means that further development towards this matter has to be stimulated. Second, traditional heating systems which make use of natural gas have to be replaced. Third, the infrastructure has to be changed dramatically, which asks for a lot of investments. This all is - directly or indirectly - tangible for the Dutch citizens, because a lot of the commonnesses will change. Nevertheless, these measures need to be taken in order to maintain a CO_2 reduction after 2020, otherwise it is possible for the CO_2 emission to rise again. Figure 4 shows the development of this CO_2 reduction for the low-temperature heat functionality.

The field of application regarding low-temperature heat in the built environment is sub-divided into new and existing buildings. The Energieagenda points out that the (future) stock of new buildings will provide a relatively small contribution to the renewability of the built environment; the biggest task is to heat the existing stock without the use of CO_2. This report only focuses on new buildings, which is why only the policy relating to those buildings will be described further.

There are a number of concrete measures that arise from this policy. In the first place, all new buildings that will be completed from 1 January 2021 onward need to be almost energy-neutral. In fact, all public buildings will have to meet this criteria already by 2019. These conditions contribute - together with the ones related to the existing building stock - to the agreements of the Energieakkoord. Additionally, the Energieakkoord asks for an energy reduction of 100 PJ by 2020 (pp. 59, 61-63). The NOS (Dutch Broadcast Foundation) adds that Dutch households and small businesses have to lower their energy-use annually by 10 PJ after 2020. This equals the usage of 50,000 Dutch households (2017b). To grasp this even more, figure 5 shows the current energy consumption of the built environment, sub-divided in households and services. Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency) reports that the energy end-use in the built environment was 679 PJ in 2015. The consumption of the households decreased the past 10 years with 41 PJ to 415 PJ; the services saw their consumption reduced with 17 PJ and still use 264 PJ (2016, p. 22). Coming back to the agreements of the Energieakkoord, a decrease of 100 PJ requires time and effort.

Besides, the Energieagenda further mentions that newly-built housing estates will not be equipped with a natural gas connection, albeit the Dutch Gas Law still gives their citizens the right (say: obligation) to be connected to natural gas. The Gas Law will be adjusted for that in order to legally enshrine an ordinary legislation to be connected to renewable energy instead of natural gas.

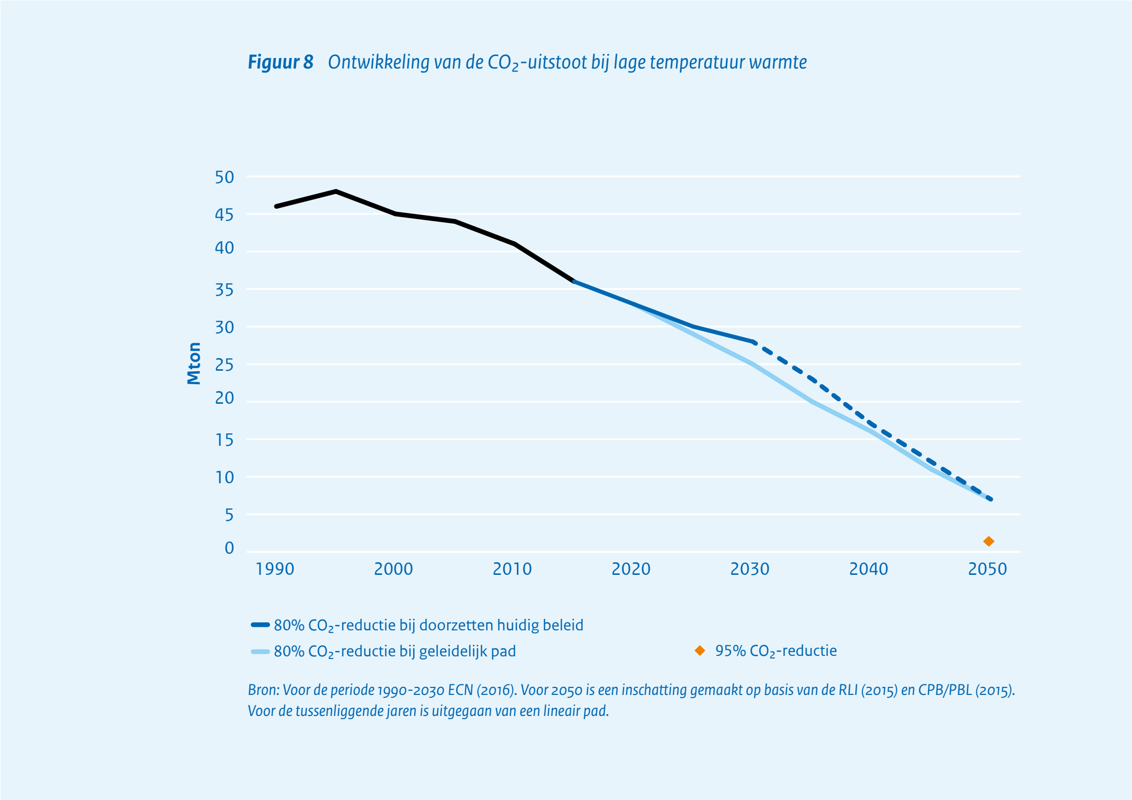


Figure 4. Development of the CO_2 reduction for low-temperature heat. (Ministerie van Economische Zaken, 2016, p. 61).

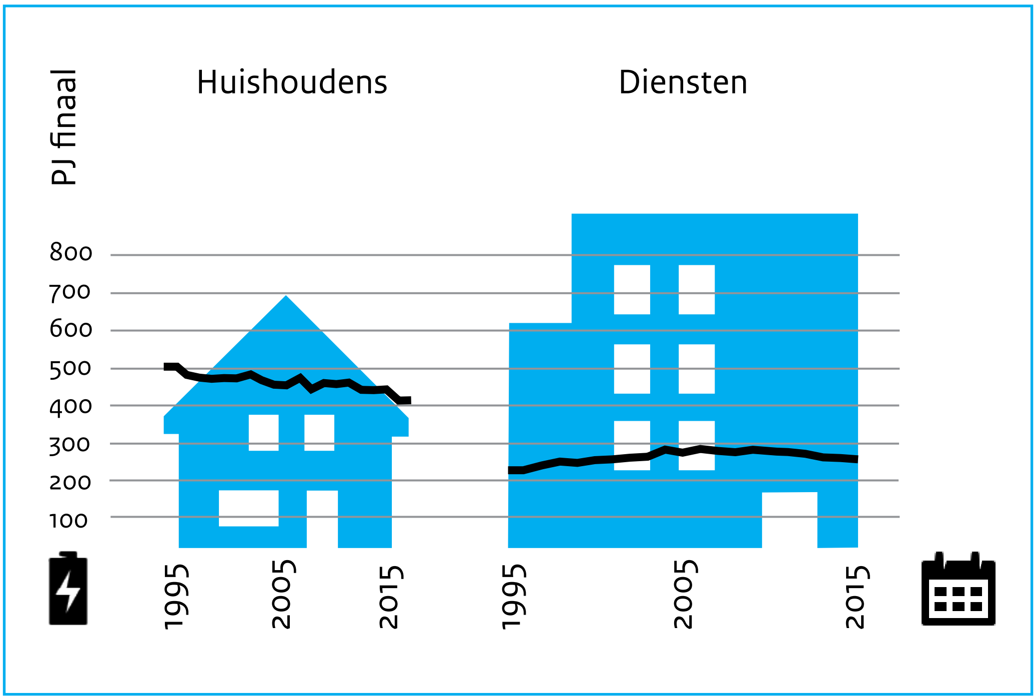


Figure 5. Energy end-use in the Dutch built environment in 2015 (Rijksdienst voor Ondernemend Nederland, as derived from ECN, 2016, p. 22).

It can reasonably be assumed that the aforementioned arrangements cannot be easily instituted. Therefore, the government took a lot of incentives to foster them, like price incentives, subsidies, low-interest-rate loans, educations, a tax-shift from electricity to natural gas and the support of regional, innovative initiatives (pp. 63-65, 68).

These incentives are already beginning to take hold, according to the NOS. Solar energy is working on a "spectacular growth". In 2015, the subsidy for solar panels was €10 million. In 2016, this amount was multiplied by one hundred to €1 billion. For the first three months of 2017, the subsidy requests already went up to €3 billion (2017a).

2.1.3 Energy consumption data of Dutch residences

The energy use of buildings in the Netherlands is generally given in m^3 (for natural gas) and kWh (for electricity). One of the problems with the switch-over from natural gas to electricity is the relative high energetic value of natural gas compared to that of electricity. 1 m^3 of natural gas corresponds to 35.17 MJ (Israëls & Stofberg, 2017, p. 280), while 1 kWh of electricity is the same as only 3.6 MJ. This means that in theory, there is proportionally almost ten times as much electricity needed compared to the current use of natural gas. However, more strict energy performance regulations of new apartments in the future entail a lower energy demand.

To get an idea of the energy consumption of Dutch households, some data is presented. According to the Centraal Bureau voor de Statistiek (Central Agency for Statistics), the average annual quantity of electricity that is used by a Dutch residence is 2.9 mWh. The dwelling typology has quite an effect on the consumption: a semi-detached house uses 3.5 mWh, while an apartment uses only 2.1 mWh. The gas use of these types of houses is respectively 1,750 m^3 and 870 m^3 (Centraal Bureau voor de Statistiek, 2017). Not only does the typology dictate the energy use, but also the amount of occupants. RVO shows that for two persons, the mean electricity use is 2.9 mWh per year. For a family with five persons, this is already 4.5 mWh per year (2017).

2.1.4 Conclusion

A CO_2 reduction of 95% by 2050 is the main objective of the Dutch government. A step in the right direction is to not only encourage the use of electricity for power and light but also aim for a carbon-free production of electricity. The use of solar-, wind- and water-based renewable electricity generation techniques contribute to this, where also an ongoing increase of electricity use seems promising. However, if civilians and companies will be using more electricity in the future, the electricity grid needs to be expanded, which asks for a lot of investments.

The diminishing of carbon dioxide seems to be a bigger problem when it comes to low-temperature heat. A lot of Dutch households use natural gas to heat up their homes and to prepare their food. The step from natural gas to renewable energy goes hand in hand with a high adaptability of people and large infrastructural changes for the current building block. New buildings will be provided with a connection to renewable energy instead of natural gas.

The policy of the Dutch government - now and in the future - together with the ongoing stimulative actions, endorses civilians and companies to contribute their bit to the energy transition. The Energieagenda clearly states that this transition makes great demands on civilians, companies, knowledge centres, social stakeholders, decentral governments and the Dutch central government, where only a proper and mutual cooperation can result into an effective climate policy. On top of that, also by working together on an international level, several projects and research funds can be taken to the Netherlands (Ministerie van Economische Zaken, pp. 8, 12).

The government's view on the energy transition is one of the backgrounds given that will serve as a motive for this research. The next paragraph will continue with renewable climate systems.

2.2 Examples of renewable energy systems for buildings

Senior researcher Benno Schepers of the research and consultancy organisation CE Delft says that approximately 95 percent of the Dutch households are connected to the gas grid. The other households mainly make use of district heating and only a small part provides their heating with electricity (Meinders, 2017).

It is no secret that the concept of natural gas is beginning to become outdated - or already is. Moreover, like the government proposes, the focus has to be directed to electricity and low-temperature heat (LTH) when it comes to residential and non-residential buildings. Those functionalities are both renewable and for LTH the energy losses are more limited compared to heating systems that work with relatively high temperatures. The implementation of electricity and LTH for the current building stock is a massive effort. While it is true that the biggest challenge is for the current buildings, the task for the new buildings should not be trivialised. It is important to design them first time right, that is, among other things, to equip them with renewable (indoor) climate systems. A PVT collector is an example of a renewable climate system and although it is not located indoor, it generates the energy that can subsequently be used by different indoor systems.

The emphasis of this research will be on new buildings, since PVT collectors as well as other renewable climate systems are very expedient for new buildings. In addition to that, as will be explained in paragraph 2.3, the application possibilities and results of PVT for multi-family buildings have not yet been researched thoroughly. This makes it very appealing to look into the effect of PVT together with its associated (indoor) climate systems on that scale. These systems are (briefly) discussed in the next sub-paragraphs.

2.2.1 Renewable heating

Israëls & Stofberg (2017) define that heating systems in new buildings need to be of less capacity because of the high insulation regulations. Consequently, this leads to lower energy demands compared to existing buildings. After all, if the thermal conductivity of a building is low and the transmission and infiltration leakages are limited, there are less energy losses, making the demands also lower. In the previous chapter, two kinds of low-temperature heating systems were mentioned: radiators and convectors together with floor and wall heating. In general, the water supply and return temperature are between 25°C and 55°C, though 55°C is considered relatively high. Therefore, 30-35°C is assumed as being a feasible supply temperature for floor heating in well-insulated buildings.

If the desired water temperature cannot be supplied by a PVT collector, a heat pump can be used to increase the water temperature. A heat pump uses a compressor to do this, which is made possible by providing the pump with electricity. Furthermore, the heat can be extracted from the soil, water or air. (pp. 164-166).

2.2.2 Renewable cooling

The low-temperature heating systems discussed in the previous sub-paragraph can also be used for cooling. Israëls & Stofberg (2017) explain that floor and wall cooling are felt as “very comfortable since there does not appear an inconvenient draught and there is a constant temperature in the room”. The cooling is defined as ‘high-temperature cooling’, as the inlet temperature of the water needs to be 16°C or higher in order to prevent condensation. This high-temperature cooling system can be combined with low-temperature heating. For instance, a heat pump can be adjusted the other way around, so that it can provide cool water (pp. 215, 217, 218). A refrigerator is a real-life example of this process: the inside of the fridge is cooled to maintain the products’ condition, while at the back of the fridge - where a heat exchange unit is placed - heat is given off to the surroundings. Besides, the return temperature of the water in case of high-temperature cooling depends on the total length of the pipes and the temperature of the room.

2.2.3 Renewable domestic hot water
Domestic hot water or DHW is mainly used in the kitchen and the bathroom. The temperature of DHW - or water in general - has to be above 60°C in order to avoid the growth of Legionella bacteria (Israëls & Stofberg, 2017). Legionella.nl mentions that a temperature above 55°C is a safe temperature to shower (n.d.). Besides the fact that heating up water with a PVT collector is renewable, there is also the possibility to use a shower-based heat recovery system: hot water that flows into the shower drain can be lead along the water supply pipe to emit its heat. Substantial savings can be made by doing so (pp. 229, 230).

To temporarily store the hot water that is warmed up by the PVT collector, a solar boiler or a buffer tank can be used. Besides storage, a boiler or buffer system exists of a heat exchanger which exchanges the hot water with a domestic hot water or a low-temperature heating system. An additional post-heater can provide extra heat if necessary (p. 206).

2.2.4 Renewable electricity
In 2015, the share of domestic production of renewable electricity was 11.1%. The Dutch government aims at 14% by 2020 (Centraal Bureau voor de Statistiek, 2016, pp. 3, 19). PV(T) undoubtedly contributes to this.

Figure 6 shows the discussed renewable energy systems and their characteristics and temperature requirements in the context of this research. It has to be noted that the return temperature of domestic hot water is not applicable, because DHW is not part of a closed circuit.

Renewable energy type	*Inlet temperature*	*Return temperature*
Low-temperature heating	*30 - 35°C*	*25°C*
High-temperature cooling	*16°C*	*20 - 25°C*
Domestic hot water	*60°C*	*-*
Electricity	*-*	*-*

Figure 6. Overview of renewable energy temperature requirements (own illustration).

2.3 Photovoltaic thermal collectors

This paragraph comes with a deeper approach and discusses the types and configurations of PVT collectors with the help of some reference examples. For the eventual building-application, the most appropriate PVT collector type will be used for further research regarding the optimisation and maximisation of system configurations as well as the integration in the building-envelope.

2.3.1 Introduction
Solar energy can be absorbed in a lot of ways. In the built environment, most of the times photovoltaic (PV) panels are used as well as solar thermal (ST) collectors. PV panels convert solar irradiation into electricity by using PV cells, while ST collectors use the solar power to generate hot water by using pipes filled with a fluid. A relatively new technology in the world of solar energy is the combination of a PV panel with an ST collector, resulting in a hybrid photovoltaic thermal (PVT) collector. In this way, the excess heat of the PV cells can be given off to the collector pipes underneath. The PV cells can therefore be cooled, which improve their efficiency. Although the technology seems new, people already started to experiment with PVT back in 1978:

> Current interest and activity in photovoltaic systems for terrestrial applications are expanding rapidly. This includes the investigation and development of hybrid or combined thermal/electric flat-plate collectors in which the absorber consists of an array of solar

cells for generation of electricity, while collector fluid circulating past the absorber also provides useful thermal energy as in a conventional flat-plate collector. (Florschuetz, 1978, p. 361)

Figure 7 shows a cross-section of the PVT model used by Florschuetz. The basis of this design is still used today, as Yandri (2017) shows in figure 8. Yandri also mentions that PVT collectors have been further analysed in the meantime on different aspects relating to their design, performance and cost-effectiveness (pp. 344, 346).

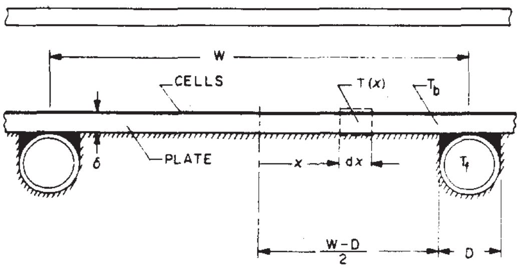


Figure 7. Cross-section of a PVT model (Florschuetz, 1979, p. 362).

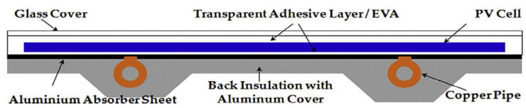


Figure 8. Cross-section of a PVT model (Yandri, 2017, p. 346).

Israëls & Stofberg (2017) mention that for one square meter of roof area, a PVT collector has a higher efficiency than a separate photovoltaic panel and a separate solar thermal collector. In other words, if one wants to use the surface of its roof in a most effective way, one should apply PVT collectors on it. The reason why PVT collectors are not yet applied on a large scale can be imputed to financial aspects (p. 262).

The conversion rate of photovoltaic cells in a PV panel is strongly related to the temperature of the cells, Lamnatou & Chemisana (2017) describe. The hotter the PV cells get, the lower their efficiency will be. This means that it is important to cool down the cells in order to obtain more electricity. This cooling can be done with either water or air, for they absorb the excess heat of the PV cells and transport it away. However, this water or air can be given a practical purpose by using it as a supply medium. In this case the photovoltaic function of the system simultaneously becomes thermal, resulting in a (hybrid) photovoltaic thermal collector or PVT collector. Because of this dual output, the total energy yield of a PVT collector is higher than a standard PV panel (p. 271).

Since the publication of the first PVT model in 1978, Yandri knows that there has been a lot of research already on all kinds of different aspects of PVT (2017, p. 344). Al-Waeli, Sopian, Kazem & Chaichan (2017) explored this in more detail. In the 1980s, the focus was on the application possibilities and design scenarios. Design improvements and cost-effectiveness were the main topics in the 1990s, where testing and innovation was done in the 2000s. In this decade, research was and is targeted at efficiency improvement and the use of additional (smart) materials like phase-change materials and nanofluids (pp. 127, 128).

The market of PVT collectors still is very small compared to that of photovoltaic panels and solar thermal collectors, but in the last decade there can be seen an increased interest in the amount of commercially available PVT products (Good et al., 2015, p. 688).

2.3.2 Types and configurations

Good et al. (2015) report that, in general, there are PVT air collectors, PVT liquid collectors and concentrating PVT collectors (p. 685). In a PVT collector status analysis of Al-Waeli et al. (2017) there is also spoken of a combination of PVT air and PVT liquid collectors. This combination together with the basic PVT types will be described in this sub-paragraph along with their possible configurations. Later on in paragraph 2.5, the aspect of integration is treated. Before all this, the basic composition of both the PV panel and the solar collectors will briefly be discussed.

PV panel types
Yanovshtchinsky et al. (2012) mention that there are four types of PV panels (p. 233):

- monocrystalline solar panels, which have an efficiency between 15% and 20%. These are notable for their uniform blue colour. However, as of April 2017, the efficiency of a monocrystalline silicon solar cell is reported to be 25.7%. It has to be noted, though, that these efficiencies are reached within laboratories; the actual efficiency will therefore be lower (Fraunhofer Institute for Solar Energy Systems ISE, 2017);

- polycrystalline solar panels, with an efficiency between 12% and 15%. They are also blue-coloured, though non-uniformly;

- amorphous silicon flexible solar panels, which are strips with an efficiency between 3% and 8%. This type has a better performance under adverse weather conditions.

- amorphous silicon rigid solar panels, which are also 3 to 8% efficient.

Figure 9 shows three different panels, where the right-most thus is available in both rigid and flexible state.

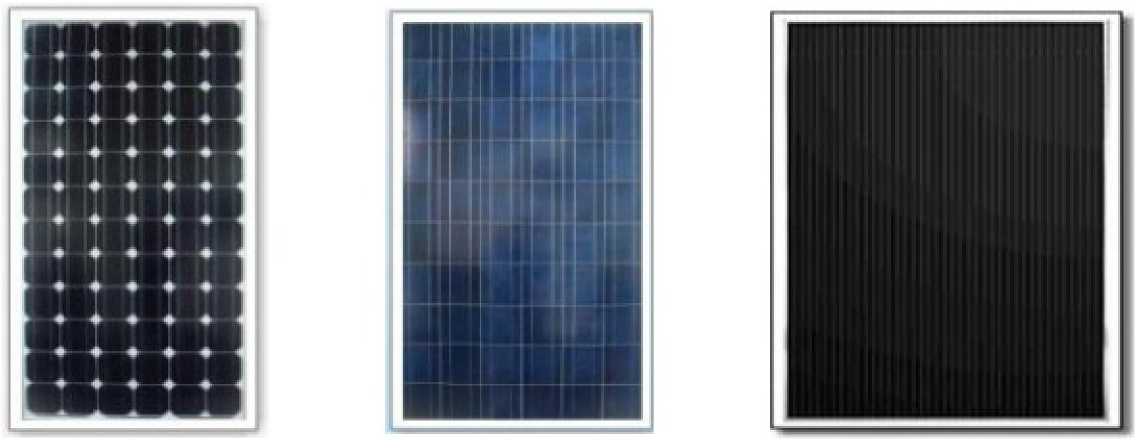


Figure 9. A monocrystalline, polycrystalline and an amorphous silicon solar panel (Solar PV panels Sungen, 2011).

Solar collector types
There can be made a distinction between two solar collector types as Goorden (2016) explains: flat-plate collectors and evacuated tube collectors. A flat-plate collector comprises of a black absorber plate, liquid- or air-filled tubes and a glazed cover. To prevent heat losses as much as possible, the tubes and the absorber plate are covered with thermal insulation. An evacuated tube collector exists of multiple tubes located side-by-side to each other. Inside these tubes there are coated pipes - filled with a fluid or a gas - which absorb solar irradiation. Between the tubes and the pipes there is a vacuumed space present, which ensures that the collected heat cannot escape and therefore increases the efficiency (pp. 40-42). Both types are shown in figure 10.

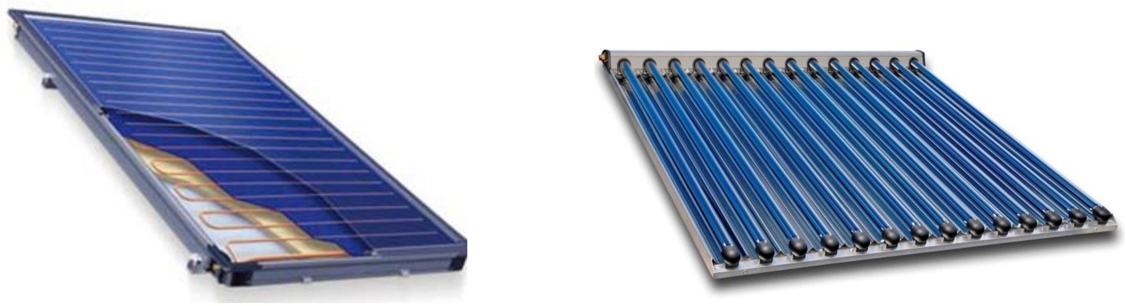


Figure 10. A flat-plate (left) and an evacuated tube collector (Goorden, 2016, p. 41).

PVT air collectors
One of the ways to cool down PV cells is to extract the excess heat and use it as a gas-based heat exchanger. This is the basic principle of a PVT air collector, which uses the extracted air for ventilation or space heating and cooling purposes. The combined efficiency of these PVT modules are currently between 20% and 40% (Al-Waeli et al., 2017, p. 112). There are numerous researches conducted on the performance of a PVT air collector which are still going on today. This section will discuss some of those researches and will review their results.

In their study into the performance improvement of PVT collectors with a natural air flow cooling, Tonui & Tripanagnostopoulos (2008) tried to extract the air behind a PV module in order to improve its efficiency. Their research consisted of two different set-ups with an air-channel behind the PV panel: the first set-up used a thin metal sheet that was suspended in the air-channel, while for the second method a couple of fins were placed at the back plate of the channel (see figure 11). It was concluded that both set-ups performed better than a regular PV panel (p. 1).

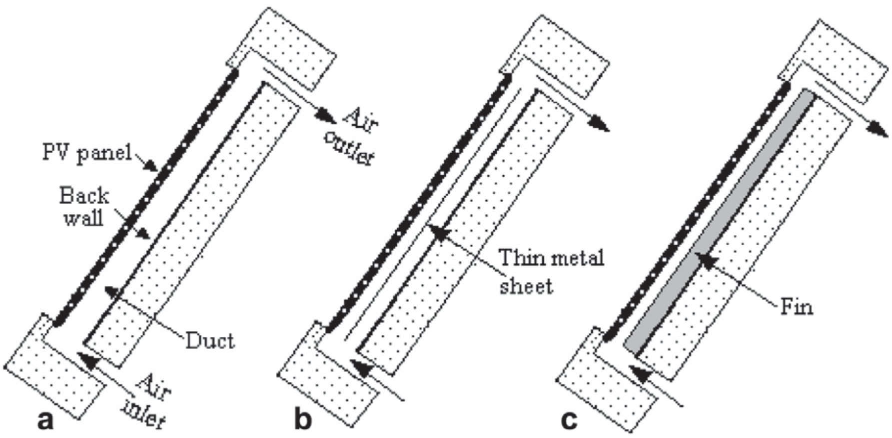


Figure 11. The three configurations of the PVT air collector (Tonui & Tripanagnostopoulos, 2008, p. 3).

A similar research was conducted by Agrawal & Tiwari (2010), where they compared the electrical efficiency of a building-integrated photovoltaic thermal (BIPVT) system to a building-integrated photovoltaic (BIPV) system, with an additional production of thermal energy for space heating. It was made clear that a BIPVT system produces the most electricity. Besides that, there is also shown a difference between a monocrystalline BIPVT and an amorphous silicon BIPVT system. The monocrystalline variant is more suitable in situations with higher energy and exergy (the maximum amount of power that can be obtained from a source) demands and where the space for the instalment is limited, like multi-storey buildings. On the contrary, an amorphous silicon BIPVT system seems to be more economic and more ideal for remote and urban areas (pp. 1472, 1480).

Ahn, Kim & Kim (2015) performed a study where they directed the heated air from a PVT air collector to a heat recovery ventilation system. The study was done in South Korea. It turned out that the thermal and electrical performance of the PVT collector was respectively 23% and 15%, resulting in an overall efficiency of the PVT collector of 38%. Therefore it was concluded that a heat recovery ventilation which is connected to a PVT air collector performs better than a usual one (p. 3012).

The effect of the distance between the PV panel and the underlying space for heat collection (or: collector depth) is analysed by Farshchimonfared, Bilbao & Sproul (2016). They linked a PVT air collector to a mechanical ventilation system of a residential dwelling in Sydney, Australia. The research tried to find out to what extent the collector depth influences the eventual temperature output. The outcome was that a smaller depth performs better with high air temperature rises, simply because a smaller volume is more easily heated up. However, this principle is more sensitive to changing air mass flow rates, because the smaller volume reacts much faster to this. Otherwise, the application of a larger collector depth gives a more homogeneous energy yield, for the air temperature rises more slowly. Consequently, this variant is less sensitive for different rates of the mass flow, since a larger volume responds much slower to that. Therefore, a PVT air collector has to be optimally designed in order to supply proper air mass flow rates at different temperatures (p. 15).

However, when there is only one inlet for a mechanical ventilation system, a situation may occur in which too much accumulated air can cause overheating, resulting in a lower energy output of the PV cells. Rounis, Athienitis & Stathopoulos (2016) compared the thermal and electrical efficiencies of a building-integrated PVT air collector for both single and multiple inlets for new buildings (see figure 12) in Canada. They did this under varying temperatures and wind conditions in both a summer and a winter situation. The target was to create more uniform PV temperatures as a result of a better heat extraction from the modules. It was found that these uniform temperatures were obtained: a 1% higher electrical efficiency was realised, which is an improvement of 7% extra power to the total outcome of a 120 kW PV system and an additional 24% higher thermal efficiency (p. 157).

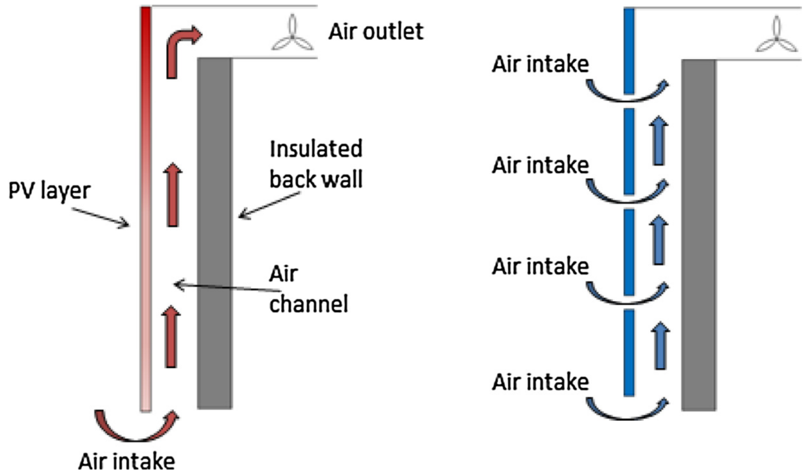


Figure 12. Single and multiple-inlet BIPVT systems (Rounis et al., 2016, p. 159).

Mojumder, Chong, Ong, Leong & Al-Mamoon (2016) looked into the dual efficiency of a PVT air collector by placing a thin flat metallic sheet fin system inside the collector to dissipate heat (see figure 13). Subsequently, they measured different temperature parameters. The study concluded that the fin system resulted in a higher thermal and electrical efficiency than a PVT collector without the fin system: 59.16% and 13.75% respectively. The researchers performed their study in Malaysia (pp. 272, 283).

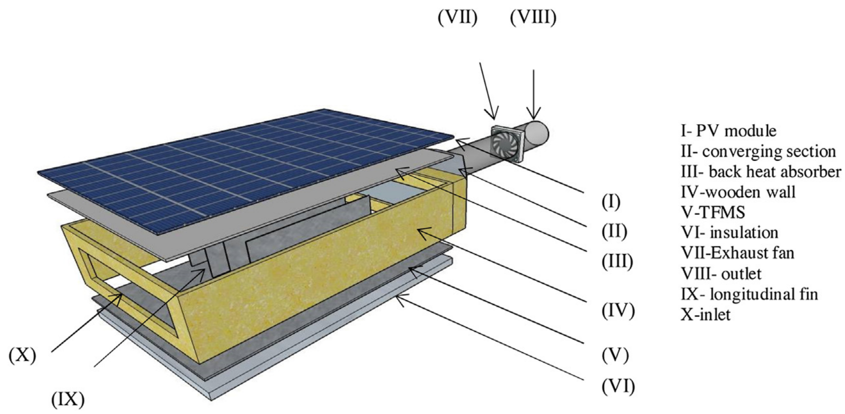


Figure 13. A 3D model of the PVT collector (Mojumder et al., 2016, p. 275).

An overall status with future perspectives on PVT air collector systems is given by Al-Waeli et al. (2017):

> A lot of research has been done in this area and there are still more aspects that need to be investigated because there are still some gaps that prevent the development of this technology from becoming widespread. Some of the drawbacks of this technique are that air has low heat capacity, so the amount of heat it pulls from the PV module is limited. The air flow rate needs to increase the amount of heat extracted. (p. 114)

Besides that, the researches mentioned in this section are performed everywhere around the world. This entails naturally many environmental conditions, which influence the efficiency of the PVT collectors.

PVT liquid collectors
As Al-Waeli et al. (2017) pointed out in the previous section, the drawback of air used in PVT systems is that air has a low heat capacity. This heat capacity of air is approximately 1000 J/kg K. A temperature variation of several hundredths of degrees does not influence this specific heat very much. However, the heat capacity of water is around 4200 J/kg K, where a temperature difference of several hundreds affects this value a little bit more (The Engineering ToolBox, 2017a; 2017b). Anyway, this difference in heat capacity should give water a higher potential for it to be used as a heat carrier in PVT systems.

A PVT liquid collector is basically comprised of the same structure as a general flat-plate collector with the only difference that the glass panel on top of this collector type is replaced by a PV panel (Al-Waeli et al., 2017, p. 115). Chow (2002) adds that this PV panel is adhered by using a layer of ethylene-vinyl acetate and Tedlar (p. 144).

An experiment of Tripanagnostopoulos, Nousia, Souliotis & Yianoulis (2002) with polycrystalline and amorphous silicon PVT systems analysed various design principles, the use of water and air as a medium, the application of glazing and other things. The experiment was done in Greece. Several conclusions were made:

- the use of water as a transport medium is more efficient compared to air circulation;

- if a higher thermal efficiency is obtained, this automatically leads to a better electrical efficiency in this specific case;

- additional glazing on top of the PVT collector renders a negative impact on the electricity output, for this will be lowered by circa 16% compared to ordinary PVT systems because of optical losses. On the other hand, the thermal part profits from this glass layer: it rises by approximately 30%;

• Tripanagnostopoulos et al. suggest the use of booster diffuse reflectors to increase the thermal and electrical efficiency. On a horizontal roof, PV(T) panels/collectors are mostly placed in rows, with a certain distance between them to avoid shadows. These reflectors could be placed in between those empty spaces to direct more solar rays to the panels/collectors resulting in a higher insolation (see figure 14). The downside of a lower electrical efficiency by using additional glazing can be compensated by using those reflectors. Additionally, these boosters are more effective in southern countries because of the higher solar altitude (pp. 217, 219, 231-233).

These results are thus gained with polycrystalline and amorphous silicon PVT systems. It is promising to know that the application of monocrystalline is even more promising, since its higher efficiency.

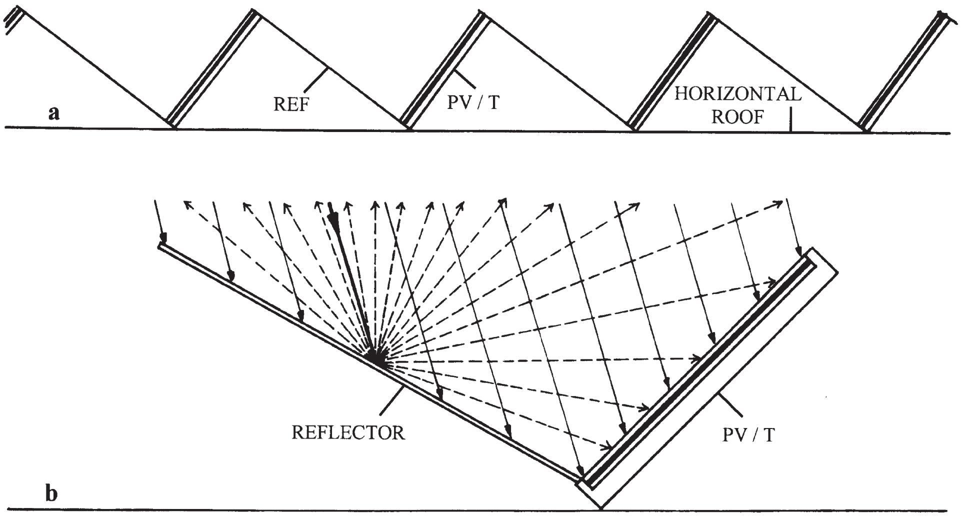


Figure 14. Booster diffuse reflectors between PV(T) systems (Tripanagnostopoulos et al., 2002, p. 219).

Mojumder, Uddin, Alam & Enam (2013) created a PVT collector with both water and air serving as the thermal output at a university in Bangladesh. A photovoltaic panel was placed on top, the water-filled solar collector below it and finally an air channel at the lowest level. They fabricated four experimental set-ups with shaped ribbed plates in the air channel to see how this would influence the thermal and electrical efficiency. The shapes were: trapezoidal, saw tooth (forward; see figure 15), saw tooth (backward) and flat. The study claimed that both saw tooth shapes resulted in the highest efficiencies (pp. 47, 49, 50, 54, 55).

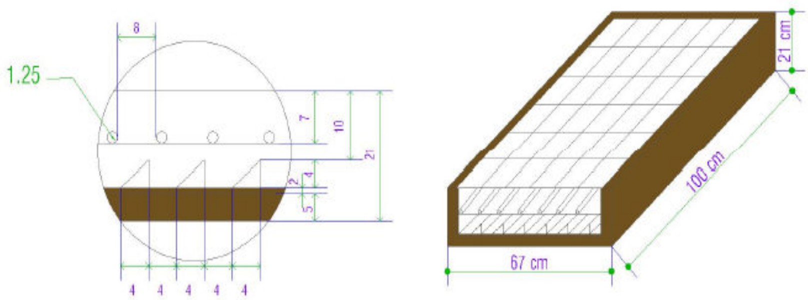


Figure 15. One of the PVT saw tooth set-ups (Mojumder et al., 2013, p. 50).

A PVT collector cooled by water was tested by Kiran & Devadiga (2014). A system that was uncooled resulted in an electrical efficiency of 7.58%, while a system that was cooled gave an efficiency of 8.16% with an additional thermal efficiency of 50.80%. The researchers concluded that the electrical and thermal efficiency of this PVT module was proven to be higher than the separate efficiencies of a solar thermal collector and a photovoltaic panel. The study was conducted in India (pp. 80, 86).

A comparably study was done by Alzaabi, Badawiyeh, Hantoush & Hamid (2014) in the United Arab Emirates. The team used a polycrystalline PV panel that was attached to a solar thermal collector. This collector was equipped with rectangular copper pipes to increase the contact area with the PV cells and therefore increasing the heat transfer. The experiment was conducted with and without water cooling to determine its effect on the efficiency. By cooling the PV cells, the electrical output significantly increased by 15 to 20%. The thermal output was between 60 and 70% (pp. 385, 386).

The use of rectangular copper pipes as described in the research of Alzaabi et al. is one of the options to improve the heat transfer. However, the installation pattern of these copper pipes inside a flat-plate collector also makes a difference. A Malaysian study by Ibrahim, Sopian, Othman, Alghoul & Zaharim (2008) researched the effect of various patterns on the total yield of a PVT collector:

- a direct flow design;
- an oscillatory flow design;
- a serpentine flow design;
- a web flow design;
- a spiral flow design;
- a parallel-serpentine flow design;
- a modified parallel-serpentine flow design.

A spiral flow absorber design configuration (as displayed in figure 16) seems to be the best choice when it comes to the total energy output of the PVT system: the electrical efficiency was 14.98%, where the thermal efficiency was 50.12% (pp. 44, 46).

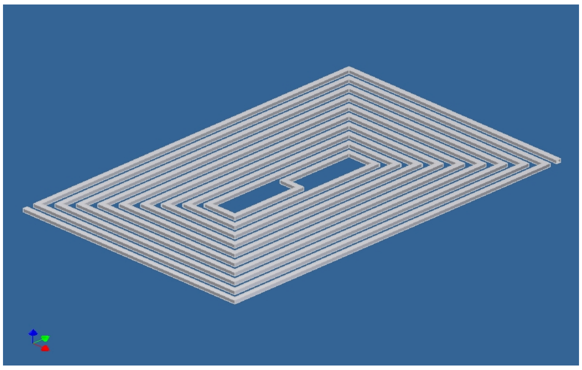


Figure 16. A spiral flow design (Ibrahim et al., 2008, p. 46).

A 'regular' PVT collector consists of a PV panel on top of a solar thermal collector. However, Italian researchers Rosa-Clot, Rosa-Clot & Tina (2011) developed a different configuration known as TESPI (thermal electric solar panel integration), where a thin layer of water flows on top of a PV module. The water is located in a polycarbonate box and absorbs the infrared radiation in order to take the heat away from the PV cells, which increases the PV efficiency. A complete composition of a TESPI module is shown in figure 17. It was concluded that the energy output of the TESPI system had an electrical efficiency of 13% and a thermal output of 54% (pp. 2433, 2434).

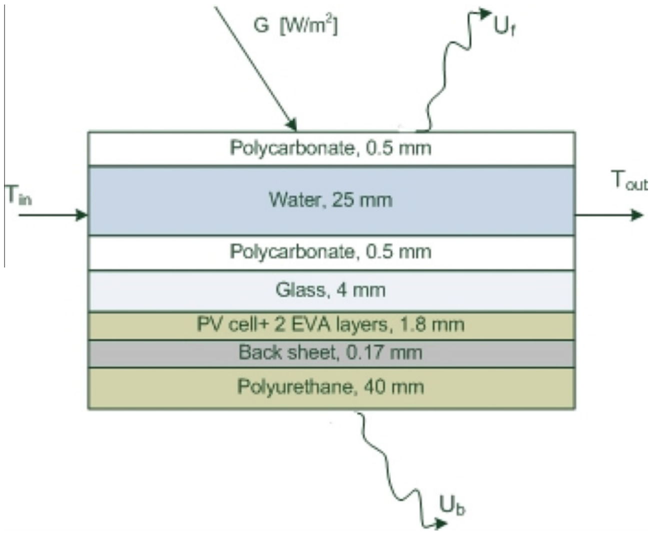


Figure 17. A diagram of a TESPI module
(Rosa-Clot et al., 2011, p. 2435).

In 2016, Yazdanifard, Ebrahimnia-Bajestan & Ameria simulated a PVT configuration with and without the glass cover and thereby examined multiple parameters. The study was performed in Iran. The outcome was, among other things, that a longer collector length generally has considerable positive implications for the total exergy efficiency, while it renders a negative impact on the total energy efficiency: the maximum quantity of power that can be obtained is more, but there is also more power loss due to a longer length. Furthermore, there is an optimum mass flow rate as well as an optimum amount of pipes that can yield a higher exergy efficiency. Moreover, a higher mass flow rate is needed when applying an unglazed system, for the heat does build up much more in case of a glazed system, which means that a higher flow rate transports the heat much faster. The study finally concluded that in general, a glazed PVT system has a higher total efficiency than an unglazed version (p. 296, 305). A glazed PVT module can be seen in figure 18.

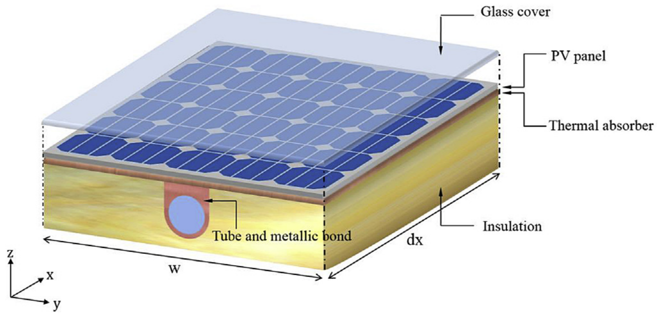


Figure 18. A glazed PVT module
(Yazdanifard et al., 2016, p. 297).

According to Brottier, Naudin, Veeser, Terrom & Bennacer (2016) “one of the most important barriers” regarding PVT “is the inexistence of a proven track record in terms of reliability and performance”. Therefore, the researchers did a practical analysis of an unglazed PVT collector and installed it in a consumer home near Lyon, France. The conclusion was that the domestic hot water need for four people was covered for 91% from the period of May until September. The average annual coverage was 50%. The maximum temperature inside the collectors did not exceed 70°C (pp. 276, 277, 283). The outcome could even be more positive if the collectors were to be glazed.

Al-Waeli et al. (2017) mentions that a PVT collector "cooled by water is one of the most efficient systems that can be integrated into buildings without any effect on its architectural design". They add, however, that there are still many things that must closely and carefully be investigated. Moreover, also the benefits of stored energy - during the moments when the sun does not shine - is still a point that is worth examining together with the application of nanofluids or nanomaterials to increase the thermal efficiency of water. Moreover, the practical part of in which way one can benefit from the water that is heated up by the PVT collectors as well as what to do with the wasted water is important to take into account. Again, the studies were performed in different countries with variable climates, which obviously affect the efficiencies (p. 118).

There are several researches done into the effect of nanofluids on the total yield of a PVT collector. Khanjari, Pourfayaz & Kasaeian (2016) tested a PVT configuration with pure water, Ag-water and Al_2O_3-water (alumina-water) as working fluids. They concluded that the more nanoparticles are used in a fluid, the higher the thermo-physical abilities of the fluid will be, which results in a higher energy exchange. That means that the Ag- and the alumina-water perform better than pure water, where the Ag-water has the greatest influence on the thermal performance. In addition to this, the researchers also found out that the fluid velocity is of great importance for the electrical and thermal efficiency. If the fluid velocity is (too) high, the thermal efficiency will be decreased, but because more heat is taken away from the PV cells, the electrical energy output will increase. On the contrary, for a (too) low mass flow velocity, the thermal output will rise because the water has more time to absorb solar irradiation. The electric efficiency will be lowered then (pp. 263, 277). The application of nanofluids is therefore a promising development.

As reported, the efficiency of PV cells will decrease if they become too hot. The reason for this is that the electrons inside these cells will become much more mobile in that case. They 'bounce' out of the cells and seek their way to the empty spots where other electrons jumped out. This improves the electrical balance in the cell, but the electrical field at the boundary layer disappears, resulting in a lower exchange of voltage (Zonnepanelen-info.nl, 2017). Yandri (2017) makes use of this effect by applying a phenomenon called Joule heating. This means that an electric current - which originates when the electrons become more mobile - is deliberately led into a resistance. By doing this, the electric energy is converted into heat and can be utilised. Yandri examined this Joule heating effect to find out if it influences the thermal efficiency of a PVT module. The conclusion was that the converted heat is partially conducted through the PV surface to the underlying thermal absorber. Therefore, Joule heating can be applied to make use of apparently wasted (thermal) energy in a beneficial way (pp, 344, 346).

PVT dual collectors
Earlier in this chapter, a PVT system of Mojumder et al. (2013) was discussed, which uses both air and liquid as a heat exchanger. The benefit of a dual collector is that there are more output possibilities than a 'conventional' PVT system. Reference literature shows that the development of PVT dual collectors is in full progress.

Su et al. (2016) experimented with these PVT dual collectors in China. They set up four different configurations, all with a solar cell in the middle, one channel on top of it and one channel below it. The set-ups were as follows (also see figure 19):

- one which consisted of water on top and air below;
- one with air on top and water below;
- a set-up with air both on top and below;
- one with water in both channels.

The researchers claimed that the water-water cooled PVT collector was "most excellent" in the electrical and thermal energy output as it can provide the most hot water (39.4°C). The air-water collector had the highest water temperature output, however (40.9°C). The highest air temperature output was reached by the air-air PVT module (45.6°C). Additionally, the increase of the mass flow rate and the height ratio between the upper and lower channel raises both the electrical (7.8%) and thermal efficiency (84.2%) (pp. 13, 23).

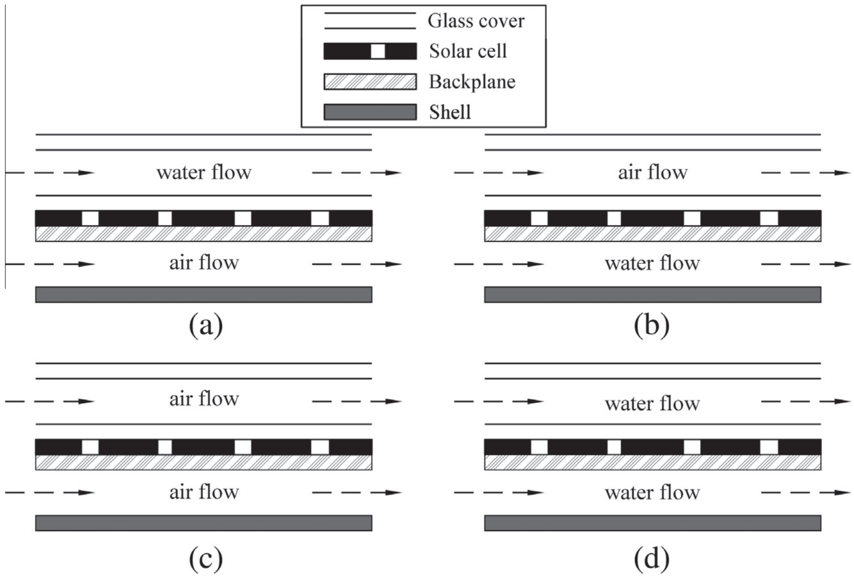


Figure 19. Sectional view of the four different dual PVT collector set-ups (Su et al., 2016, p. 16).

A similar study was done by Othman et al. (2016). They fabricated a PVT module with transparent PV and two channels for a double air pass with a suspended thermal collector plate (see figure 20). The outcome was that both the electrical and thermal efficiencies were 17% and 76%, respectively. Furthermore, the mass flow rate has an important role in the cooling of the PV cells. The dual function of the PVT collector also covers the weaknesses of stand-alone PVT air and PVT liquid systems, such as a lower construction cost and a more compact integration.

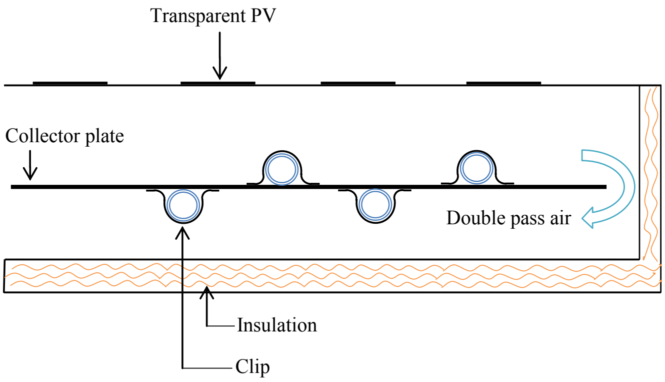


Figure 20. Cross-section of a dual PVT system (Othman et al., 2016, p. 297).

Concentrated PVT

According to Good et al. (2015), the technologies used for concentrated PVT are based on parabolic shapes. These collectors generate higher temperatures than most of the flat-plate collectors, which can attract industrial companies and other non-residential businesses who usually benefit from these kinds of temperatures. These types of collectors are not suitable to serve as building-integrated PVT (pp. 685, 687).

2.3.3 Conclusion

This paragraph gave an overview of the current status and developments of three types of photovoltaic thermal collectors: a PVT air collector, a PVT liquid module and the combinatory PVT dual collector. Although an air-based PVT system is generally less attractive than a liquid-based one, several experiments show that with the right set-ups and additions, the thermal efficiency can be improved as well as the electrical efficiency. Moreover, a PVT air collector can be connected with a (mechanical) ventilation system that can provide pre-heated air for residences. It is also important to determine a proper air mass flow rate in order to absorb solar irradiation in an effective way.

As mentioned, a liquid-based PVT module is more appealing than a system that uses air as a heat transfer medium: the specific heat of water is approximately four times higher than that of air. In addition to this, it was proven that the total efficiency of a cooled PVT collector is higher than an uncooled one. Also, the section design - rectangular instead of circular - of the fluid-carrying copper pipes and even the installation pattern design is of influence on the eventual efficiencies. Some researchers, however, decided to move in a new direction when it comes to the configuration of a PVT liquid collector by creating a thermal electric solar panel integration (TESPI) module, where a layer of water is used to absorb the heat instead of - the more common - copper pipes. Furthermore, the addition of a glass panel on top of a PVT liquid system proves to make a difference - also for air-based PVT collectors. This is equally the case for the liquid mass flow rate. Also, the addition of nanoparticles can improve the thermo-physical abilities of water to let it absorb more heat. Finally, inability of PV cells to generate proper efficiencies with higher (outside) temperatures can be overcome by the Joule heating technique, although this asks more electricity input to pre-heat the water.

The advantage of a PVT dual collector over the other two types is that hot air and water can be obtained in one fell swoop. This could be convenient for multi-family buildings, since these buildings require both hot water and ventilation. This - of course - is dependent on the specific demands of the building. Besides, an additional method that is independent of the PVT type is the application of (external) booster diffuse reflectors to direct more sunlight to the collectors.

Figure 21 gives a summary of all the researches and experiments given in this chapter. Figure 22 shows a scheme that gives an overview of the measures that can be taken - based on this paragraph - in order to optimise the design of a PVT module.

Since a PVT liquid collector results in the highest efficiencies, this type will be chosen over the air-based module. Figure 22 can be very useful to further specify which exact type of a liquid-based PVT module is desirable. The next step therefore is the choice between a glazed and an unglazed system. A glazed version results in an increase of the thermal efficiency, because the heat builds up inside the collector can easily be used. However, the electrical efficiency is lowered because of an abundance of accumulated heat. Despite this, there is chosen for a glazed PVT module, for this makes a huge difference when it comes to the thermal energy output. Calculations later on in this thesis will substantiate this choice. Furthermore, it was made clear in this paragraph that squared pipes and a spiral flow design result in a higher total efficiency. Finally, by determining the optimal mass flow rate in combination with the dimensions of the collector, both the exergy and energy efficiency can be controlled. A larger PVT collector gives a higher exergy efficiency, because the quality and quantity of the incoming energy is higher than when a smaller module is chosen. On the contrary, more energy can get lost in the process if a collector is larger. Glazing can lower this loss, however. It seems therefore wise to have the collector length as high as possible, since in this way there can be optimally benefited from the exergy.

The PVT collector that will be chosen for the continuation of this research is therefore the relatively large, covered, liquid-based module, supplied with a squared-pipe, spiral flow design.

Authors	*Year*	*Country*	*PVT type(s)*	*η_{el} [%]*	*η_{th} [%]*
Tonui & Tripanagnostopoulos	*2008*	*Greece*	*air*	*-*	*-*
Agrawal & Tiwari	*2010*	*India*	*air*	*7.13*	*33.54*
Ahn et al.	*2015*	*South-Korea*	*air*	*15*	*23*
Farshchimonfared et al.	*2016*	*Australia*	*air*	*-*	*-*
Rounis et al.	*2016*	*Canada*	*air*	*16.5*	*48*
Mojumder et al.	*2016*	*Malaysia*	*air*	*13.75*	*56*
Tripanagnostopoulos et al.	*2002*	*Greece*	*water*	*-*	*70*
Mojumder et al.	*2013*	*Malaysia*	*air & water*	*9.25*	*30*
Kiran & Devadiga	*2014*	*India*	*water*	*8.16*	*57.9*
Alzaabi et al.	*2014*	*United Arab Emirates*	*water*	*15-20*	*60-70*
Ibrahim et al.	*2008*	*Malaysia*	*water*	*11.4*	*55-62*
Rosa-Clot et al.	*2011*	*Italy*	*water*	*13.19*	*62*
Yazdanifard et al.	*2016*	*Iran*	*water*	*17*	*70*
Brottier et al.	*2016*	*France*	*water*	*-*	*-*
Khanjari et al.	*2016*	*Iran*	*water & nanofluids*	*13.2*	*55*
Yandri	*2017*	*Indonesia*	*water*	*-*	*72*
Su et al.	*2016*	*China*	*water & air*	*7.8*	*76.4*
Othman et al.	*2016*	*Malaysia*	*water & air*	*17*	*76*

Figure 21. Summary of the PVT subject matter (own illustration).

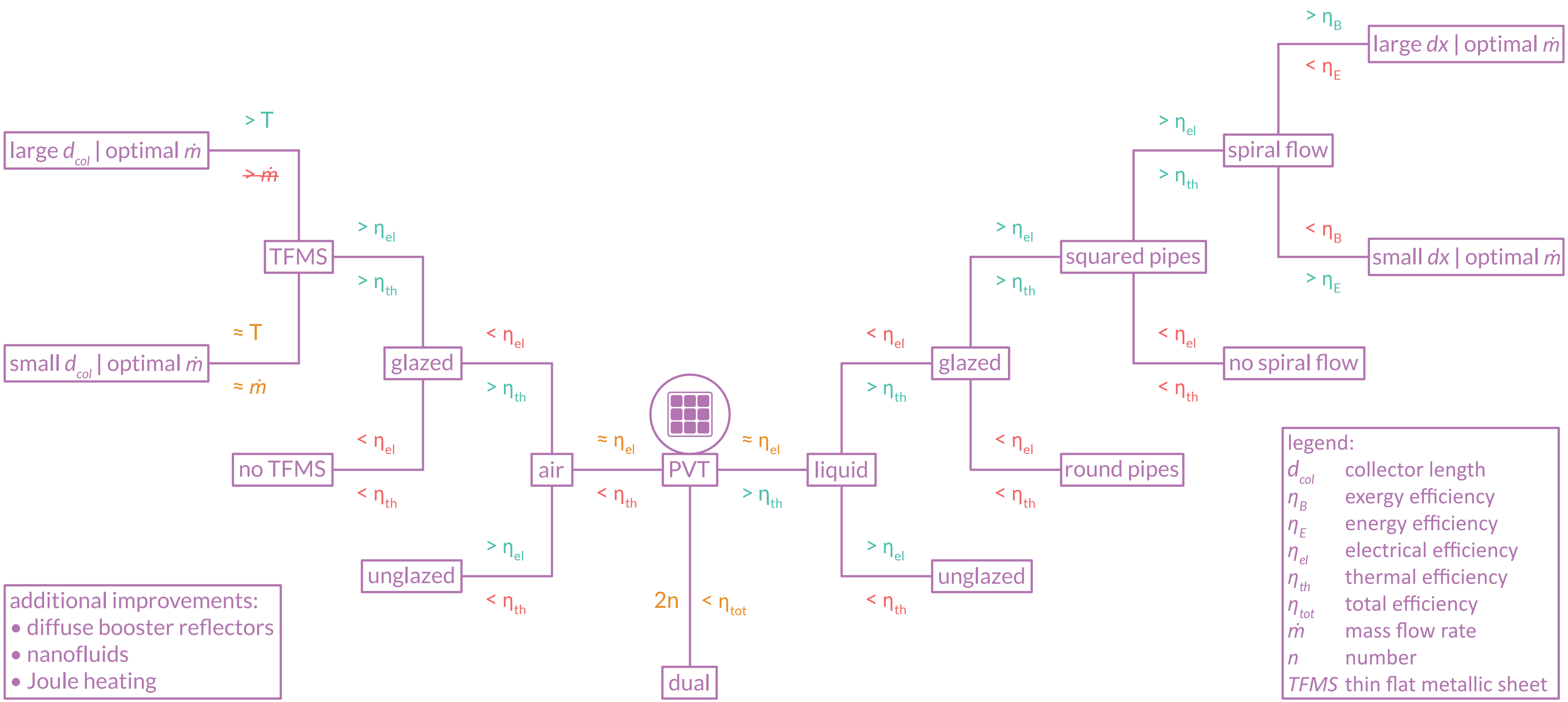


Figure 22. Schematisation of PVT optimisation measures (own illustration).

2.4 Other relevant technologies

Now that the PVT technology has been discussed, the report will focus on various energy distribution and storage techniques.

2.4.1 Heat pump

Since a heat pump serves as a temperature upgrading device, it is considered an important link in a PVT system configuration. A heat pump upgrades low-value heat to usable, high-value heat, which is for example mentioned by Yanovshtchinsky et al. (2012). This heat can be in the form of water or air. There are electricity-based heat pumps and gas-based heat pumps (p. 107), but in this report only the ones that use electricity will be considered.

The main principle of a heat pump is as follows. Low-value heat arrives at the evaporator, where a refrigerant is transformed into a gas. In order to evaporate, the temperature of the refrigerant needs to be lower than that of the low-value heat. After this evaporation occurs, the refrigerant is transported to a compressor, where its temperature rises because of its increasing pressure. This high-pressurised gas is then directed to a condenser, where it is given off to a water supply system of a colder temperature. The water absorbs the energy of the gas, which can be used for various (domestic) purposes. The cooled refrigerant - with less pressure - then goes to the expansion valve, where its pressure is even more lowered. Finally, the refrigerant arrives in a liquid state at the evaporator, where the cycle starts once again. The cycle is shown in figure 23.

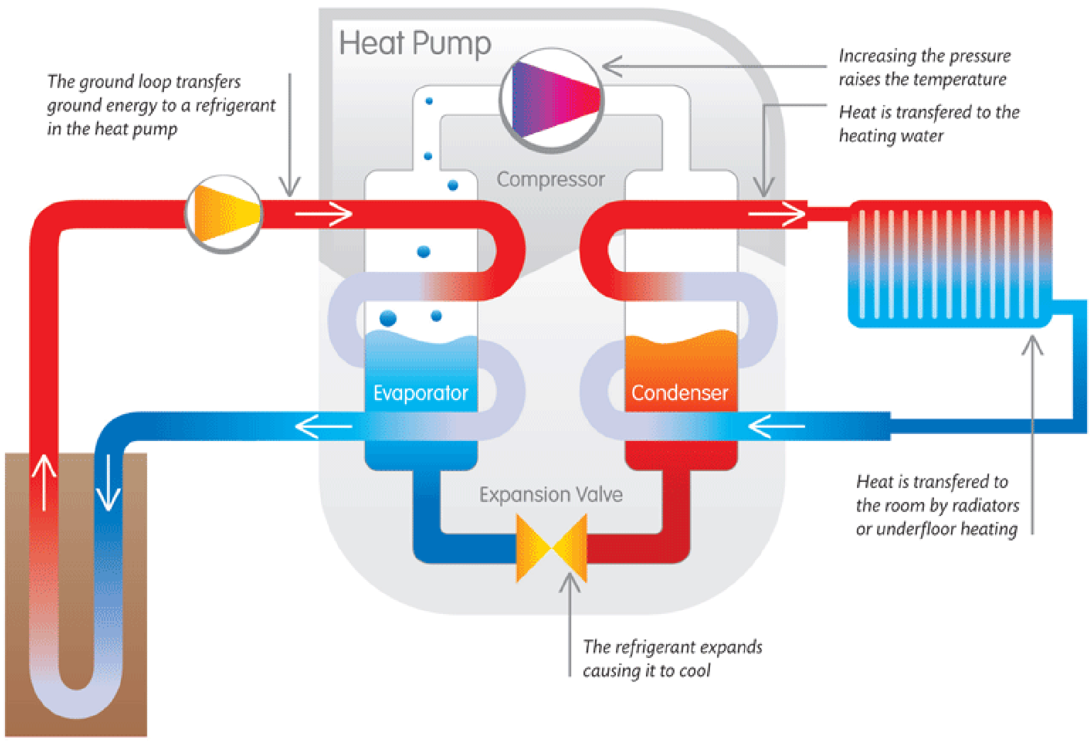


Figure 23. Heat pump cycle (Pinterest, as derived from Global Energy Systems, n.d.).

From the cycle it can be derived that the lower the temperature of the low-value heat is, the lower the temperature of the refrigerant needs to be to be able to evaporate. This means that the type of refrigerant depends on the temperature of the low-value heat. It is therefore hardly surprising that the lower this temperature is, the more energy a heat pump needs. When in this case really high temperatures are needed, the compressor needs to do a lot of work to upgrade the gas to a high pressure, which asks more electricity.

According to Yanovshtchinsky et al. (2012), the maximum output temperature of a heat pump is 55°C for residential purposes. For non-residential buildings, 60 to 65°C is also possible (p. 109).

A heat pump can also be used in a reversed way. This is exactly what happens with refrigerators: warm air is extracted from the inside of the fridge and is transported to the heat exchangers on the back of the fridge.

Regarding the sources of a heat pump, there are geothermal, water-based and air-based heat pumps. A ground-source heat pump extracts the warmth of the earth, according to Gommans (2017, p. 27). Water-based heat pumps obtain energy from bodies of water such as canals, lakes or seas. Outside air is the mean energy provider for air-based heat pumps. However, because the specific heat of air is lower than that of water - as discussed in sub-paragraph 2.3.2 - an air-based heat pump is less attractive than a water-based one. It is therefore wise for the heat source to be a liquid, since it is more efficient to have a liquid-to-liquid heat transfer.

There are also different operation configurations possible for heat pumps, as Yanovshtchinsky et al. (2012) mention:

- a heat pump with a monovalent operation heats a dwelling or an apartment exclusively, thus without an auxiliary back-up system. It is important that the heat demand of the room is predetermined. Because of the constant need of energy - and also domestic hot water - a monovalent heat pump uses quite a lot of power;

- a mono energy type heat pump provides most of the domestic heating, but is supported by an additional electric heating element in case the outside temperature gets too low. About 70 to 80% of the demand is supplied by the heat pump; the rest is done with electricity. This heat pump type is mostly applied in residential buildings;

- a bivalent parallel heat pump is complemented by a gas- or oil-fired boiler as an additional heater, but this is out of the question for this research;

- a bivalent alternative heat pump is applicable for an air-source heat pump and can fully provide the heat demand of a dwelling by using only the outside air. However, when the temperature of the outside air is too low, a different heating system is activated (p. 108).

Finally, the efficiency of a heat pump is expressed in a coefficient of performance or COP. The COP is loosely defined as follows:

$$COP = \frac{output\ energy}{input\ energy}\ [-] \tag{1}$$

So for instance, if the input of the heat pump is 10 kWh and the output is 50 kWh, the COP is 5. Also, when a heat pump has a COP of 3 and you want 75 kWh of power, you need 25 kWh. Thus, the higher the COP is, the more efficient the heat pump is. Yanovshtchinsky et al. (2012) report that a heat pump can have a COP of 3 to 7, depending on the heat pump and the source type. Heat pumps can last for 15 to 20 years, but there are real-life examples with a life-time of 25 years (p. 110).

The COP can also be defined more precise. Israëls & Stofberg (2017) point out that the COP represents the delivered heat Q_h divided by the work input W for the compressor:

$$COP = \frac{Q_h}{W}\ [-] \tag{2}$$

In addition to this, there is also a factor named the seasonal performance factor or SPF, which takes into account auxiliary energy for the source pump and the distribution system, measured over an entire heating season (p. 196):

$$SPF = \frac{Q_h}{W + E_{aux}} \; [-] \tag{3}$$

2.4.2 Floor heating

A frequently applied low-temperature heating system is floor heating. It basically consists of liquid-filled plastic pipes that are combined with or embedded in various floor types. These pipes come together at a floor heating manifold. Depending on the demand, one can speak of floor heating or floor cooling. To prevent uncomfortable situations, the maximum floor temperature may be 29°C and 33°C in bathrooms or at edge zones, as Israëls & Stofberg (2017) say. The value for the supply temperature has to be 45°C, but for buildings which meet the latest insulation requirements, 30°C is feasible most of the times. There are several types of floor heating on the market:

• wet systems: this type consists of pipes (Ø10 - 20 mm) that are laid on or attached to an insulation layer, with a cement screed or anhydrite substrate poured over it. The whole package is placed on top of the structural floor and is also known as a floating substrate. It is important that the insulation layer always functions as a separation between the substrate and other structural elements like columns and walls to prevent cracking and unnecessary heat transmission. An example of a wet system is shown in figure 24;

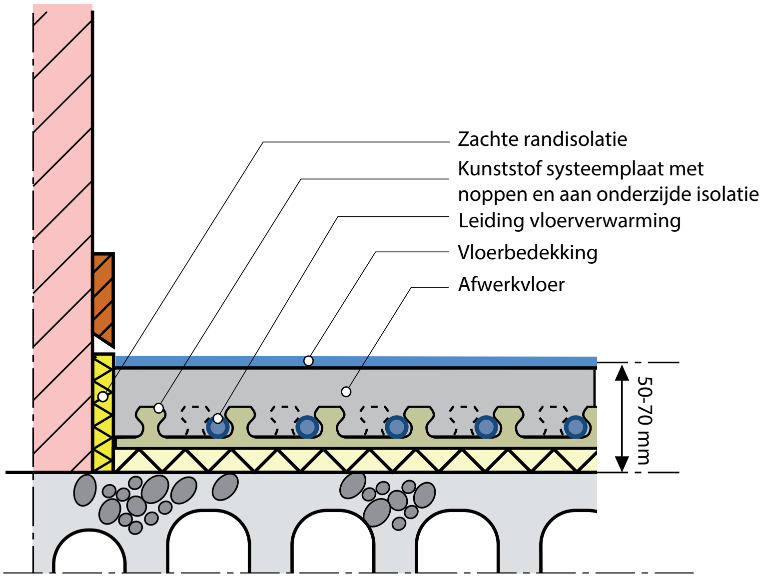


Figure 24. Example of a wet floor heating system (Israëls & Stofberg, 2017, p. 172).

• dry systems: the benefit of a dry system over a wet system is that a dry system speeds up much faster. The reason for this is that it is attached to an insulation layer with a conductive metal sheet between the pipes and the insulation. The pipes are covered with gypsum fibre boards or wood coverings, which makes it interesting for the timber frame construction industry;

• capillary systems: a collection of many small pipes with a diameter of 4 mm that are connected to a main tube. Because of the small diameter of the pipes, the system responds fast, which makes lower output temperatures possible. Moreover, the substrate can be thinner. It needs to be ensured that there is a separation between the pipes and materials that are prone to corrosion, since the pipes are oxygen-permeable.

• concrete core activation: pipes are integrated in the structural (concrete) floor. This technique uses the heat-accumulating ability of concrete to store the heat and to subsequently release the heat at a later moment. Concrete core activation is not desirable for apartment buildings and (other) high-rise constructions, though, because it is a quite uncontrollable system: the heat propagates through the complete concrete structure. The technology is therefore more suitable for detached buildings (pp. 170-172).

• electric floor heating: this system uses floor mats that are powered by electricity. However, the efficiency is doubtful as the system results in a high energy consumption, as Vasco Group (2016) says on their website.

Israëls & Stofberg (2017) continue by saying that since floor heating is a low-temperature heating system, it can perfectly be combined with solar energy. Besides, floor heating emits a more homogeneous heat dissipation, without any uncomfortable draught like for example warm-air heating. A downside can be the formation of air bubbles in the pipes and the relatively slow response. As is the case with solar thermal collectors, the installation pattern of the pipes is important in order to ensure a uniform heat output (pp. 173-175). Yanovshtchinsky et al. (2012) add that this output lies between the 50 to 100 W/m^2 (p. 129).

2.4.3 Wall heating
Wall heating consists of a similar piping system compared to floor heating, with one of the differences being the maximum wall temperature of 35°C (Israëls & Stofberg, 2017, p. 175). Yanovshtchinsky et al. (2012) mention that wall heating is possible in various forms, like the placement of pipes inside milled grooves in a wall. Even special panels or complete heat walls are available with integrated water pipes. The output is similar with that of floor heating. However, the wall has to be susceptible to swelling and shrinkage, for the constant heating and cooling of a wall asks this flexibility (pp. 130, 131).

2.4.4 Radiators and convectors
Radiators make use of radiation and convection to provide heat. Israëls & Stofberg (2017) know that the 'usual' high-temperature radiators are approximately two and a half times smaller than the low-temperature versions. The reason for this is that low-temperature radiators need to provide heat of a comparatively lower temperature (55°C), which increases their size. The return temperature is 45°C or less.

Just as radiators, convectors also contain water as a heat medium. The heat dispersion is somewhat different, though, as they use convection to spread the heat. Convectors are mostly placed in a floor duct (pp. 168, 171).

2.4.5 Drain water heat recovery
There is an abundance of heat that can be re-used when taking a shower. This is known as drain water heat recovery or DWHR. NEN 7120 determined the saving rate of a DWHR to be 40%. Israëls & Stofberg (2017) know some examples:

• a copper pipe-in-pipe construction (see figure 25): the hot waste water from the shower drain flows through the centre pipe. A second copper water supply pipe is wrapped around the centre pipe, and serves as a heat exchanger. Because the waste water falls down, the counter-flow principle occurs, making the water basically stick to the walls of the pipe to result in a better heat transmission. Adding ridges inside the central pipe could enhance this effect even further;

• a shower tray heat-exchanger: this unit is placed underneath the shower tray and absorbs the warmth of the hot water that is present in the tray;

• a shower channel heat-exchanger: this technique uses an integrated heat-exchanger in the shower channel (p. 230).

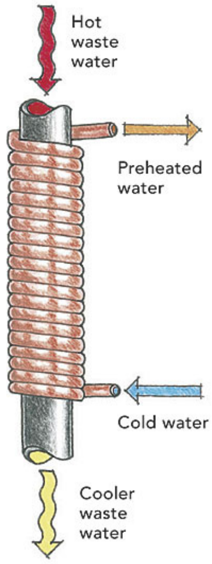


Figure 25. A pipe-in-pipe DWHR
(The Taunton Press, Inc., 2012, p. 23).

2.4.6 Cooling
Although cooling may not be needed as much as heating during a year, it still is relevant to keep a comfortable indoor climate on a hot summer's day. As mentioned in sub-paragraph 2.4.1, a heat pump can also be used for cooling. The minimum temperature of this high-temperature cooling is required to be 16°C, as shown in sub-paragraph 2.2.2.

The cooling principle of a heat pump does not differ very much from the heating principle. The only difference is that you want the output temperature to be 16°C instead of 30°C. At first glance, it can be wise to combine the heat pump with a seasonal thermal energy storage, for the cold well can provide relatively low temperatures in the summer, just like the hot well can give the higher temperatures during the winter. In this way, a heat pump and the underground storage can fruitfully work together. However, floor cooling can even be done without the use of the heat pump, as the temperature of the water under the ground can be led directly - albeit with the use of one or more heat exchangers - to the floor pipes. The underground storage phenomenon is further described in sub-paragraphs 2.4.8.

2.4.7 Integrated collector storage solar water heaters
When the energy of the sun is absorbed by a solar collector, the heated water can be transported to a buffer tank or a boiler. Both short-term energy storage systems can be used to store the water for a specific amount of time. In this situation, energy collection and energy storage are separated. Singh, Lazarus & Souliotis (2016) report that there are integrated collector storage solar water heaters or ICSSWHs. The researchers talk about the recent developments of ICSSWHs, including various types and categorisations. One of the main points of interest is its susceptibility for thermal losses during the night, since an insulated ICSSWH usually is not covered on the top side. Various studies have been performed to investigate the effects of adding different types of insulation material on top of the tank, while the solar irradiation is still able to be absorbed. Covering the tank at night was also suggested (pp. 270, 285). ICSSWHs are particularly interesting for building-integrational aspects.

2.4.8 Seasonal thermal energy storage

Another way to cover the mismatch - as mentioned before - is by applying seasonal thermal energy storage (STES). An example is the creation of two 'bubbles' or 'wells' where heat and cold can be stored in. In his graduation thesis, Goorden (2016) mentions many types of STES, such as aquifer and underground thermal energy storage, storage with phase-change materials, and - the main research topic of his thesis - thermochemical energy storage (pp. 45-48).

A relatively new type of STES is the SolarFreezer, developed by a Dutch start-up company. The basic idea of the SolarFreezer is a buffer sack that can best be placed in a colder, low-lying area of a building (for example a crawl-space). Thermal energy from a solar thermal collector can be stored in this buffer, after which a heat pump extracts the heat from the buffer (SolarFreezer B.V., n.d.). This results in the creation of slush ice in the buffer, while the extracted thermal energy can be used for domestic heating purposes (Stichting Kiemt, 2014).

Another storage system is the Ecovat (see figure 26). This collective system consists of a container-in-container principle. The insulated inner container is large concrete tank filled with water. Because the water in the tank is of various temperatures, a certain stratification originates. The difference with most other energy storage techniques is that in case of the Ecovat, no water will be pumped out of it; only external thermal energy is upgraded. By maintaining a narrow thermocline (the transition between two layers of water with different temperatures) the overall efficiency will increase. Especially at this transition, one or more heat exchangers can be placed that upgrade the external thermal energy (Ecovat Renewable Energy Technologies, 2017a; 2017b). Due to its size, it is sensible to apply an Ecovat collectively.

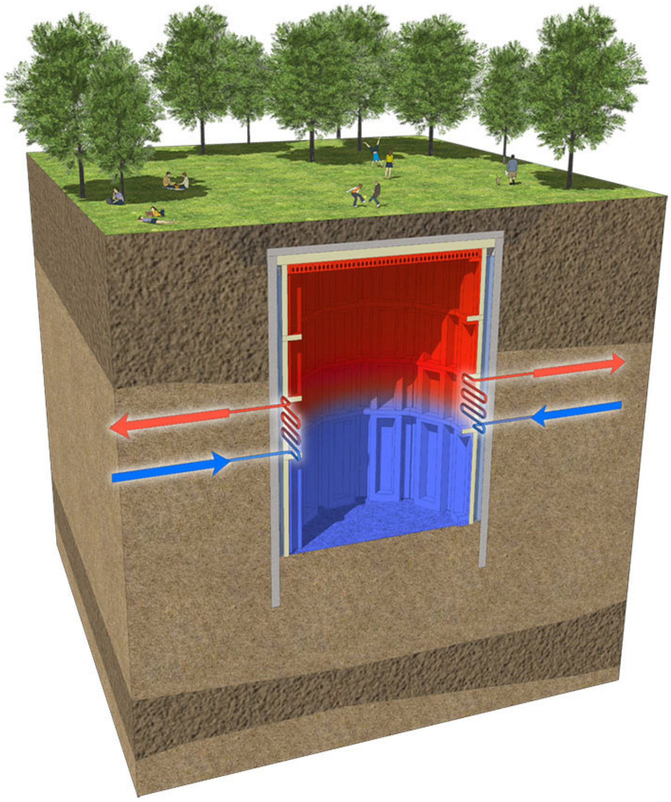


Figure 26. A section view of the Ecovat
(Ecovat Renewable Energy Technologies, 2017).

One of the dangers of seasonal thermal energy storage is a disturbance of the thermal balance. This happens when there is too much hot or cold energy extracted. A heat pump can also cause such a disturbance. In the worst case, permafrost can occur which has very negative implications for the building structure - especially for the foundation. Anyhow, thermal energy systems like solar thermal and PVT modules can regenerate and restore the thermal balance by directly storing it inside a buffer or bubble.

2.4.9 Electricity storage

The downside of generating renewable electricity on a domestic scale at this moment is the lack of storage. Electricity storage is, however, an advancing and promising technology. For example, the American company Tesla developed the Tesla Powerwall (see figure 27) that can be used as a residential stationary energy storage 'home battery' system. Solar irradiation is absorbed during the day so that its energy can be used in the evening. The storage space of a second generation Powerwall (Powerwall 2) is currently 13.5 kWh (Tesla, Inc., 2017). For comparison: the mean annual electricity consumption of a Dutch household was 2980 kWh in 2015 (Centraal Bureau voor de Statistiek, 2015). This is 8.2 kWh per day, which means that the Powerwall can store approximately 1.5 days of power. For 'ordinary' people this is not directly a problem but for large consumers this could be inconvenient. Moreover, the Powerwall is relatively expensive and has some additional limitations such as its power output. Svarc (2017) claims that the power output of the Powerwall 2 is 5 kW, with a peak of 7 kW. Using multiple electronic equipments and devices at the same time could therefore be a problem. It should, however, be mentioned that the Powerwall is a brand new invention which is still young and evolving.

Figure 27. The Tesla Powerwall (Tesla, Inc., 2017).

2.4.10 Conclusion

This paragraph showed that there are a lot of possibilities to apply renewable energy systems on a building level. First of all, a heat pump is considered indispensable to be included in the proposed energy configuration network, because it has the ability to upgrade low-value heat to usable heat in a very energy-efficient way. Second, low-temperature heating systems like floor heating, radiators and convectors are similarly appropriate to be applied. The high insulation values that are characteristic for the buildings constructed these days, do not ask for high-temperature space heating systems anymore, thus making low-temperature heating more and more attractive. Additionally, for high-temperature domestic purposes like showering, it is a waste of energy to let the hot waste water just flow away. A drain water heat recovery seems can be the solution for this. Fourth, seasonal thermal energy storage is essential to either deal with the energy mismatch and to provide water with a relatively low temperature that can be used for cooling during the summer months. And finally, the integrated collector storage solar water heater is promising, but it has to turn out in which way the total volume of it affects the construction of a building in which it potentially can be integrated in. Electricity storage will not be given much attention, since it is - despite its great potential - not in a development phase to make it appealing for this research.

2.5 Building-integrated photovoltaic thermal collectors

This paragraph discusses the integration of the PVT collectors treated in paragraph 2.3, hereinafter known as BIPVT (building-integrated photovoltaic thermal) collectors. As mentioned before, the PVT modules will be liquid-based. To have an overall understanding of this integration technology and the architectural and building-technical (integration) aspects, reference examples will be studied. Later on in this research, a reference building will be presented to which the BIPVTs will be applied.

2.5.1 Introduction

Lamnatou & Chemisana (2017) mention that "there is a new tendency for integration of solar systems into the building" (p. 272). Gautam & Andresen (2017) further mention: ""Building-integrated solar" is a concept by which solar modules serve as a building material, produce energy, and add architectural value simultaneously". 'Building-integrated' means that PV panels or solar collectors are integrated in the envelope of a building, which can both be the facade or the roof. If this integration is only done for photovoltaic panels, one speaks of BIPV; if it concerns photovoltaic and thermal, it is called BIPVT (p. 93). Figure 28 shows and example of what BIPV can look like.

Figure 28. Integrated PV panels on a house in the Dutch town of Callantsoog (Van der Leun, 2016).

Where the PVT technology emerged in the 1970s, BIPVT gained more attention in the 1990s, Gautam & Andresen (2017) know. One of the first known examples of BIPVT was in fact an air-based BIPV system: hot air from the back of BIPV panels was extracted and transported to an air-to-water heat exchanger, resulting in heated water. Liquid-based BIPVT started to get more attention in the 2000s (p. 94).

Yang & Athienitis (2016) say that the installation of a BIPVT component changes the relationship in terms of energy exchange between inside and outside. If the usual facade or roof component is replaced by a BIPVT collector, this energy exchange becomes less, for the collector absorbs the solar irradiation. In turn, this influences the R-value of a building, where a continuous insulation layer must be maintained when integrating a PVT module. Besides that, the building design, orientation and requirements are largely decisive for in which way a BIPVT collector can be applied (p. 887).

BIPVT systems can be categorised as shown in figure 29. In paragraph 2.3, configurations like air-based and liquid-based PVT systems were defined. It turned out that liquid-based systems were the most promising in terms of energy efficiency, and therefore the focus in this paragraph will lay on the flat-plate, liquid-based BIPVT. Figure 29 also shows the term 'thermosyphon', but this will not be treated further. Besides, concentrating PVT seemed to be unattractive for residential purposes. Phase-change materials are a completely different research branch and are not discussed further on.

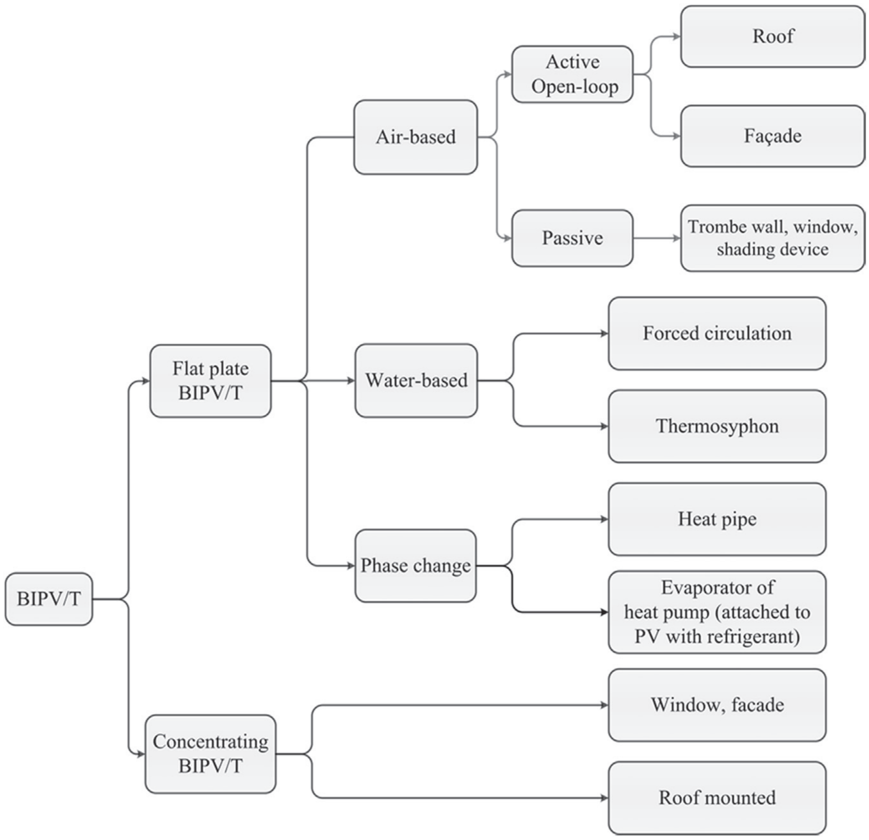


Figure 29. Categorisation of BIPVT systems (Yang & Athienitis, 2016, p. 888).

In contrast to building-integrated or BI, there is building-added (BA). The last term means that an element is an addition to a building. For example, when a PVT collector is placed on top of a roof, this is a BAPVT module. Although this research covers an in-depth investigation on BIPVT, BAPVT is not neglected. That is to say that PVT collectors will and can be added on top of the (flat) roof of the multi-family building, whereas they will be integrated into the facade of the building. The reason for this is that it is much more easier and (cost-)effective to not integrate the modules in building parts where they are not visible. Integration in the roof would mean that the PVT collectors are not tilted, producing some 32 percent (Isoleads BV, n.d.) less energy. The BIPVT modules in the facade serve as a complement to the energy that the PVT system on the roof cannot produce.

2.5.2 Integration requirements and reference examples

In general, the envelope integration of PVT collectors requires attention to two different aspects: the aesthetical and the building-technical quality. Both aspects are discussed here, together with some reference examples taken from literature and practice.

Aesthetical quality

Yang & Athienitis (2016) mention that a BIPVT component replaces the exterior elements of a building, such as traditional roof tiles or common cladding materials. BIPVT needs to be taken early in consideration in the building design in order to achieve the most expedient results. When it comes to the aesthetical quality of a PVT building-integration, the following criteria should be taken into account:

- it is architecturally satisfying to integrate PVT in a natural way into a building;
- the composition between materials, colours and dimensions has to be proper;
- it has to match with the concept and face of the building;
- the integration has to be thoughtful and well-engineered (pp. 887, 888).

In case of a covered BIPVT module, the glass cover of the photovoltaic part determines the appearance. Not only colour is therefore important, but also the shape and composition of the glass. Casini (2016) reports about so-called spherical cells that can be integrated in the PV glazing. These cells are produced by the Sphelar-Power Corporation and are shown in figure 30. The difference with conventional silicon cells is that spherical cells are made of small spheres of 1 to 2 mm in diameter, which makes them able to absorb solar irradiation from multiple directions, thus being more effective. The cells are compatible with glass of any desired shape or size. The density of the cells can be adapted to suit the desired (architectonic) representation (pp. 343, 344).

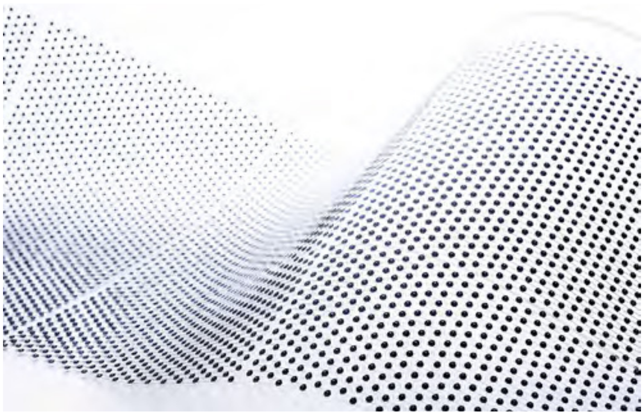


Figure 30. Spherical PV cells (courtesy of Sphelar-Power Corporation) (Casini, 2016, p. 344).

As spherical PV cells influence the shape and composition, there is another technique that can dictate the colour of the glazing, Casini (2016) points out. Semi-transparent PV films can be placed in-between two glass panes (for windows) or on the inner side of external PV glazing. The transparency of these semi-transparent films can be adjusted accordingly, though resulting in a lower efficiency when it gets more transparent. The efficiency of commercial thin film solar cells in general is about 10 to 16 percent (pp. 333, 334).

Casini (2016) continues by stating that a different development in the PV technology is that of the organic solar cells (OPVs) and dye-sensitised solar cells (DSSCs) (p. 336). Here, there has to be made a distinction between organic and inorganic PV cells. Helmenstine explains that in chemistry, the word ‘organic’ has a different meaning than in the food industry. An organic substance always contains carbon, while an inorganic compound mostly does not (2017). Silicon is an example of an inorganic substance. The difference of OPV with (traditional) inorganic cells like silicon is that OPV is photoactive, which means that its colour can be controlled depending on the type of light falling upon it, Casini (2016) mentions. Additionally, a DSSC is composed of both organic and inorganic materials, making it a hybrid solar cell. Just like organic photovoltaic cells, dye-sensitised ones are photoactive. However, the efficiency of both solar cell types are around 12%, but since they are much more user-friendly in terms of colour, shape and composition, they are highly appealing for it to be used as architectural elements (pp. 336-338, 340). Figure 31 shows an example of a DSSC facade.

Figure 31. A DSSC facade (courtesy of Solaronix SA) (Casini, 2016, p. 340).

OPV and DSSC cells can also be printed to a shape according to a self-chosen image file. At Aalto University in Helsinki, Finland, researchers are experimenting with photovoltaic ink that can be used for inkjet-printed solar cells. Photovoltaic ink converts a part of the solar irradiation to electricity and since darker colours absorbs the most solar energy, the most efficient solar cell would be black. Compared to conventional solar cells, the inkjet-printed ones show equal durability qualities (2016).

Another development in the world of photovoltaics are perovskite solar cells, journalist Bard van de Weijer of Dutch newspaper De Volkskrant knows. Perovskite can be laid on top of a layer of silicon, creating a so-called tandem cell. Lab tests show that the efficiency can go all the way up to 39%. A research team compared the efficiency outcomes of roof-added perovskite cells in the Dutch town of Utrecht and in Denver, USA. It turned out that the electrical yield of the solar cells in the Netherlands is quite disappointing, which is due to the cloudy weather conditions. Also, because the layer of perovskite performs negatively under these conditions, it badly influences the working of the silicon underneath it. According to the researchers, there has to be more research into perovskite. Nonetheless, an efficiency improvement of 4% seems achievable (2017).

Building-technical quality

Regarding the building-technical aspects, Yin, Yang, Kelly & Garant (2013) list a number of requirements that have to be borne in mind when applying building-integrated PVT. One has to think of:

- mechanical strength: the PVT modules need to be able to deal with external factors like wind, rain and snow;

- thermal efficiency: much of the heat gain in the summer has to be on account of the collectors;

- vapour barrier: the water-permeability of the PVT construction has to be taken good care of. It is not desirable that water slips through the seals of adjacent modules or envelope elements (p. 189);

• thermal resistance and structural integrity are additional aspects that are important. The substrate of a usual PVT collector is insulation. If multiple collectors are integrated in a building, the insulation layers need to be mutually installed in a proper way. On top of that, an integration with the structure of the building is also a possibility. Additional calculations should substantiate the practical feasibility of combining a PVT module with the building structure.

Various researches show different kinds of substrates where the PVT collector can be attached on. In their research, Yin et al. (2013) developed a BIPVT system that consists of a glass-covered PV panel on top of a layer of so-called functionally graded material (FGM). In this context, FGM exists out of a top part with a high aluminium concentration and a bottom part of high-density polyethylene. Water tubes are embedded in the top part and, because of the thermal conductivity of the aluminium, incoming heat can be effectively given off to the tubes. The bottom part serves as an insulation layer. The researchers add that delamination, which can be a problem in the case of multi-layered materials, is avoided because of the application of FGM. The last part of the structure comprises of a structural substrate made of fire-treated plywood. The advantage of this BIPVT component is that it can easily be attached to rafters or purlins. Besides, a point of consideration are the connections between the components, which need to be sealed properly to prevent moisture transmission (pp. 187, 188). The BIPVT composition is depicted in figure 32.

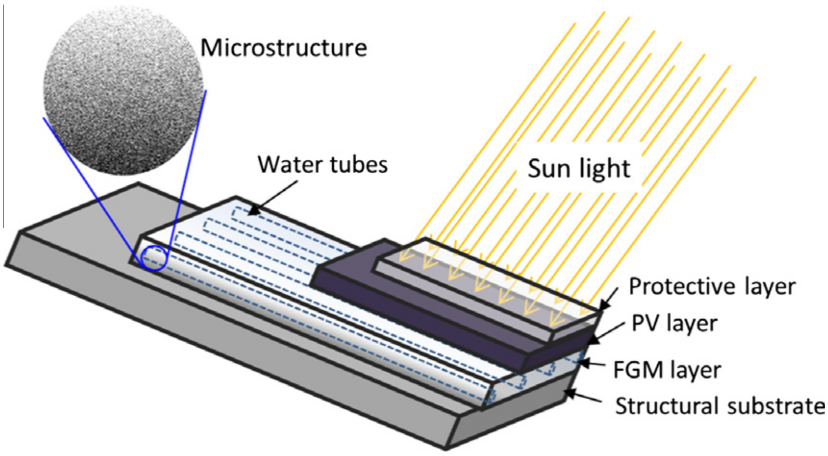


Figure 32. Illustration of the BIPVT system (Yin et al., 2013, p. 185).

Buker, Mempouo & Riffat (2014) studied a BIPVT roof collector with polyethylene heat exchangers on a roof in Nottingham, United Kingdom (see figure 33). The covered solar cells are attached to a plastic layer, which is in turn placed on top of the heat exchangers. The whole package is mounted on a steel roof support (p. 166).

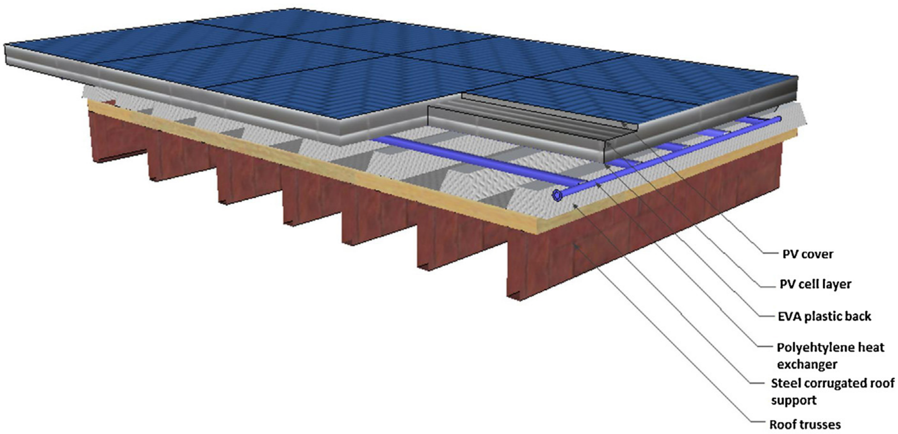


Figure 33. Cross-section of some BIPVT components (Buker et al., 2014, p. 166).

Not only the roof can be used for integrating a PVT module, as Athienitis, Bambara, O'Neill & Faille (2011) show. They looked at a so-called unglazed transpired collector, which is basically a corrugated and/or perforated facade made out of a dark porous cladding to attract outdoor air that is heated by the sun. This air is subsequently drawn into the building. The researchers investigated the effect of combining this transpired collector with BIPVT on an insulated facade of an office building in Montreal, Canada. It turned out that the thermal efficiency of an unglazed transpired module is higher than the combined thermal and electrical efficiency of BIPVT, but since electricity is generated by the solar cells, the thermal efficiency of a BIPVT system is higher in the end (pp. 139, 151, 152). The scheme is displayed in figure 34.

Despite the fact that this research was performed with PVT-air modules, it could also be done with liquid-based collectors. In that case, it has to be taken into account that slightly more pumping energy is needed for the water due to the vertical positioning of the flow pattern. Moreover, the overall harvested energy is expected to be lower compared to a roof-integrated system, because of a different altitude and angle.

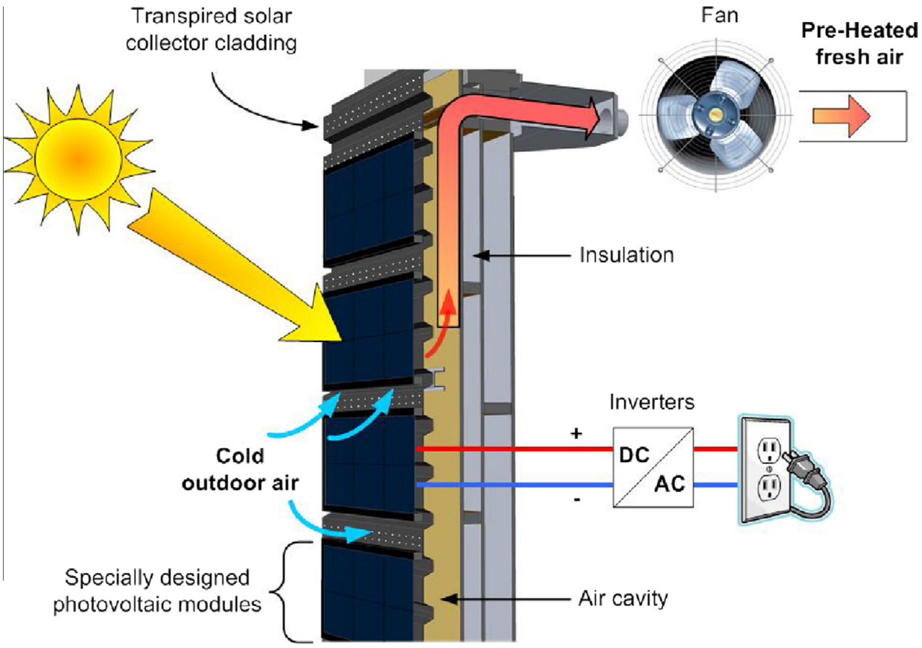


Figure 34. Illustration of an air-based facade-integrated PVT system (Athienitis et al., 2011, p. 142).

In their brochure about solar thermal roofs, Agentschap NL (2012) mentions various producers of such roofs. In general, the composition of a solar thermal roof comes down to the application of dark-coloured roofing to absorb sunlight on top of a layer of insulation material. This layer contains a pipe system which is applied in or on the top part of the insulation in order to collect the heat that is conducted by the roofing. This system is most of the time used for flat roofs. For sloped roofs, there are systems available where the roofing, the pipes and the insulation are integrated in one 'sandwich-element' (pp. 3, 4). The Dutch company Triple Solar developed this sandwich-roof, which consists of an aluminium roof covering. Depending on the thickness of the element, it can span a length of 6 meters (Triple Solar B.V., 2017). Figure 35 shows the element.

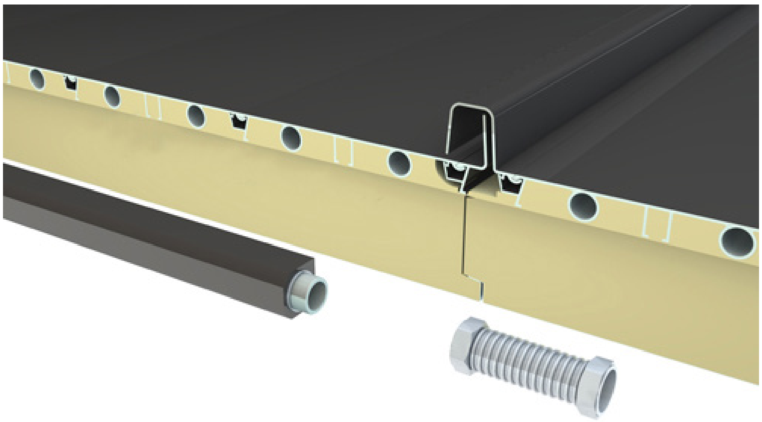


Figure 35. Section of the sandwich-roof (Triple Solar B.V., 2017).

Before installing a solar thermal roof, Agentschap NL (2012) explains, it is important to ensure that the roof construction is suitable for it, as the weight of a solar thermal roof can vary between 4 to 25 kg/m^2. Besides, it has to be noted that solar thermal roofs only produce hot water and no electricity. Also, they are uncovered and directly exposed to the outside, which results in low-value output temperatures of around 25°C (pp. 3, 8). In the light of this research, a solar thermal roof can be considered as an uncovered building-integrated solar thermal collector.

These collectors are also produced by the company Energydak and can be both applied on flat as well as sloped roofs (Energydak BV, 2015). The construction of this 'Energydak' (energy roof) exists of polypropylene lamella panels, which are installed in-between an insulation layer, directly underneath the roofing. The whole package rests on the structural part of the roof, with a damp-proof membrane in-between (p. 2). The difference with the design of Triple Solar is that the Energydak does not have its piping surrounded by the insulation material of the roof, but is located within the polypropylene modules. The downside of this is that more heat can get lost through the roof, since the R-value of the relatively thin polypropylene is lower than that of the thicker roof insulation material (Omgevingsvergunning.com, n.d.). This can also be an advantage, because more heat can be absorbed through the roof covering. Also a benefit of this polypropylene box is that it is more easily detachable from the roof construction, rather than the insulation-embedded pipes of the Triple Solar sandwich-roof. The Energydak is depicted in figure 36.

Another company has developed a similar solar thermal roof like Energydak, though the pipes are a little bit smaller in diameter. Solar Tech International (n.d.a) claim that their 'Energiedak' can also be upgraded with amorphous PV covering, making it a BIPVT system (p. 5). This 'Energiedak-Plus' is shown in figure 37.

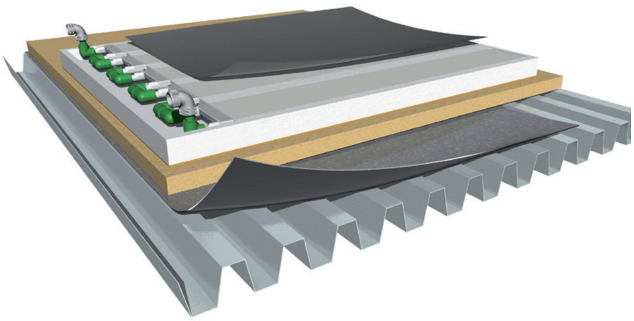


Figure 36. Section of the Energydak (Energydak BV, 2015, p. 2).

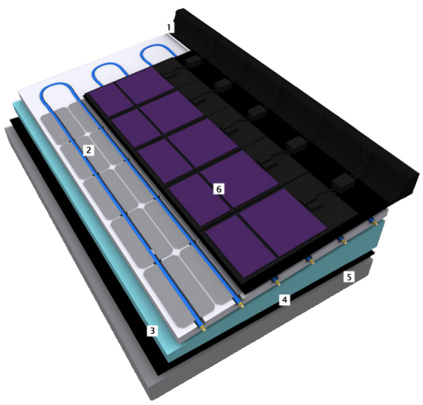


Figure 37. Section of the Energiedak (Solar Tech International, n.d.b).

2.5.3 Facade typologies

Dutch facades can consist out of many different kinds of materials. Common structural materials are masonry, sand-lime stone, (reinforced) concrete, timber-frame and steel. Facade cladding can for example be made of wood, aluminium and natural stone. The design freedom does not only get influenced by the type of material, but also by the standardisation of materials, window or curtain wall sizes, reveals, the insulation shell and the air- and water-tightness of the facade.

In chapter 7, this integration is further elaborated with facade views and facade details. This sub-paragraph numbers several facade compositions in which PVT can possibly be integrated in. It has to be kept in mind that the outer leaf or the cladding of the facade is replaced by PVT elements in case of an integration. This means on the one hand that the inner leaf or inner constructional part of the facade is an important factor that can determine how the PVT parts can be mounted. The outside of the original facade can be a guideline for the distance between the PVT elements and the inner construction, but in case the original facade is partially retained, mutual connections also become relevant. The facade typologies that are chosen, are the following:

- a traditional cavity wall;
- aluminium cladding;
- a curtain wall.

2.5.4 Conclusion

The integration of a PVT module in a facade asks to take a closer look at various aesthetical and building-technological aspects. For example, by using organic or dye-sensitised solar cells, one can influence the colour of the cells. It could even be possible to create your own image on the solar cells by using the inkjet printing technique. When it comes to the technical qualities of building-integrated photovoltaic thermal elements - as the collector replaces the traditional outer construction materials of a building envelope - careful attention has to be given to the structural integration, the mutual sealing between different modules and envelope elements, a proper integration with the building insulation and an adequate damp-proofing. Various producers have brought (some of these) technical qualities into practice by developing building-integrated solar thermal roofs, where solar energy can be utilised to make hot water. Besides that, it is also interesting to take a look at the integration possibilities of various facade typologies.

2.6 Renewable energy systems in practice

In addition to the previous oversight of PVT, BIPVT and other renewable climate systems, it is interesting to find out the effectiveness of (some of) these systems in practice. This paragraph therefore explains a reference example/case study that shows the effect of implementing them.

2.6.1 Introduction

The application of PVT collectors is, for example, dependent on the (available) area of the roof, so the effectiveness of these collectors relates to the building or buildings on - or in - which it is applied. This is also the case for low-temperature heating, high-temperature cooling, domestic hot water and electricity: how does the use of these systems - in both a collective and/or an individual way - influence their effectivity? In the next sub-paragraph, the application on district level will be analysed on the basis of an example reference project in the Amsterdam neighbourhood of Buiksloterham.

2.6.2 Case study description

The neighbourhood of Buiksloterham is located in the northern part of Amsterdam. In their study on the energy transition of Buiksloterham, Jansen et al. (2016) researched the suitability of three different energy facilities which can be applied for both living and working (p. 5):

- natural gas and electricity;
- all-electric;
- district heating.

The first variant is of a traditional nature: the heating is provided with high-efficiency boilers and the electricity can be obtained from the grid. The rest of the electricity use is compensated by using photovoltaic panels and small wind turbines on the roof. Cooling is realised with air-conditioning. The result is that for more than two-thirds, the total electricity demand can possibly be covered by renewable energy sources (with a most optimal use of the roof area). However, only 4% of the gas demand can be covered with biodegradable waste and black water. This means that for 96%, gas cannot be obtained locally (Jansen et al., 2016, pp. 43, 44)

The second, all-electric version consists of a heat pump connected to a heat and cold storage which can both provide heating and cooling. The electricity - including the electricity for the heat pump - is generated by PV panels and PVT collectors; the remaining demand is given by the electricity company. The PVT collectors can also be used to regenerate the heat and cold storage in case the storage becomes unbalanced. This second solution - obviously - has a better assessment than the first one. The electricity demand can be covered for more than 50% by PV(T), though there should be noted that this number gives a somewhat distorted view: because only electricity will be used, the coverage is lower. For both the first and the second variant, net metering is assumed and no storage of electricity. This means that people will sell back a lot of electricity in the summer (Jansen et al., 2016, pp. 48-50).

The third option that was proposed, is based on space heating and domestic hot water provided by district heating. Electricity will be generated by PV panels and small wind turbines; de rest comes from the grid. In addition to the previous variants, this variant also looked at the contribution of residual waste to the total supply of heat and electricity. This third solution is characterised by heat losses because of the district heating. The effect of the electricity generation is the same as for the first option. Finally, the contribution of the residual waste is very little. This solution is, however, preferred by the local authorities since it ties with the current policy (Jansen et al., 2016, pp. 54, 55, 58)

The final energy use of the previous described situations (as well that of the current situation) is displayed in figure 38. From this figure it can be understood that an all-electric energy facility results in the lowest final energy use. However, it turned out that there could be made some improvements. These improvements show that:

- regarding the local heat generation, low-value heat of 15-25°C is sufficiently available. High-temperature heat generation influences the electricity production of a solar system in a negative way. Additionally, calculations show that it is the most promising to use PVT collectors together with a heat pump and heat and cold storage, since these collectors generate the most energy per m^2. The downside is that there is a lack of electricity in the wintertime, but this can be compensated for by high-temperature heat storage;

- the limited roof area in the neighbourhood limits the electricity generation. Possible fallow land could be used for placing more PV(T). The stability of the electricity grid has to be maintained, however;

- the mismatch between supply and demand calls for flexible energy storage possibilities. Electricity storage currently is in the pipeline, so (researches on) seasonal thermal energy storage is the order of the day;

- so-called smart grids have a great deal of potential, since they monitor the behaviour and actions of all connected users and respond to that. Besides, many applications, techniques and systems work with direct current, while the grid still uses alternating current, causing two times the need of a converter (Jansen et al., 2016, pp. 67, 68).

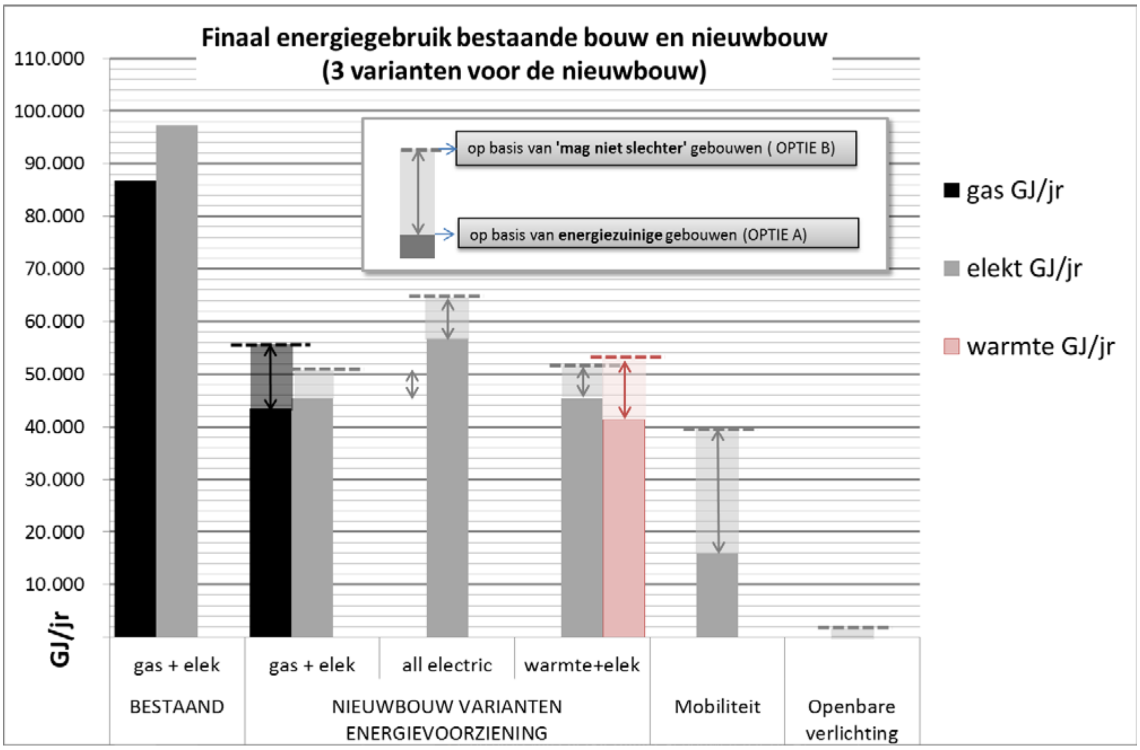


Figure 38. Final energy use for the existing and new building stock (Jansen et al., 2016, p. 38).

Based on these improvements, a fourth alternative has been proposed, which comprises of the following ideas:

- a mini heat grid with temperatures between 40°C and 50°C. This grid provides both space heating and domestic hot water in the winter.

- a collective heat pump that upgrades low-value heat from the PVT collectors and residual heat of the sewage system;

- both heat storage for low-temperature heat and for slightly higher temperatures (45-50°C). The heat pump provides heat for the higher temperature storage.

- multiple possibilities for domestic hot water;

- a mini cold grid for cooling, which is supplied by the heat and cold storage.

It can be expected that the heat pump in this situation operates more efficiently than the one in the all-electric situation. The benefits of the flexible set-up of the collective heat pump in combination with the heat and cold storage are the relative little temperature transitions and the optimal switching between various sources. Moreover, in case of a high electricity supply by the PVT collectors, the heat pump can be activated to generate high temperatures which can subsequently be stored in the underground storage. Furthermore, the heating temperatures of 40-50°C are directly useful for space heating. There are foreign examples of domestic hot water systems at these temperatures, but this has to be researched further for application possibilities in the Netherlands.

The alternative option is shown in figure 39. The ideas are still subject to research (Jansen et al., 2016, pp. 67-70).

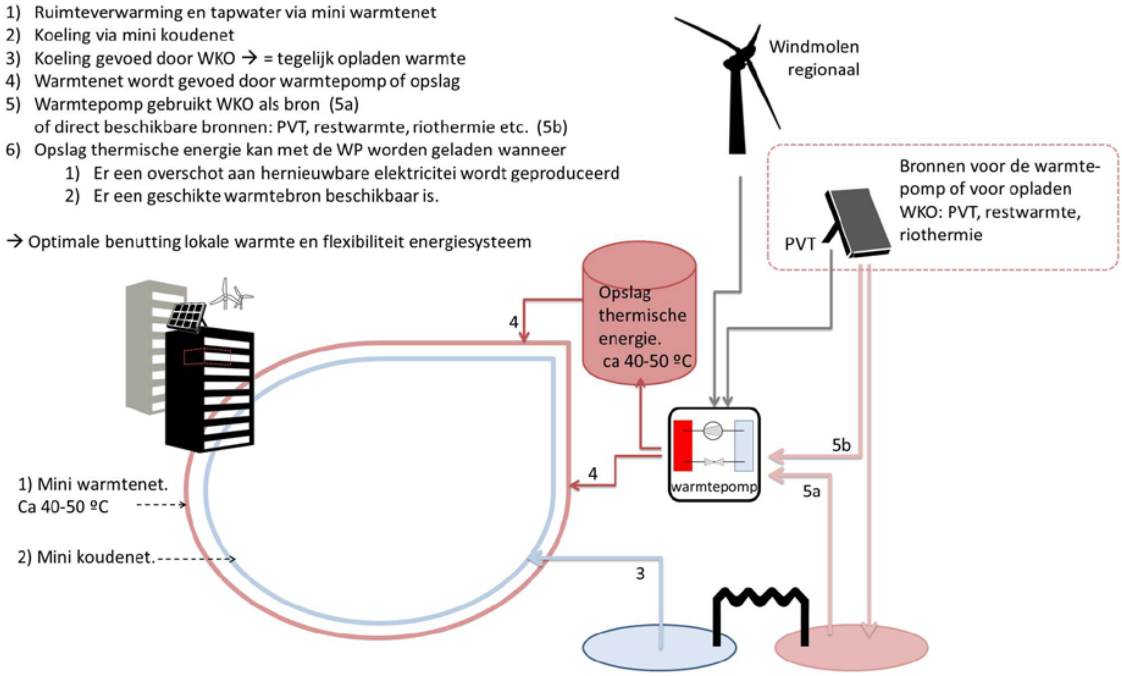


Figure 39. A schematic representation of the fourth alternative (Jansen et al., 2016, p. 69).

The research by Jansen et al. (2016) clearly points out that a collective energy system with PVT collectors, a heat pump and heat and cold storage is theoretically the most attractive on a district level (p. 70). This encourages a research on building scale. The further development of this research will partially be based on the application possibilities of a multi-family apartment building. Partially, because there is also an opportunity to look into the integration of PVT in such a multi-family building.

2.7 Technical requirements of residential buildings

This penultimate paragraph gives an explanation of the insulation requirements and energy types of a residential building.

2.7.1 Insulation requirements of residential buildings

The insulation requirements of new Dutch buildings are established in the Bouwbesluit (the Dutch building code). The insulation value of almost all parts of a building is expressed in a thermal resistance value or R-value. For the performances of windows and doors, however, the thermal transmittance value or U-value is mostly used. The R-value is expressed in m^2K/W and the U-value in W/m^2K, making the U-value the reciprocal of the R-value. The energy performance coefficient (EPC) is an overall indication of the energetic quality of a building.

According to the Dutch government gazette *Stb.* 2014, 245, the most recent R-value criteria date back from 2015. There is made a distinction between the R-values for floors, facades and roofs:

- for floors: R=3.5 m^2K/W
- for facades: R=4.5 m^2K/W
- for roofs: R=6.0 m^2K/W

For the U-value, there is not a specific value that every window or door needs to achieve; the mean U-value per building needs to be 1.65 W/m^2K for all windows and doors, with an upper limit of 2.2 W/m^2K. Besides that, Agentschap NL (2013) knows that the EPC value is currently set to 0.4 and is expected to decrease further to 0.16 (p. 27) and finally to 0.

There are three different ways of losing the energy from inside a building to the outside: by transmission, by infiltration and by ventilation. Transmission losses generally occur through the building skin, while small gaps and cracks - like window sealings - cause infiltration losses. Ventilation losses speak for themselves. Accompanying regulations will not be further treated.

2.7.2 Energy use of residential buildings
Yanovshtchinsky et al. (2012) mention three energy types of a building:

- the building-related energy or BRE: the energy needed to climatise the building, that is, energy for heating, cooling, lighting and ventilation. The orientation of the building, glass surfaces, room volumes, building-physical properties, etc., affect the BRE;

- user-related energy or URE: this is the energy used for devices and lighting, such as the power supply of a washing machine or plugging in the charger of a mobile phone;

- material-related energy or MRE: the energy that is consumed to produce the materials that are needed to construct the building (p. 49).

It has to be mentioned that this research primarily focuses on the BRE and the URE, because the implementation of PVT collectors together with a distribution system practically only concerns those two energy types. The MRE, however, needs to be taken into account for all materials added or integrated in a building, but this issue goes beyond the limits of this research and will therefore be neglected.

Building-related energy (BRE)
As mentioned, the BRE is about heating, cooling, lighting and ventilation. The BRE can be subdivided in different uses:

- low-temperature heating;
- high-temperature cooling;
- domestic hot water;
- ventilation;
- power supply for boilers, heat pumps and other pumps.

To get an idea of the average energy requirements for the above-mentioned BRE types, some examples are shown. The heat output of a low-temperature floor heating system lies between 50 and 100 W/m^2, Yanovshtchinsky et al. (2012) for instance mention. For high-temperature floor cooling, this value is about 5 to 10 W/m^2 (p. 129).

For domestic hot water, the heat demand is taken into account. The heat demand depends on the activity where the hot water is used for. The energy needed can be calculated with the following formula:

$$Q = mc_w \Delta T \ [MJ] \tag{4}$$

Here, *m* represents the mass of a substance in kg, c_w is the specific heat of water (4,200 J/kg K) and ΔT is the bridgeable temperature difference. Imagine one wants to take a shower and uses 100L of water with a temperature of 35°C. The temperature of the mains water is 10°C (Vitens N.V., 2015). The amount of energy required is then:

$$100 \times 4{,}200 \times (35 - 10) = 10.5 \ MJ \ \triangleq 2.9 \ kWh$$

The power supply for all the electronic equipment that make heating, cooling, lighting and ventilation possible is - of course - dependent on the usage of the equipment. The power of a heat pump varies between 4 kW up to more than 400 kW (Yanovshtchinsky et al. 2012, p. 109). This powered should be tailored to the energy demand.

User-related energy (URE)
For the URE there can be distinguished:

- cooking;
- room illumination;
- power supply for television, laptop, mobile phone, washing machine, etc.

For cooking, there can be made a distinction between gas-fired and electrical cooking. According to Milieu Centraal, gas-fired cooking results in a mean annual energy use of 37 m^3 of natural gas, where electrical cooking asks between 175 and 225 kWh per year, depending on the type of device (2017). Gas-fired cooking costs up to the equivalent of 1.3 GJ. Electrical cooking asks only between 0.63 to 0.81 GJ per year.

Milieu Centraal also knows the average annual energy use of room illumination, which is about 490 kWh annually (2016). The power consumption of other applications and devices - just as is the case with lighting - is strongly dependent on the type and the use of it. For example, a dish-washing machine consumes 230 kWh and a tumble-dryer uses 315 kWh (Milieu Centraal, 2016).

2.8 Conclusion

In the beginning of this chapter, the Dutch government's view on the energy transition was discussed. Various renewable systems and technologies that can be applied to complete this energy transition have been presented afterwards. A main element within these systems and technologies are photovoltaic thermal (PVT) collectors, which have the ability to convert solar irradiation into electricity and hot water. This energy can subsequently be used for domestic purposes, which requires a system configuration consisting of various technologies that make energy distribution, energy use, energy re-use and energy storage possible.

PVT collectors come in different configuration types, of which the liquid-based one is deemed as the most effective one. Moreover, it can be implemented as a building-addition (BAPVT) or a building-integration (BIPVT). Integrating PVT in a building asks for various requirements, both in an aesthetical as a building-technical way.

Finally, to get an idea of renewable energy in practice, a case study was described in this chapter together with an explanation of the energy use of residential buildings. In the next chapter, an own and main case study for this research is presented.

3. CASE STUDY

Before a start can be made with the analysis and optimisation of the PVT system configuration, a reference case is developed to which this system can be applied on. This chapter will therefore introduce a multi-family apartment building, together with the associated system configuration. The apartment building concerned is Docklands, a residence block that was completed in 2015. Some energy data of Docklands will be given, together with practical information. When all the relevant data is known, the calculation program ENORM will be used to determine the final energy use of Docklands. The final part of this chapter consists of discussing the results ENORM provides.

3.1 Case study description

Docklands is located at the Ridderspoorweg in Buiksloterham, a neighbourhood located in the northern part of Amsterdam. Building properties and technical drawings are going to be used to gain an accurate picture of the final energy use of Docklands. This information is provided by Marcel Lok of architectural office Marcel Lok_Architect. A picture of Docklands is shown in figure 40. Also, two floor plans - the ground floor and the second floor - are depicted in figures 41 and 42:

Figure 40. Bird's-eye view on Docklands (Vink Bouw, n.d.).

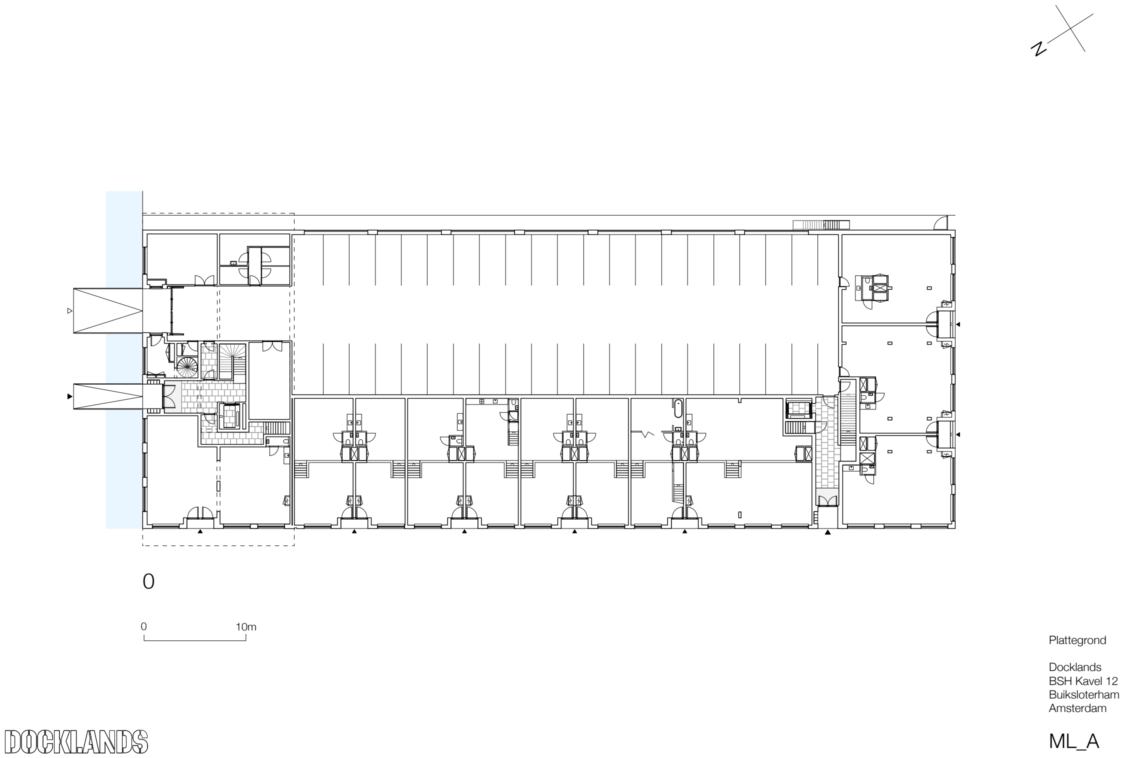


Figure 41. Ground floor plan of Docklands
(Marcel_Lok Architect, personal communication, n.d.).

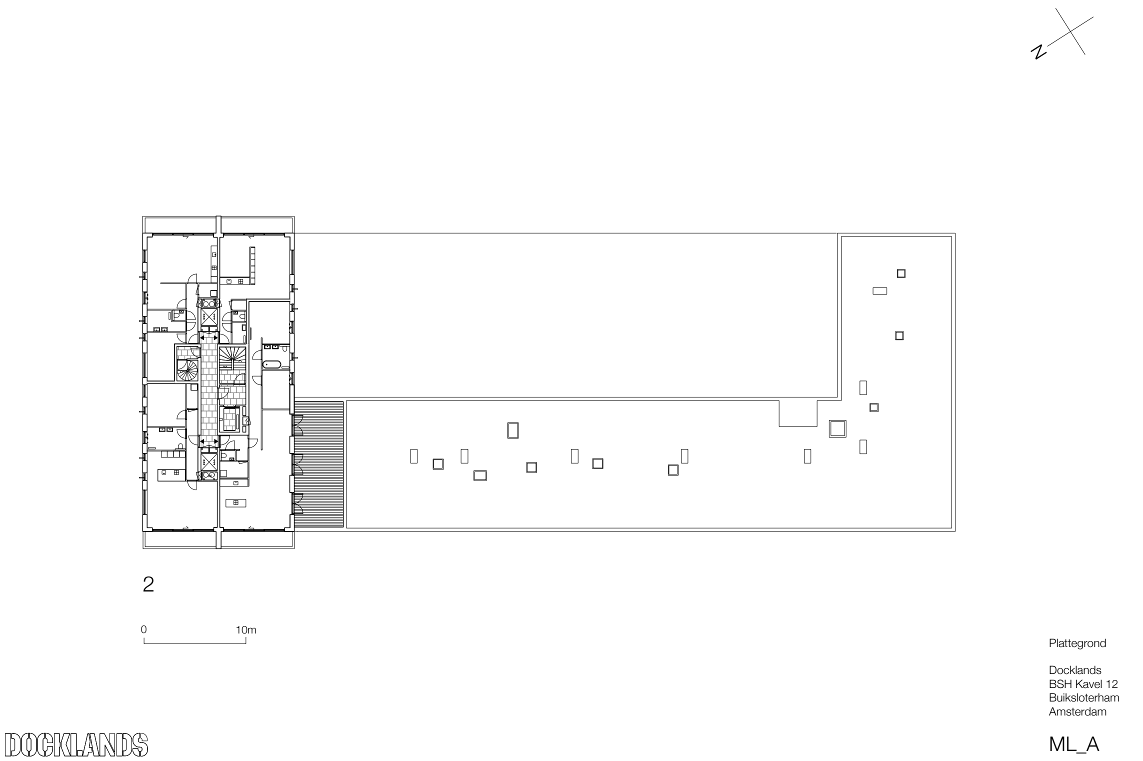


Figure 42. Second floor plan of Docklands
(Marcel_Lok Architect, personal communication, n.d.).

First, an overview of the building properties:

- Docklands has 44 three-room, owner-occupied apartments. The total useful area varies from 53 up to 125 m^2 with balcony or private rooftop garden. Also, there are 13 working units on the ground floor;

- the building has nine storeys, without counting basements;

- Docklands has an EPC of 0.24;

- the R-value of the closed facade sections, the floors above the unheated rooms and the roof are successively: 5.0; 5.0 and 6.0 m^2K/W;

- the used energy sources are heat pumps, solar thermal collectors (with solar boilers), photovoltaic panels and domestic hot water systems;

- Nieuwbouw Amsterdam adds that the building also uses underground energy storage (2017);

- Docklands uses low-temperature heating with a maximum supply temperature of 55°C;

- the ventilation system is a collective, balanced ventilation;

- finally, Docklands has a collective roof or/with vegetable gardens.

3.2 Simulation of the energy demand

3.2.1 Selected software program
The previously-mentioned building properties, together with some technical drawings make it possible to import Docklands into the energy calculation program ENORM. This program is written in Dutch, but for the sake of clarity, the English terms are explained. Also, the 13 working units of Docklands are 'changed' to apartments, making the total number of apartments equal to 57. This is done to avoid problems related to the EPC calculation, since different regulations apply to working units. The importation is described step-by-step in the next sub-paragraph.

3.2.2 Input data
We start with the 'Schematisation' tab. In this tab, a climate zone has to be defined. Since all the apartments in the building are connected to each other, they are treated as one climate zone. The heating and cooling systems are low-temperature heat and high-temperature cooling, respectively. This is defined later on. The user function is residential, with a total area of 4,588.50 m^2. This value is derived from the drawings, but is not an exact value, since it is based on the drawing scale.

The next tab is 'Building Construction'. There is a possibility to create a construction type - a floor, wall or roof - in the first sub-tab, but since only the thermal resistance values are known, these values are being used instead. The building is considered as one big box, with one floor, four facades and one roof. Obviously there are intermediate floors, but they are already included in the total floor area. Anyway, the area of the ground floor is 999.30 m^2, and is located above ground level and on top of a crawl-space. Additional numbers are based on the R-values and information from the (cross-section) drawings. The roof has the same area as the ground floor. The facades of Docklands are faced north-east, south-east, south-west and north-west. Their specifications are:

- north-east: total area of 960.09 m^2; window area: 258.96 m^2;
- south-east: total area of 1357.40 m^2; window area: 317.86 m^2;
- south-west: total area of 960.09 m^2; window/door area: 271.34 m^2;
- north-west: total area of 1357.40 m^2; window/door area: 432.38 m^2.

The U-value of the windows is the cumulated value of the window frame and the window itself, and is set to 1.50 W/m^{2}K. The g-value is 0.60. Finally, the building is a traditional, relatively heavy construction with a standard facade.

The 'Installations' tab offers options to fill in data for low-temperature heat, domestic hot water, high temperature cooling and ventilation. It is important to mention that many installation data is not known and is therefore considered 'fixed'. The low-temperature heat is a heat pump-based individual heating system with individual control. The heat pump source is groundwater, with a supply temperature of ≤ 30°C. The COP of the heat pump is 5.4. Furthermore, the hot water is heated by the solar collectors and additionally by an electrical heating device. The COP of this process is 2.3, because the output temperature is higher than in the case of low-temperature heat. Next, the high-temperature cooling is defined. This system uses the cold bubble of the underground energy storage to create floor cooling. The COP is 10. The last part is about the ventilation, which is a collective, balanced system with waste heat recovery and a yield of 95%.

For the 'Renewable Energy' tab, the data of the PV panels and solar thermal collectors are imported. Their areas are based on figure 40. For the photovoltaic panels this is approximately 213 m^2; the solar thermal collectors have an area of circa 72 m^2.

3.2.3 Results

The total annual energy demand of Docklands is displayed in two types:

- the primary energy E_P, which is the gross energy demand of the building. This value is 1,026 GJ;

- the reduced primary energy $E_{P;\,red}$, which stands for the gross energy demand minus the building-related and non-building-related electricity production, is 788 GJ;

The final energy use is E_F.This value is 401 GJ and is sub-divided in low-temperature heat (LTH), domestic hot water (DHW), high-temperature cooling (HTC), ventilation and lighting:

- LTH consumes 138 GJ;
- DHW requires 36 GJ;
- HTC demands 24 GJ;
- ventilation requires 120 GJ;
- lighting asks 83 GJ.

Figure 43 shows a pie-chart of the final energy use:

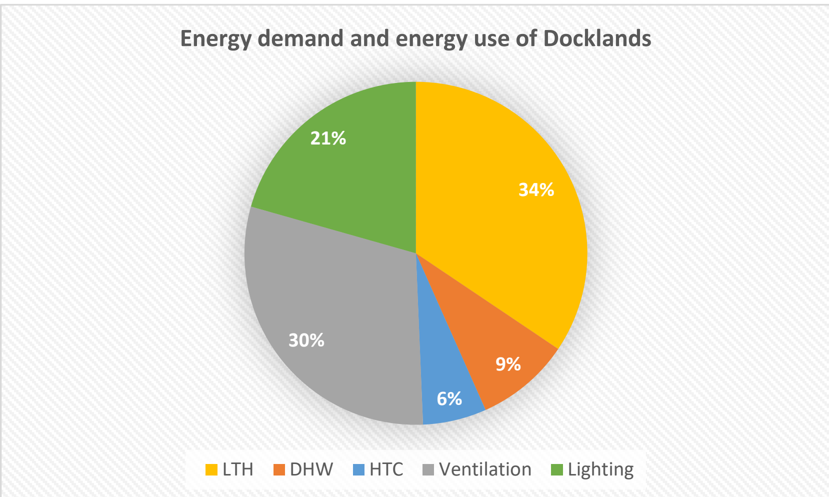


Figure 43. Total annual energy use of Docklands (own illustration).

It is important to stipulate the difference between the (primary) energy demand and the (final) energy use. The energy demand is a value that is needed to keep the whole system up and running. The energy use is a value that appears on the bill of the occupant. The relatively large difference between both values is mostly accountable to the heat pump, since this device is a significant energy-saver.

ENORM also knows the demand Q_{nd} (heat demand according to NEN 7120) of the space heating, cooling and hot water that Docklands consumes per month. This is very important to compare to the energy output of the PVT system. The yield of those collectors is presented in the next chapter, but an overview of the monthly energy needed for heating and cooling is presented here. Figure 44 gives an illustration of that:

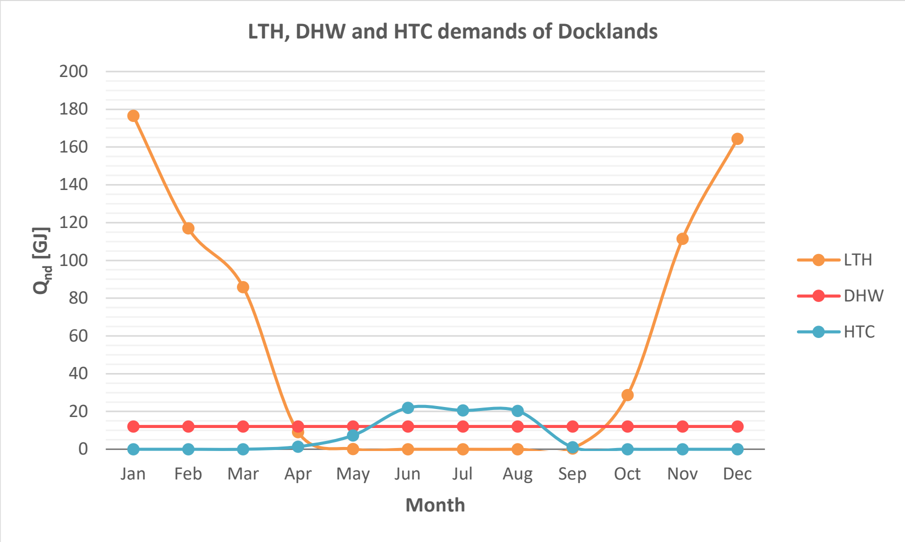


Figure 44. Heating and cooling demand of Docklands (own illustration).

In addition to this, the ventilation and lighting also ask electricity, though this is - as with the domestic hot water - approximately a straight line. Moreover, according tot NEN 7120, there is no energy demand known for the energy performance of ventilation and lighting. That is why for these two provisions, the electricity use $E_{EPus; el}$ is considered. Figure 45 shows this:

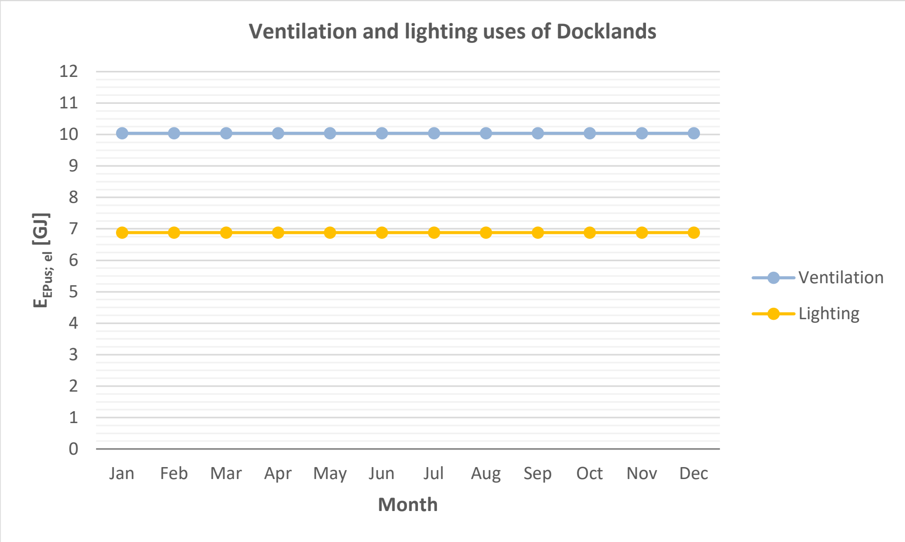


Figure 45. Ventilation and lighting demand of Docklands (own illustration).

The total energy requirements are given in figure 46. With 1,115 GJ, this number slightly differs from the primary energy because of the energy uses for ventilation and lighting.

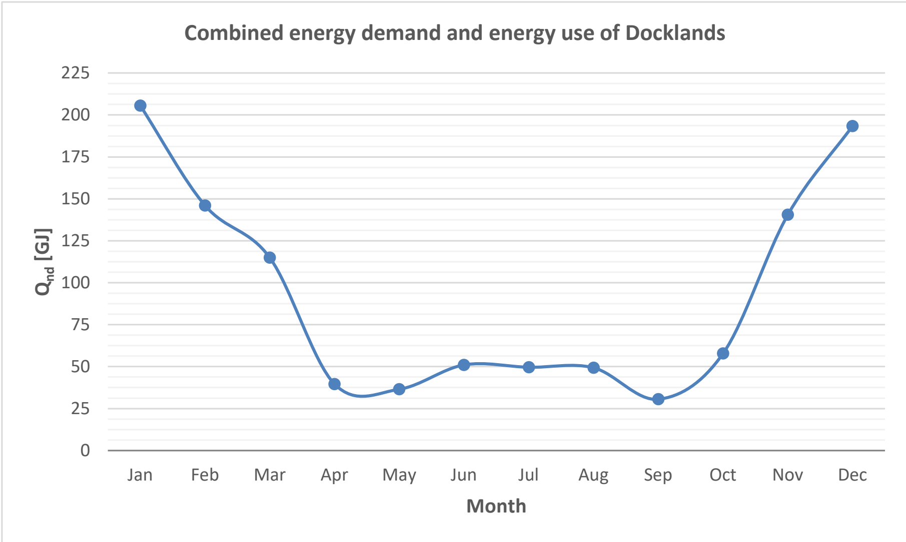


Figure 46. Total energy requirements of Docklands (own illustration).

Currently, ENORM gives an EPC of 0.37. This value is different from the original value, since not exactly all input information is known. Only some of that information is provided by architect Marcel Lok. However, one of the goals of this research is not to recreate an exact copy of Docklands in ENORM. The challenge rather lies in finding a way how the implementation of the PVT collectors can be elaborated, in such a way, that it can meet the demands of Docklands in a most effective way, taking into account how it affects the EPC. This means that the amount of available m^2 of the building envelope must be determined. For the roof, this space will be based on the current photovoltaic panels and solar thermal collectors that are placed there, for they are to be replaced by PVT collectors. For the facades of the building, only the south-east and south-west facades are considered, since they are the most profitable when it comes to the energy output. Basically all required and available space of the facades will be swapped with facade-integrated PVT modules, with the exception of the doors and windows.

From the photograph in figure 40, an estimate can be made of the total area of the amount of photovoltaic panels and solar thermal collectors. This value is approximately 285 m^2, though it can differ from the reality. The facade space that is theoretically available on the south-east and south-west parts is circa 1728 m^2, derived from the technical drawings.

However, it is not only relevant to know what the PVT collectors can do, but also how these elements interact with the rest of the system configuration, most notable the energy storage. An excess of generated energy can be stored in here, but it is not sensible to produce too much energy. This means that an energy balance is essential.

3.3 Conclusion

This chapter introduced the multi-family residence building that will be used as a case study in this research. Furthermore, the energy demand and energy use was simulated.

The next chapter will treat the development of the three different PVT outputs and their accompanying calculations.

4. DEVELOPMENT OF PVT TYPES AND OUTPUT CALCULATIONS

As shown in chapter 2, a photovoltaic thermal collector is an ideal way of making use of the sun as a natural resource. One of the most important aspects for the building-application of a PVT collector is to design it in such a way that it can absorb a significant amount of energy in order to cover most of the total demand of the multi-family building. This chapter will show several configuration types, substantiated by calculations.

4.1 Introduction

The first paragraph of this chapter treats the theory and formulas related to the different output possibilities of three PVT collector types. Three different outputs are distinguished: thermal energy output, temperature output and electricity output. After that, three collector types are presented and on the basis of the theory and formulas, the collector type that delivers the highest thermal output, is chosen. Finally, temperature and electricity calculations are performed for the chosen collector.

4.2 Theory and formulas

4.2.1 PVT thermal output

The thermal output of a PVT collector is comparable with that of solar thermal collectors, for the thermal insulation capacities of the solar cells are negligible. The output can be estimated by using the following (simplified) formulas, as given by Bokel (2016, pp. 16-19). In general, the energy output Q_{coll} of a PVT module can be known by determining the amount of energy that is provided by the sun - and absorbed by the collector (Q_{sun}), minus the energy that is lost through transmission (Q_{trans}):

$$Q_{coll} = Q_{sun} - Q_{trans}\ [W] \tag{5}$$

with:
Q_{coll} = thermal output of collector
Q_{sun} = energy provided by the sun and absorbed by the collector
Q_{trans} = energy that is lost through transmission

In formula (5), Q_{sun} is defined as follows:

$$Q_{sun} = Aatq_{sun}\ [W] \tag{6}$$

with:	A = absorber area of the collector	[m^2]
	a = absorption coefficient of the collector material	[-]
	t = transmission coefficient (if applicable) of the glass cover	[-]
	q_{sun} = solar irradiation	[W/m^2]

In formula (5), Q_{trans} is defined as follows:

$$Q_{trans} = \frac{T_m - T_e}{R_e} + \frac{T_m - T_i}{R_i}\ [W] \tag{7}$$

with:	T_m = mean inside water temperature	[°C]
	T_e = outside temperature	[°C]
	R_e = resistance to the outside	[m^{2}K/W]
	T_i = inside temperature (or underneath the collector)	[°C]
	R_i = resistance to the inside	[m^{2}K/W]

4.2.2 PVT temperature output
For a PVT element, the temperature difference *ΔT* between the input and output needs to be calculated. This is for example comparable to formula (4). The following formula will therefore be used to calculate the temperature output of a PVT collector:

$$\Delta T = \frac{Q_{coll}}{\dot{m}c_w} \text{ [°C]} \tag{8}$$

with: $\dot{m}$ = mass flow rate of the water [kg/s]
c_w = specific heat of the water [J/kg K]

4.2.3 PVT electrical output
The final output of a PVT collector is the electrical output of its photovoltaic part. According to Martins (2017, p. 174), the following formula is needed to calculate the electricity output *E* for a PV panel:

$$E = Arq_{sun}PR\ [kWh] \tag{9}$$

with: *A* = total area of the collector [m^2]
r = efficiency of the photovoltaic panel [-]
q_{sun} = solar irradiation [W/m^2]
PR = performance ratio [-]

The performance ratio causes an important difference between the electricity output of a photovoltaic panel and a PVT collector. According to Martins (2017), the performance ratio (or the coefficient for losses) ranges from 0.5 to 0.9, with a default value of 0.75 (p. 174). Because of the presence of an additional thermal part, the performance ratio of a PVT collector is higher than that of a photovoltaic panel - in case the temperature is low. However, there is not a fixed performance ratio for the PV part of a PVT element, for this depends on the temperature of the water. De Keizer et al. (2016) investigated the "performance analysis and yield assessment of several uncovered photovoltaic thermal collectors", which also includes the performance ratio of these PVT collectors. The correlation between the performance ratio and the water temperature resulted in the following graph (pp. 2649, 2651):

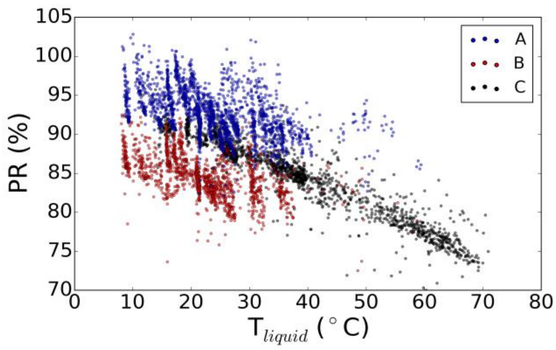


Figure 47. Performance ratios of various PVTs
(De Keizer et al., 2016, p. 2651).

However, certain reservations must be expressed, since the results in figure 47 are based on uncovered collectors. That means that the electrical efficiency in general is higher than a covered collector. Moreover, the graph of figure 47 shows that the performance ratio decreases when the temperature of the water gets higher, which makes sense, since the electrical efficiency goes down if the environment of the solar cells becomes too hot.

4.3 Calculation procedures

The thermal output Q_{coll} will be calculated for three collector types, where additional graphs are meant to clarify mutual differences. Both roof-mounted and facade-integrated collectors are treated. The thermal output is given in kilowatt hours per month. After this, the collector type which has overall the highest thermal output, will be chosen. The temperature and electricity outputs are then calculated. Sub-paragraphs 4.3.2 and 4.3.3 elaborate further on the calculation procedures regarding the collector properties and flow data. First, the temperature and solar irradiation data is treated.

4.3.1 Weather data

Moreover, as defined before, both roof-added and facade-integrated PVT collectors are applied on and in the multi-family building. The collectors on the roof are placed in a most optimal altitude and azimuth, respectively 35° and 180° (south); the facade-integrated elements are integrated under an angle of 90° in the facade, facing south-east (225°) or south-west (135°). The energy output for these two directions do not significantly differ much from the south, the solar irradiation diagram of figure 48 shows. However, for the calculations, only the solar irradiation values of the south-east orientation are used, to prevent erroneous values.

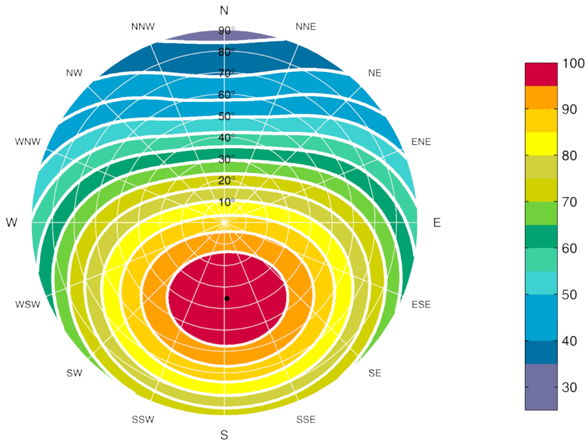


Figure 48. Irradiation diagram (Volta Solar BV, n.d.).

To get a clear picture of the weather conditions in the direct vicinity of the project location, hourly data from a TRNSYS TMY2 file of Amsterdam Airport Schiphol is consulted. This means that for every hour in one specific climate year, the outside temperatures together with solar irradiation values (per orientation) are presented. Thus, the PVT output is calculated for each hour. Using hourly data is much more effective than, for instance, daily or monthly data. This is because hourly data gives a more reliable and realistic representation of the weather data. Moreover, when the solar irradiation is zero, the PVT collector will be switched off to prevent losses. The calculations are performed in Microsoft Excel. This file is available as an addition to this research.

Figure 49 shows the outside temperatures per month of the climate year. Figure 50 illustrates the solar irradiation for 35°/south and 90°/south-east:

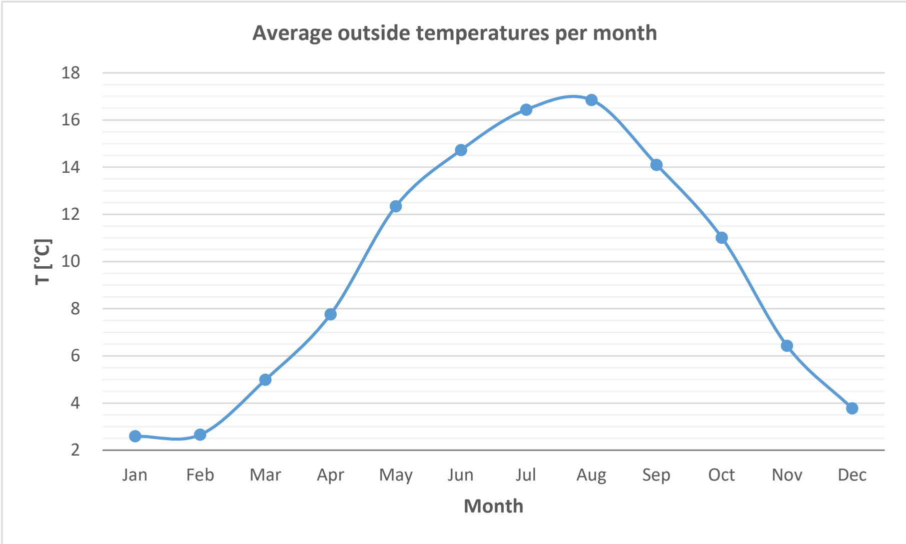


Figure 49. Temperature data per month (for the TMY2 year) (own illustration).

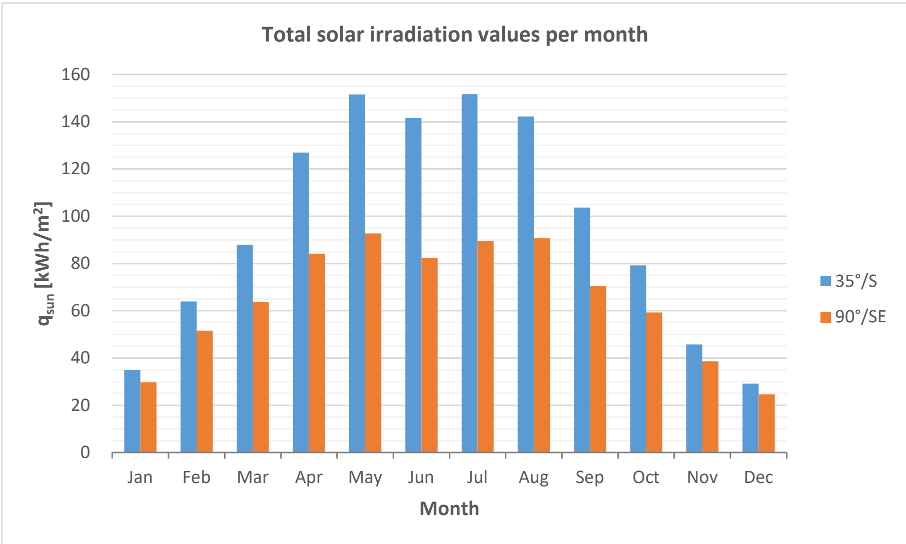


Figure 50. Solar irradiation data per month (for the TMY2 year) (own illustration).

Finally, the inside temperature T_i is practically always similar to the outside temperature, except for facade-integrated. In this case, it is equal to the local, internal temperature of the facade. It may be clear that T_i both depends on the outside temperature, the water temperature inside the collectors and the inside temperature of the building. To make it not too complicated, T_i is set to 20°C in this case

4.3.2 PVT types and data

In sub-paragraph 2.3.3, it was stated that the addition of a glass cover on top of a PVT collector shows a significant improvement when it comes to the thermal energy output. This will be proven by calculating this. The types are chosen on the basis of two kinds of insulation that can be applied: a glass cover on top or polymeric insulation underneath the actual PVT module. The three types are illustrated in figure 51:

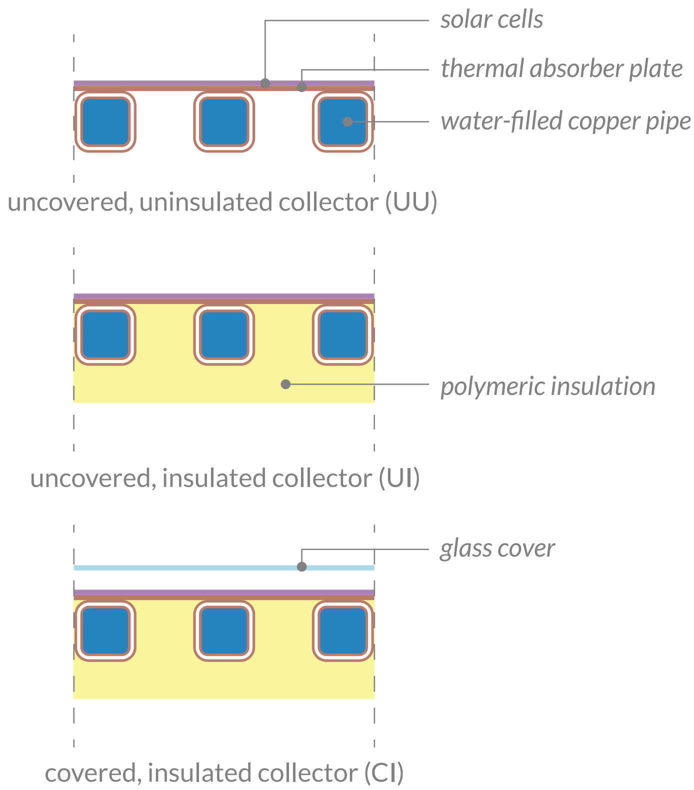


Figure 51. The three collector types (own illustration).

The PVT collector used for the calculation input data in this report is based on a collector by the Italian company Brandoni Solare. There are various module numbers available, ranging from SBP-230 to SBP-255. The higher these numbers, the better the electric performance of the collector is and therefore, SBP-255 is chosen. It has to be clear that these numbers do not affect the thermal properties of the collector. The collector has various properties.

The absorber area *A* is 1.44 m^2 (Brandoni Solare S.p.A., n.d.).

Its absorption coefficient *a* is 0.9. For the absorption coefficient of a random solar thermal module, literature and data sheets mention various numbers of around 0.9 to 0.95. Bokel (2016, p. 18) uses 0.9. To be on the safe side, the value of 0.9 will be used.

The transmission coefficient *t* of the glass is 0.9. The model is equipped with 4 mm of so-called solar glass. A producer of this type of glass, AGC Solar, mentions transmission coefficients of around 0.9 for different types of solar glass (pp. 7, 8, 13, 14). Therefore, 0.9 will be used. If there is no glass cover present, the transmission coefficient is - obviously - not applicable.

The resistance to the outside R_e = 0.174 m^2K/W. This value is determined by adding the transition resistances of 0.04 and 0.13 to the thermal resistance of the solar glass. According to AGC Solar, the solar glass has a thermal conductivity of 1 W/m K (pp. 8, 14). Dividing the thickness of the glass by the thermal conductivity gives a thermal resistance of the solar glass of 0.004 m^2K/W. If there is no glass cover present, the resistance to the outside is 0.04 m^2K/W.

The resistance to the inside R_i = 0.28 m^2K/W. This is the result of adding the thermal resistance to the outside (0.04) to the thermal resistance of the insulation. ENF Ltd. mentions that the collector insulation is ethylene-vinyl acetate (n.d.). A producer of this polymeric insulation, Meriton East (HK) Ltd., states that its thermal conductivity is 0.055 W/m K, giving a thermal resistance of 0.24 m^2K/W. If there is no insulation present, the resistance to the inside is 0.04 m^2K/W.

For the efficiency of the panel, 0.154 is chosen according to the specification by the distributor (Brandoni Solare, S.p.A., n.d.). However, for the facade it is sensible to choose dye-sensitised solar cells to get the most out of the aesthetical quality of the building. This means that the yield of the facade-integrated collectors is 0.12 (Casini, 2016, p. 340). Furthermore, according to Martins (2017), formula (9) requires the value for the solar irradiation to be given in kWh/m^2/year (p. 174). Since monthly values are used in this thesis, the average monthly values of the solar irradiation need to be converted from W/m^2 to kWh/m^2/month.

Besides, according to Schoder, the technical data sheet of a PVT collector mentions the term 'temperature coefficient'. This property means that with every 1°C increase of the module temperature above 25°C, the performance of the PV panel decreases (2017). For the PVT collector used in this research, this is -0.44/°C (Brandoni Solare, S.p.A., n.d.). If we look to figure 47, the performance ratio of a PVT collector is approximately 0.90 for a temperature of 25°C. So for example, if the temperature output is 45°C, the performance ratio decreases with 8.8% to 0.82. This corresponds very closely to figure 47.

Another important aspect is the amount of PVT collectors that can reasonably be connected to one partial distribution system, i.e. in series. Connecting too much of these modules to the same system is not effective when it comes to acquiring higher temperatures. Zelzouli, Guizani, Sebai & Kerkeni (2012, p. 887) claim that after the fifth collector, the temperature output has flattened. However, by reducing the volumetric flow rate of the water and choosing a proper number of collectors connected in series, there can comparatively be more collectors attached to the same system. The maximum amount of PVT collectors connected in series will be determined during the temperature output calculations. This is done by adding the outcomes of the temperature difference ΔT. It is assumed here that the temperature difference rises - more or less - linearly. Besides, the temperature difference in summer can and may be higher, due to better weather conditions, than in winter. This means that during summer, ΔT is set to 25-30°C. In winter, this is about 5 to 10°C.

Figure 52 shows the technical data of the three PVT types as used in the calculations:

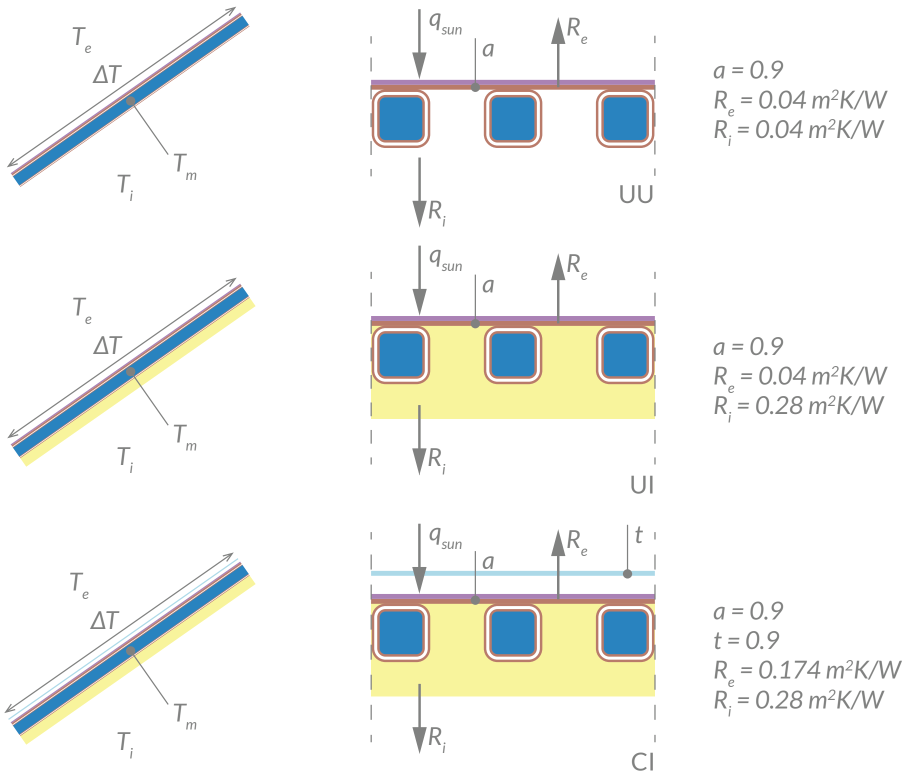


Figure 52. Technical data for the three collector types (own illustration).

4.3.3 Flow data
To have an understanding of how the mean inside temperature T_m affects the output of the PVT collector, this variable will range from 10°C to 50°C, with 10°C intervals. Moreover, this parameter varies throughout the year: it will be higher in summer than in winter. That is why for November until February, the value for the mean inside temperature will be set to 20°C. From May until August this is to 40°C. During the other months, this value is set to 30°C.

Besides, the mass flow rate $\dot{m}$ of the water is given in kg/s. However, a collector flow rate is mostly expressed in l/min or l/h, which hereinafter is referred to as the flow velocity *v*. For the avoidance of doubt, the mass flow rate is used only for the calculations and is thus similar to the flow velocity divided by 3,600. The collector used in this research has a recommended mass flow rate of 120 l/h (Brandoni Solar S.p.A., n.d.). Various specifications of other distributors show ranges of 30 to 150 l/h. Therefore, five different flow rates are tested: 30, 60, 90, 120 and 150 l/h.

4.4 PVT calculations, thermal energy output

4.4.1 Uncovered, uninsulated collector (UU)
The fact that the UU collector is not covered and is uninsulated at the back, gives it both an advantage and a disadvantage. The upside is that - because of the absence of insulative materials - the collector can practically always collect heat. The downside of a UU module is that it can just as easy lose its heat again, which makes its exergy efficiency quite low. Figure 53 shows a comparison of different values for the mean inside temperature T_m and the outcome:

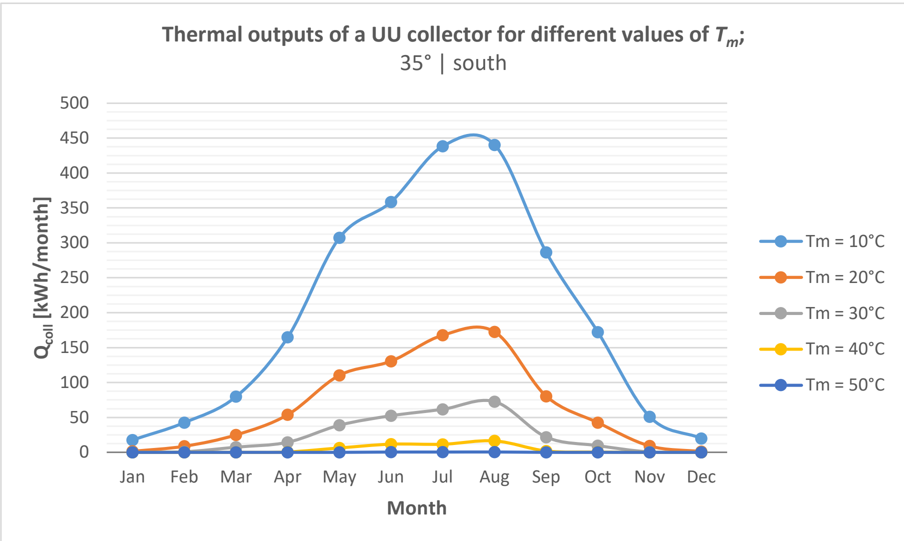


Figure 53. Thermal outputs of a UU collector for different values of T_m, according to calculations as explained in paragraphs 4.2 and 4.3 (own illustration).

4.4.2 Uncovered, insulated (UI) collector
An uncovered, insulated collector distincts itself from a UU collector by having a different resistance to the inside R_i (0.28 m^2K/W). Because of this, there is less heat lost through the bottom part of the PVT collector. Figure 54 illustrates a more flattened thermal output of a UI collector:

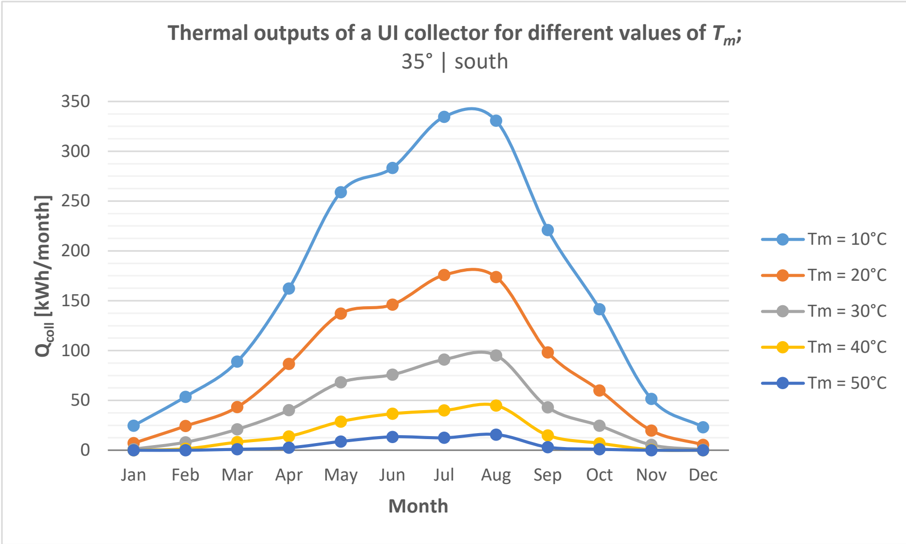


Figure 54. Thermal outputs of a UI collector for different values of T_m (own illustration).

4.4.3 Covered, insulated (CI) collector

The same calculations are carried out for the CI collector. Figure 55 shows that a collector design which uses insulation at the back and glazing on top is even more independent from the weather conditions:

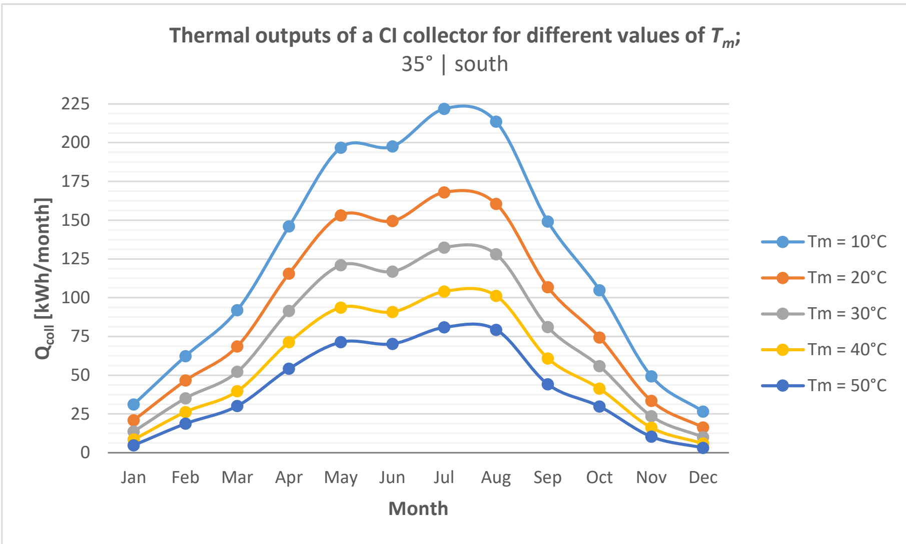


Figure 55. Thermal outputs of a CI collector for different values of T_m (own illustration).

4.4.4 Conclusion

From the graphs it can be concluded that the insulative capacities of a collector highly influence the (levelling of the) thermal energy output. Since these insulative capacities are also linked to the mean inside water temperature T_m, it can be said that a higher T_m renders a negative impact on an uncovered, uninsulated collector and - to a lesser extent - an uncovered, insulated collector. On the contrary, a covered, insulated collector loses much less heat for a higher T_m. Besides, the dip that is visible in the month of June is nothing more than the result of beneath the average weather conditions.

The differences between the three collector designs are even better visible if the mean inside temperature is compared to the thermal output, as illustrated in figure 56:

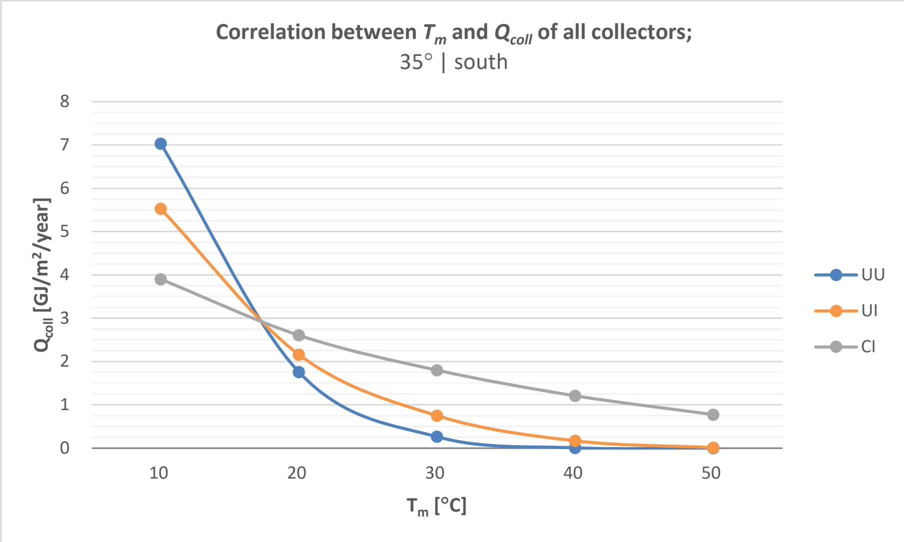


Figure 56. Correlation between T_m and Q_{coll} of all collectors (own illustration).

4.4.5 Facade-integrated PVT collectors

With the inclination of the facade-integrated PVT modules being 90°, their yield is therefore lower. The thermal outputs of the three facade collector types are visible in figure 57:

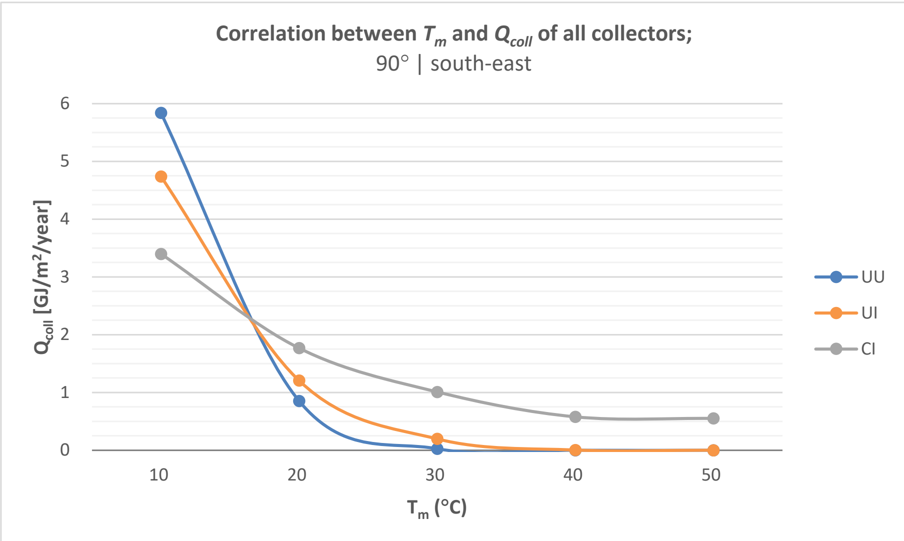


Figure 57. Correlation between T_m and Q_{coll} of all facade-integrated collectors (own illustration).

4.4.6 Validation of the collector yield calculations

The collector yield calculations will be validated by comparing them to reference material. In this way, it can be verified if those calculations are realistic. Some remarks should be made when comparing:

- the annual thermal output depends on a lot of parameters. This means that when comparing different outputs, this must be done carefully;

- a very important parameter when it comes to the thermal output of PVT, is the temperature of the water. The temperature that is chosen/tested by a distributor will therefore be compared to the representative part of figure 56.

The company Triple Solar tested their uncovered, uninsulated PVT modules, which resulted in a curve that is initially comparable to the blue line in figure 56. For this test, the energy output was plotted against the incoming water temperature of the collector (see figure 58):

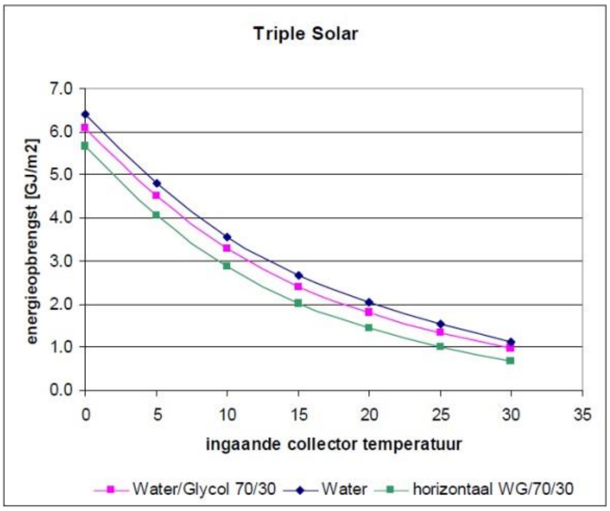


Figure 58. Test results of the uncovered, uninsulated PVTs of Triple Solar (Triple Solar, 2016).

Triple Solar thus used the inlet water temperature, while in this report, the mean water temperature is used. If a temperature difference of about 10°C is assumed, an incoming temperature of 15°C here can be compared to a mean temperature of 20°C in figure 56 (Triple Solar, p. 4). Anyhow, a difference is visible: the output values that Triple Solar calculated, give a more flattened curve than the one in figure 56. This can be accounted to, for instance, different insulation values and needs more attention for further research.

Agentschap NL (2012) compared the thermal output to the incoming collector temperature for a solar thermal roof (p. 7). This roof type is comparable to an uncovered, insulated collector. The result is shown in figure 59:

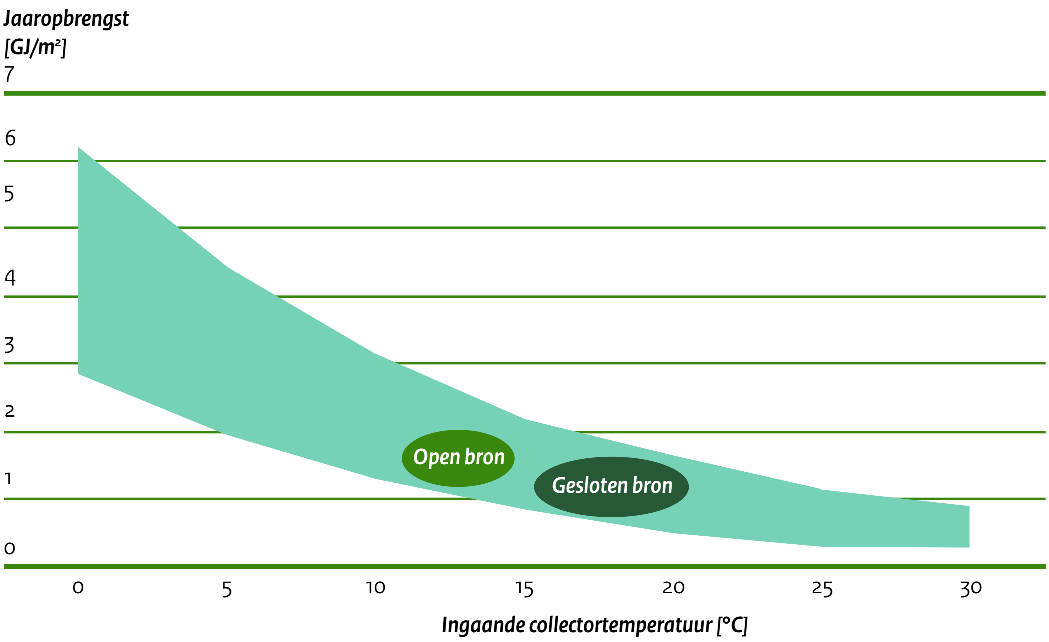


Figure 59. Comparison of the thermal output to the incoming collector temperature for a solar thermal roof (Agentschap NL, 2012, p. 7)

The two figures show quite some similarity. In figure 59, an inlet water temperature of 15°C gives an output between 0.8 to 2.2 GJ/m². Figure 56 shows an output of about 2.1 GJ/m² (for a mean temperature of 20°C).

Van Helden, Roossien & Mimpen (2013) compared the energy output of a covered PVT collector with that of a photovoltaic panel and a solar thermal collector on an office building in Zoetermeer, the Netherlands. The measurements took place from July 2011 to August 2012. The paper shows that the annual thermal output of the PVT system, with an inlet temperature of 12°C, was 546 kWh/m²/year (p. 85), which corresponds to 2.0 GJ/m²/year. Figure 56 shows an output of 2.6 GJ/m²/year (for a mean inside temperature of 20°C). It must be noted that a difference in the absorption and transmission coefficients can make a significant difference here. For example, if those coefficients were 0.8 instead of 0.9, the outputs would be similar.

Practical examples show that the annual thermal output of PVT collector types are mostly lower - and sometimes similar - compared to the calculated values. Differences can be accounted to alternate values for the absorptivity of the collector, the glass transmittance, the applied insulation values and ambient temperatures. However, additional losses like wind are not taken into account.

4.4.7 Choice of PVT collector type

The final choice of the PVT collector type is given in this sub-paragraph. It was already made clear in sub-paragraph 4.4.4 that the covered, insulated collector results in the highest total energy output. Sub-paragraph 4.4.3 proved that this type is less susceptible to temperature-related changes than the other two types. Therefore, the type that is chosen as being the most promising and favourable is the covered, insulated collector. This type is used for the rest of the calculations.

4.5 PVT calculations, temperature output

4.5.1 Temperature difference and amount of collectors in series

We start with the temperature difference in the winter, when a mean inside water temperature of 20°C is used. Figure 60 illustrates the results:

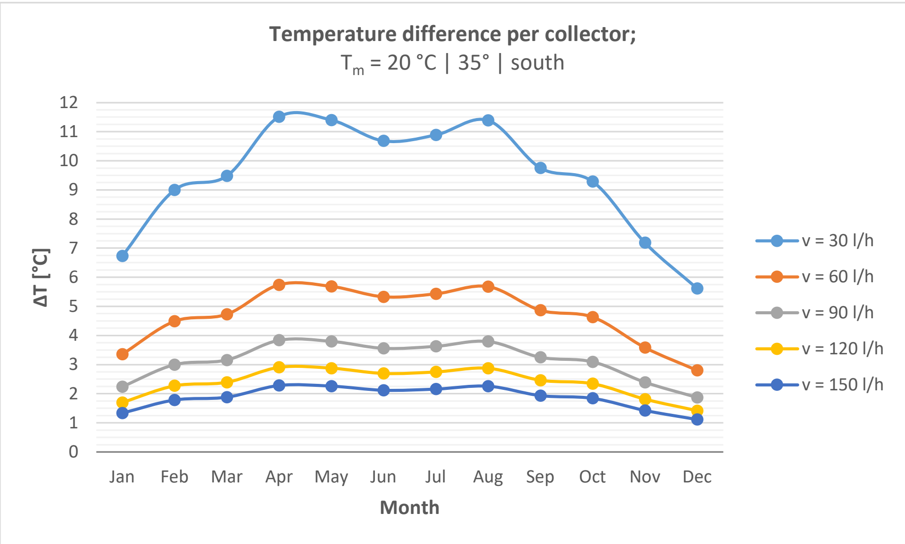


Figure 60. Temperature difference for T_m = 20°C and different values of *v* (own illustration).

Keeping in mind the fact that in winter, significantly more water is needed, a higher flow velocity is desired. If we look at figure 60, it can be seen that the higher flow velocities all give a temperature difference of about 2°C. This means that three to five PVT collectors in series are needed in wintertime to reach a cumulative temperature difference of 5-10°C.

To determine the amount of PVT modules connected in series in the summertime, the following graph can be used:

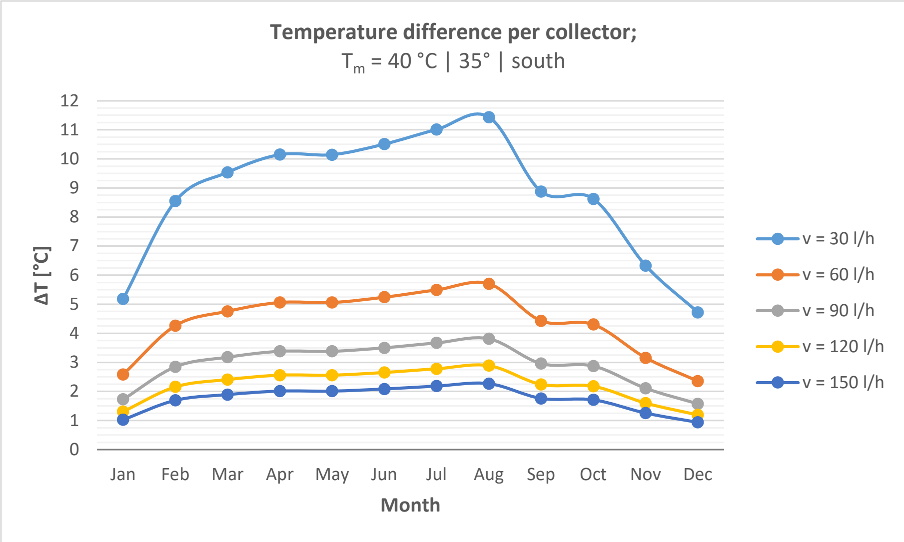


Figure 61. Temperature difference for T_m = 40°C and different values of *v* (own illustration).

Figure 61 makes clear that the mean inside temperature of the water actually does not have a large impact on the temperature difference. This can be substantiated by figure 62, which shows an inversely proportional correlation between the flow velocity and the temperature difference for various mean inside temperatures:

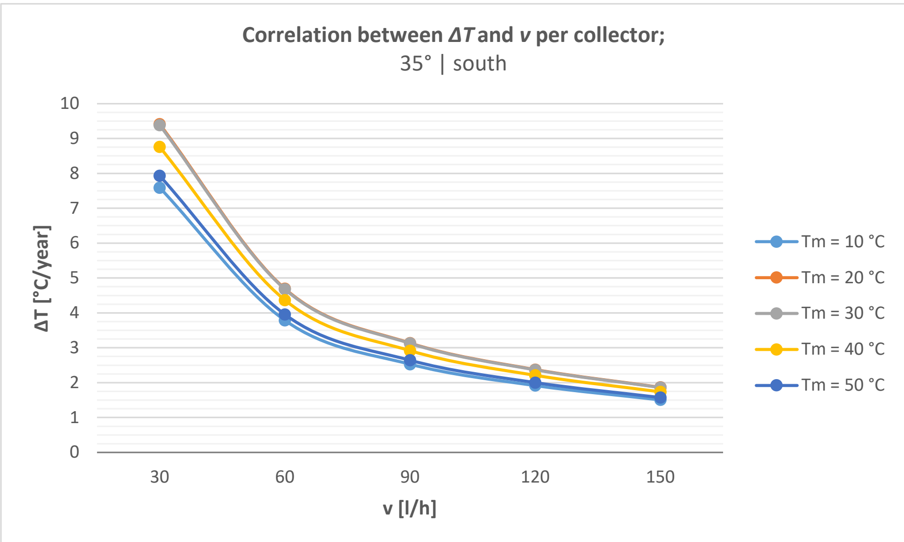


Figure 62. Correlation between *v* and *ΔT* (own illustration).

Obviously, the flow velocity does affect the temperature difference quite much. Anyway, figure 61 shows that for lower flow velocities of 30 and 60 l/h - since there is less water needed in summer - about three to four PVT collectors have to be placed in series to get a total temperature difference of about 25-30°C.

Based in figures 60 and 61, it can be concluded that during the whole year, four PVT collectors in series can suffice. This only applies for the roof-mounted collectors. The facade-integrated modules are treated in the next sub-paragraph.

4.5.2 Facade-integrated PVT collectors

It may be clear that the temperature differences for the facade-integrated modules are lower, figures 63 and 64 show:

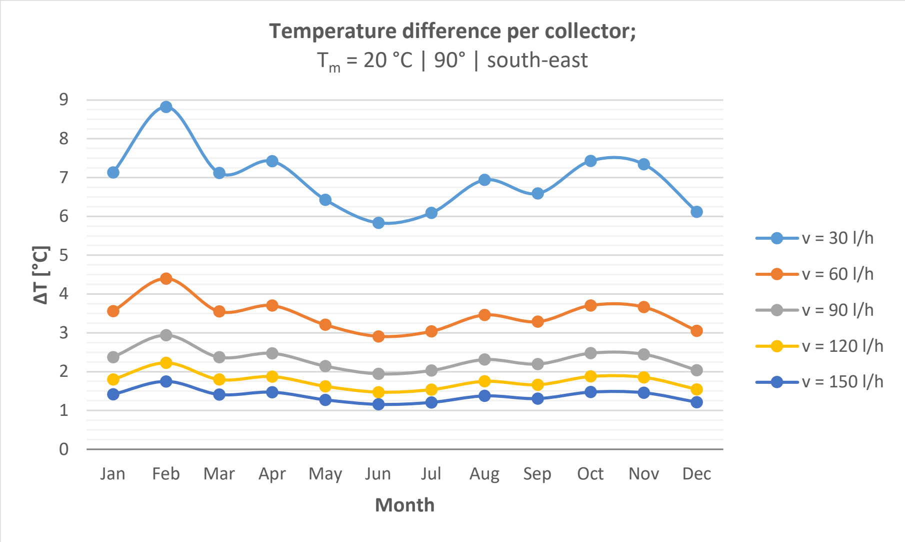


Figure 63. Temperature difference for T_m = 20°C and different values of *v* for a facade-integrated collector (own illustration).

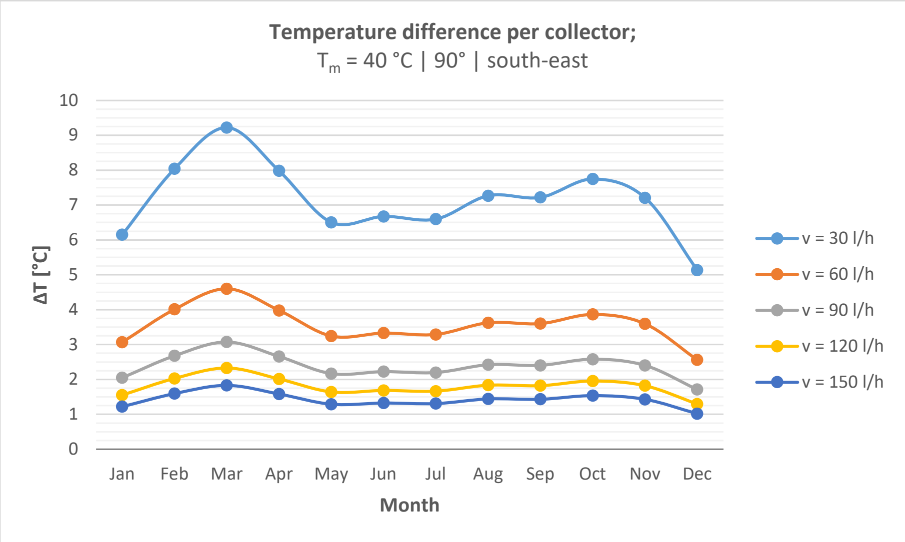


Figure 64. Temperature difference for T_m = 40°C and different values of *v* for a facade-integrated collector (own illustration).

In this situation, three to five collectors in series should be enough for the winter and five to six collectors in series would be sufficient for the summer. It is therefore advised to install five PVT facade-integrated collectors in series.

4.5.2 Effects of high temperatures on the facade

In addition to the amount of collectors in series, it is also interesting to have an idea of how the facade reacts to a relatively high value of the solar irradiation. This is especially the case in the summer, when also the outside temperatures are comparably high. It is not inconceivable that hot weather conditions in this season have an unambiguous impact on the facade. If the PVT collector would become too warm, there are some solutions of overheating. One of these solutions is a drain-back system, which means that a pump empties the collector loop when there is a risk of overheating (Marken, 2011).

According to Van der Linden, Erdtsieck, Kuijpers - van Gaalen & Zeegers (2006), the thermal resistance of a construction with different layers can be calculated. The formula that can be used to calculate the temperature progression per layer is the following:

$$\Delta T_n = \frac{R_n}{R_l} \Delta T \ [°C] \tag{10}$$

with: ΔT_n = temperature progression along layer n [°C]
R_n = thermal resistance along this layer [m^2K/W]
R_l = thermal resistance of the whole construction [m^2K/W]
ΔT = temperature difference between the air on both sides of the construction [°C]

It is important to not forget the transition resistances r_e and r_i when making these calculations for a wall (p. 11). In order to know the parameters of the formula, parameters like the thickness of a layer d and its thermal conductivity λ have to be known - since the thermal resistance is obtained by dividing the layer thickness by its thermal conductivity.

For the thermal behaviour of the integrated facade of Docklands, it is not only interesting to find out the temperature progression from the hot water in the PVT collector to the inside of the building, but also the temperature progression to the outside. We take an outside temperature of 20°C - to represent the summer. If a temperature difference of 25°C is assumed, together with a mean inside water temperature of 40°C, it can reasonably be expected that the temperature output is 65°C. Furthermore, the inside of the building is set to 18°C.

Two ΔTs have to be taken into consideration: the temperature difference between the outside and the water (ΔT_e), and between the water and the inside (ΔT_i). This gives ΔT_e = 45°C and ΔT_i = 47°C. The same accounts for the thermal resistance. Furthermore, for the composition of the cavity wall of Docklands, the thickness of the glass wool is assumed 180mm - resulting in a total thermal resistance of the facade of around 5.0 - and a concrete inner leaf of 150mm.

The surface temperature of the glass is discussed upfront. First, the temperature of the outside of the glass pane is substantiated (the thermal absorber plate is neglected, for its thermal conductivity is extremely high). The thermal resistance R_n of the glass is 0.0025 m^2K/W, $R_{tot;\,e}$ = 0.070 m^2K/W and ΔT_e = 45°C, which gives a ΔT_n of 1.6°C. This results in a temperature of the glass of 63.4°C.

For the temperature of the inside of the glass wool, only one calculation will not suffice, since the temperatures of some layers in-between (the polyurethane and the cavity) have to be calculated also. However, since the ventilated air cavity actually has a negligible thermal resistance, its ΔT_n is practically zero degrees. This means that only the temperature drops caused by the polyurethane and the glass wool have to be cumulated. Eventually, the temperature of the inside of the glass wool is 30.4 °C.

The table of figure 65 shows all kinds of input parameters as well as the inside temperature of the Docklands PVT-integrated facade. The values for λ are taken from Joostdevree.nl (n.d.a), except the one from ethylene-vinyl acetate, which was already known.

Layer	d [m]	λ [W/m K]	R_n [m²K/W]	$ΔT_n$ [°C]	T_n [°C]
outside air	-	-	-	-	20.0
r_e	-	-	0.04	25.7	37.7
glass pane	0.0020	0.80	0.0025	1.6	63.4
thermal abs. plate	0.0020	390	n/a	n/a	65.0
water	0.016	0.60	0.027	-	65.0
ethylene-vinyl acetate	0.013	0.055	0.24	1.6	63.4
cavity	0.040	-	0	0	63.4
damp-proof course	0.0002	0.01	0.02	0.1	63.3
glass wool	0.18	0.036	5.0	32.9	30.4
concrete	0.15	2.0	0.075	0.5	29.9
r_i	-	-	0.13	0.9	29.0
inside air	-	-	-	-	20.0
total			$R_{tot;e}$ = 0.07 m²K/W $R_{tot;i}$ =7.15 m²K/W		$ΔT_e$ = 45°C $ΔT_i$ = 47°C

Figure 65. Temperature progression of the Docklands facade (own illustration).

Although the fact that especially the glass wool greatly reduces the temperature on the inside of the construction, there are two aspects that have to be taken into account. On the one hand, the temperature of 65°C is present on a relatively small part in the facade, having a quite low impact on the facade. Moreover, these temperatures are not very common. On the other hand, the temperature of the glass pane in this situation is around 63°C, which can cause significant burns to humans and animals.

4.6 PVT calculations, electricity output

4.6.1 Electricity output and panel yield

Now that the temperature differences and the amount of collectors in series are known, the electricity output and the performance ratio can be calculated. We start with the results in winter, when the mean water temperature is 20°C (see figures 66 and 67):

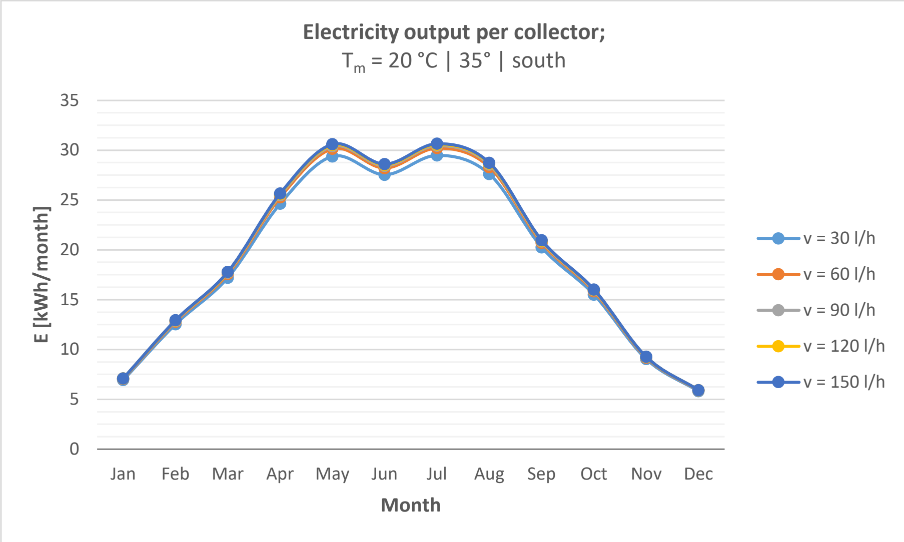


Figure 66. Electricity output for T_m = 20°C and different values of *v* (own illustration).

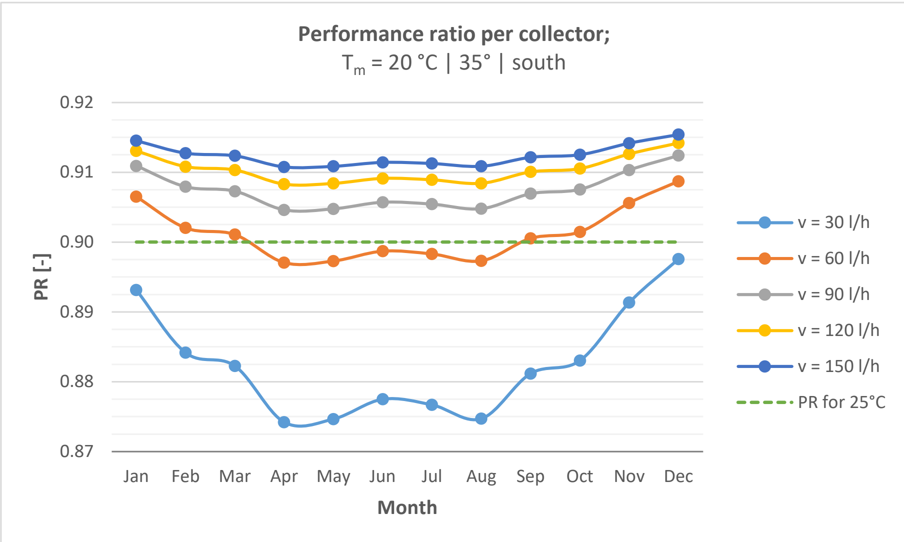


Figure 67. Performance ratio for T_m = 20°C and different values of *v* (own illustration).

Figure 66 shows that the flow velocity has a limited effect on the electricity output. Furthermore, it seems that the flow velocity does affect the performance ratio quite a lot.

The next figures show the electricity output and performance ratio in the summertime, when the mean inside temperature of the water is 40°C:

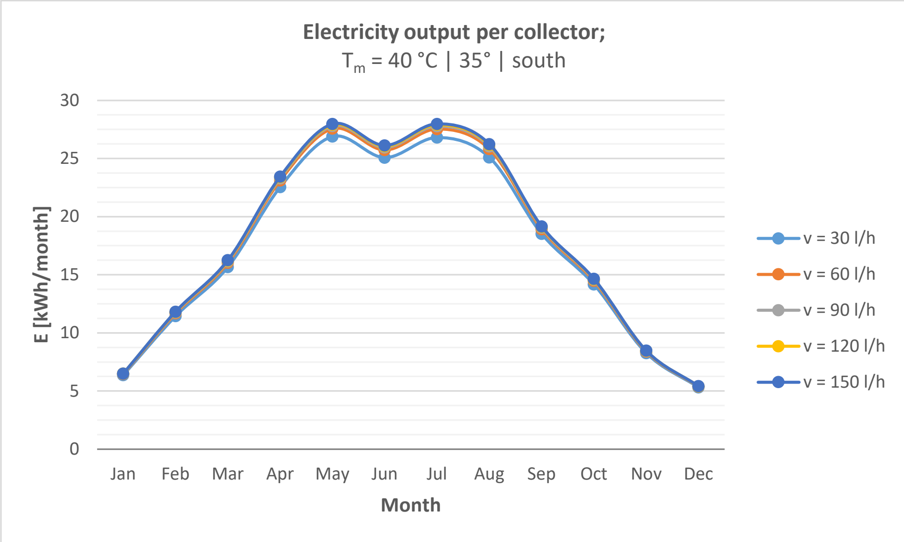


Figure 68. Electricity output for T_m = 40°C and different values of *v* (own illustration).

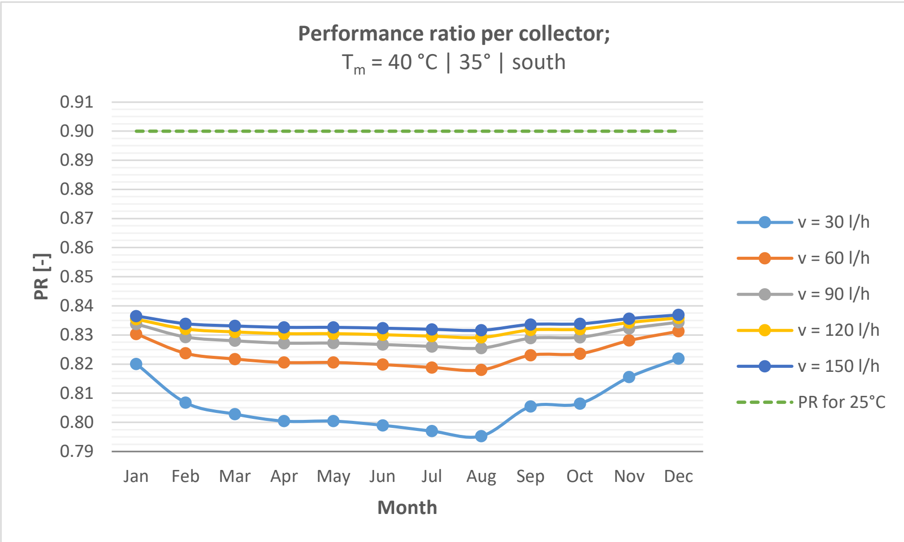


Figure 69. Performance ratio for T_m = 40°C and different values of *v* (own illustration).

Here, the performance ratio in figure 69 is about 9% lower compared to figure 67, because of the lower panel yield. However, since the panel yields are close together for different flow velocities, the electricity outputs also are very much the same. Still, the output in summer is about 16% lower compared to the winter.

Finally, the effect of the mean inside temperature on the electricity output will be presented in figure 70:

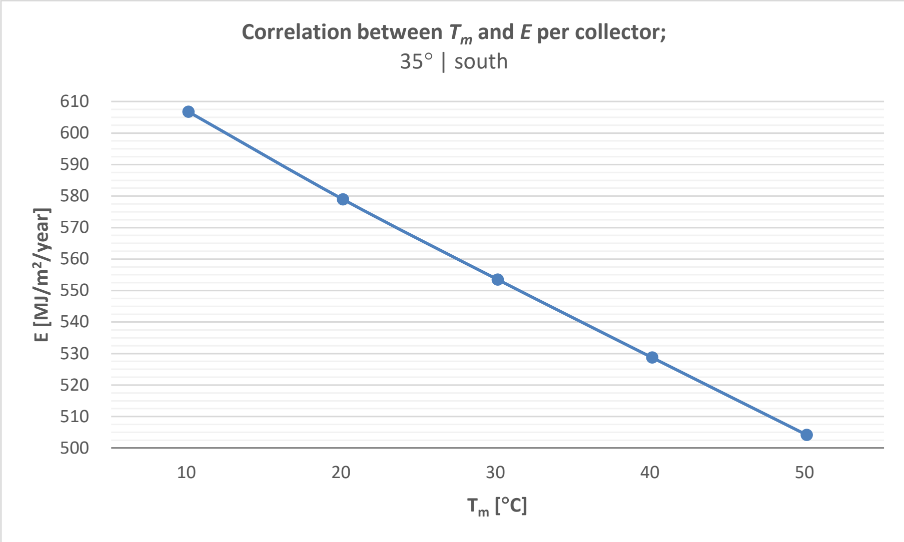


Figure 70. Correlation between T_m and E. The electricty output values are average values (own illustration).

4.6.2 Facade-integrated PVT collectors

For the building-integrated elements, the PV panel yield is lower (0.12) and due to that as well as its inclination, the electricity output of the facade elements is less. Figure 71 shows the correlation between the mean inside temperature and the electricity output:

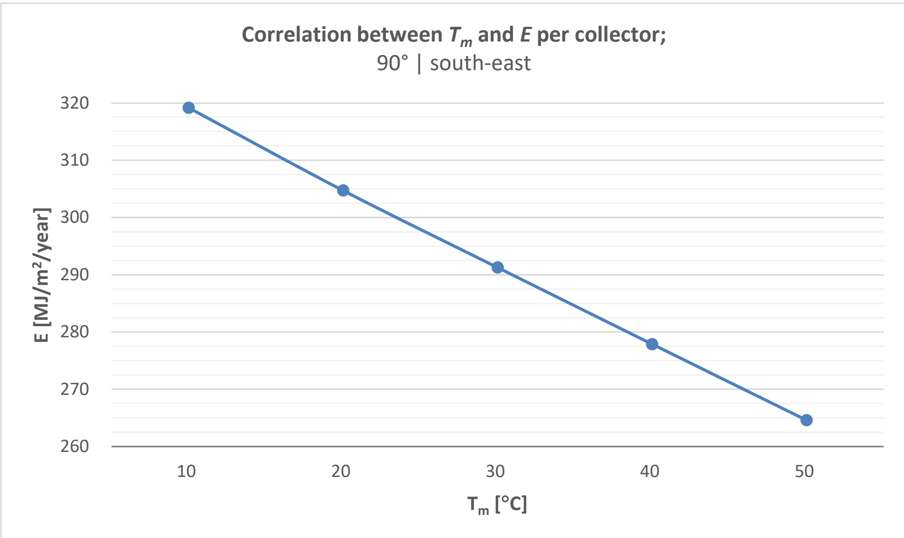


Figure 71. Correlation between T_m and E of a facade-integrated collector. The electricty output values are average values (own illustration).

4.6.3 Validation of the collector yield calculations

If the electrical outputs of the PVT elements were to be compared to practical examples, some annotations have to be borne in mind:

- the annual electrical output depends on a lot of parameters. This means that when comparing different outputs, this must be done carefully;

- it also has to be taken into account that PV panels can be made out of multiple materials;

Besides the thermal energy output of a PVT collector, Van Helden et al. (2013) also looked at the electrical performance of a PVT collector. The research shows that this value was 165 kWh/m^2/year (with an inlet temperature of 12°C). For a mean inside temperature of 20°C, figure 70 gives an electrical output of 578 MJ/m^2/year, which is the same as 161 kWh/m^2/year.

In a report about solar thermic systems, Zegers (2013) talks about PVT collectors. According to the author, the annual electricity output of a glazed PVT element lies between 80 and 110 kWh/m^2 (p. 26). This implies a difference of 53% to 92% less than the calculated output. It still has to be said that factors like the absorption coefficient, the temperature coefficient and PV type are not known in the example of Zegers.

The two reference examples show that the annual electrical output of a PVT collector may be quite realistic. The first research had a somewhat higher output. The second example had rather lower outputs. In both situations, differences can firstly be attributed to the PV material, as their yields can vary a lot. Also, different performance ratios, absorption coefficients, transmission coefficients, flow velocities, water temperatures, applied insulation values and ambient temperatures can make a difference.

4.7 Conclusion

This chapter started with presenting the theory and formulas for the calculating different PVT outputs: thermal, temperature and electricity. On top of that, three different PVT modules were chosen: the uncovered, uninsulated (UU) collector; the uncovered, insulated (UI) collector and the covered, insulated (CI) collector. One of these collector types was to be chosen to continue with. Before the calculations could start, the calculation procedures of all relevant parameters were treated. Besides roof-mounted PVT collectors, the outputs of facade-integrated modules were calculated, which have a lower yield due to their inclination.

Results showed that the PVT types with no or partial insulation performed the best when the mean input water temperature was relatively low. However, in reality, this temperature rises during the day. Bearing this in mind, the covered, insulated (CI) collector is judged to be the best choice of the three. The reason for this is that in principle, more heat is being lost if the mean inside water temperature increases, for the temperature difference becomes higher. This is especially the case during the colder parts of the year. And specifically during those seasons, the other two collector types show significant energy losses, despite the fact that throughout the summer, these two module types give a higher output than the CI collector. However, on average, the CI collector performs the best and gives more modest and flattened, but overall cumulatively higher outputs than the other two collector designs. Therefore, the CI collector was chosen to be continued with.

To - more or less - validate the outputs of all collectors, the results were compared to literature examples. This comparison showed that the outputs of the collector types were lower or similar. Various collector and environmental parameters can cause any differences.

The next assignment was to determine the temperature outputs of the chosen collector design, or more specifically, the difference between the in- and outgoing water temperature of the collector. In addition to this, it is important to explain how many collectors can be connected in series in order to achieve a higher temperature difference. An essential element here is the flow velocity of the water. Results pointed out that the temperature output is inversely proportional to the flow velocity, which basically means that the lower this velocity is, the higher the output temperature becomes. This correlation also means that the output temperature gets less and less influenced by an ever-increasing flow velocity. On the basis of the performed calculations, it was determined to connect four roof-mounted PVT modules in series and five facade-integrated collectors. Besides this, it is also important to know what the effect of a heat-producing, facade-integrated PVT collector is on the facade itself. The effect on the inside of a building could be marginalised, under the condition that the building is properly insulated. On top of that, the polymeric insulation of the collector also lowers the heat transmission. However, since the insulative capacities of a covered collector to the outside are quite low, the glass cover of the collector could reach temperatures that can harm humans and animals when touching.

The last output parameter of the PVT collectors that needed to be calculated, was the electricity. The electric performance of a PVT collector is comparable to that of a photovoltaic panel, except for the so-called performance factor. This factor is higher for a PVT collector because the working of the underlying solar thermal part increases the performance of the PV cells. Besides, a distinction had to be made between the building-added PVT and the building-integrated PVT collectors, since the aesthetical appearance of the facade-integrated elements would be dictated by dye-sensitised solar cells. The efficiency of these cells is lower than the monocrystalline silicon of the collectors on the roof. Also, the comparison with two reference examples made clear that the calculated output is realistic, though a bit lower than one the references, but it has to be said that all the parameters and characteristics of the references were not always known.

In the next chapter, the PVT system configuration is described.

5. DEVELOPMENT OF THE SYSTEM CONFIGURATION

Now that there is a lot more known photovoltaic thermal collectors, the rest of the system can be analysed and calculated. In paragraph 2.4, some relevant technologies for the system configuration were already discussed. This chapter chooses several of those technologies and explains why they are essential or desired in the complete configuration. The simulation program Polysun is used to substantiate the proposals.

5.1 Introduction

The first part of this chapter treats the selected technologies that are being applied in the system configuration. After that, several connection and operation modes are explained to illustrate various heat flows that depend on the amount of solar irradiation and the instantaneous energy demand. It is important here to point out how the energy flows make their way and are characterised by their temperatures - for various seasons - from the PVT collectors into the rest of the system. In the end, this will lead to three specific system designs: a summer, a winter and a spring/autumn configuration. All this will be substantiated by calculation and simulation results.

5.2 Selected technologies

Before a start will be made with the explanation of the thermal and electrical energy distribution (and storage), the selected technologies that make the system configuration possible are explained.

The first element in the system is the PVT collector, which is already discussed and calculated in detail. After the water is heated by the PVT module, a device is needed that upgrades the heat - if necessary - to above 55°C in order to avoid Legionella. To be on the safe side, 60°C is chosen to be used. Most of the times, it is inevitable to choose a heat pump for this process, as it is (one of) the most energy efficient and sustainable devices that can be chosen. Sub-paragraph 2.4.1 made this clear. A mono energy heat pump is chosen as the second element, since it has an electric heating element as back-up (in case the inlet temperature is too low).

The third element is a technique that somehow needs to store abundant energy and uses this in case the sun cannot reasonably provide enough energy to the PVT collectors. The SolarFreezer and Ecovat described in sub-paragraph 2.4.8 are interesting technologies. It may be clear that an (underground) energy storage system is costly, which is a good reason to develop a collective energy storage for multiple buildings. In this way, energy storage and distribution is shifted from building level to district level, sharing the total costs. The Ecovat is an attractive option for it to be used as a collective storage, not least because the water that is inside the container gives off its energy rather than that it is physically used as a transport medium. However, choosing the Ecovat would entail many additional temperature- and storage capacity-related calculations which increase complexity. To determine what can be sensible in this case, a brochure of Agentschap NL (2012) is consulted. According to this brochure, seasonal thermal energy storage can be applied for buildings where the heat demand is unequal to the cold demand and can also be combined with solar thermal roofs in order to regenerate the energy storage (p. 5). The question then is whether solar thermal roofs - or a PVT roof and facade in the case of this report - functions better with an open-source or a closed-source underground energy storage. In figure 59 of the previous chapter, the annual yield of a solar thermal roof is plotted against the incoming collector temperature for both an open-source (light green) and a closed-source (dark green) energy storage. The reason that the incoming collector temperature of the closed-source storage is higher than that of the open-source can be explained by the fact that the regeneration energy is not completely given off to the ground-source heat exchanger. This does happen, however, for an open-source storage, resulting in a lower incoming collector temperature for open-source storage (pp. 5, 7, 12). The benefit of this is that there is more heat directly available in the ground, which can yet again be used. On top of that, Agentschap NL (2012) shows that an open-source energy storage has a heat and cold 'bubble' in which the heat can be stored (p. 10).

In addition to this, Van Helden et al. (2013) show that from a primary energy point of view, the combination of a PVT collector and a heat and cold storage are annually the most favourable compared to photovoltaic panels and solar thermal collectors (p. 85). According to Joostdevree.nl (n.d.b.), the maximum temperature that is allowed for heat and cold storage, is 25°C.

Taking all the previous information into account, an aquifer, open-source energy storage is chosen. This type of storage has a hot and a cold well, with a hot well temperature between 15 and 25°C and a cold well temperature of about 8-10°C, depending on the time of year (Rijksdienst voor Ondernemend Nederland, 2017, p. 1). This relatively large difference in temperatures is a reason to choose for this type of energy storage.

Another important (fourth) element of the configuration is an additional heating system which also has the possibility to store water. This would be an electric boiler for the domestic hot water and a (smaller) buffer tank for the low-temperature heat. They have three functions: transferring the heat that is provided by the heat pump to the accompanying distribution system, giving cold water back to the heat pump, and temporarily storing water. There can even be a fourth function given to the boiler: directly obtaining hot water from the PVT modules if this water temperature is already around 60°C.

The last technologies that can be applied are the integrated collector storage solar water heater (ICSSWH) and the drain water heat recovery (DWHR). The ICSSWH may be very appealing and efficient solution, though the increased thickness of this solar water heater in combination with a PVT collector makes the total package relatively thick. This is not desirable for the facade of Docklands. On the other hand, a DWHR is very convenient to cut the energy use and will therefore remain to be applied in Docklands.

Finally, there are some heat exchangers located in the system configuration. These will be commented upon in the next paragraph.

5.3 Parts of the system configuration

When it comes to the thermal energy, there can be made a distinction between an individual and a collective distribution system. An individual system generally means that only one household or a small amount of people will be the end-user(s). A collective one is meant for two or more households. Gommans (2017) shows both systems together with several configuration possibilities for the use of thermal energy (see figure 72) (p. 14).

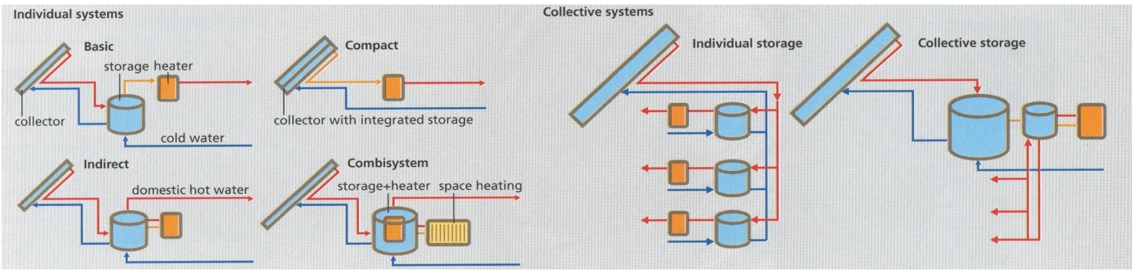


Figure 72. System configurations of thermal energy use (Gommans, 2017, p. 14).

The thermal energy distribution system of Docklands will be a collective one. Figure 72 shows two configuration possibilities for a collective system: individual storage or collective storage. From an energy efficiency point of view, an individual control and storage per apartment or apartment groups is chosen. The reason for this is that additional heating in smaller post-heaters consume less energy. Moreover, the length of the distribution pipes is much shorter, because the individual elements are already installed in the apartment itself.

The energy flow starts at the four PVT collectors - connected in series (the roof is chosen in this case). Depending on the season, there are different temperature outputs of the water that have their additional consequences for various conversion and end-use purposes. This is explained later on in sub-paragraphs 5.5.1 to 5.5.3. Anyway, after the heated water leaves the PVT modules, it flows towards a heat exchanger in order to keep the water of the collector separated from the rest of the system. This is done because on the one hand, the medium can be a different liquid than water (i.e. glycol) and on the other hand, to prevent that water that is not heated up enough - to rule out the possibility of Legionella - can be used by people. Besides this, a water distribution system that is longer, results in more energy losses, giving a lower return temperature to the PVT collectors. Thus, the heat exchanger in between transfers the heat to a different distribution system. This process entails a temperature drop of a couple of degrees. Figure 73 shows this first part of the system:

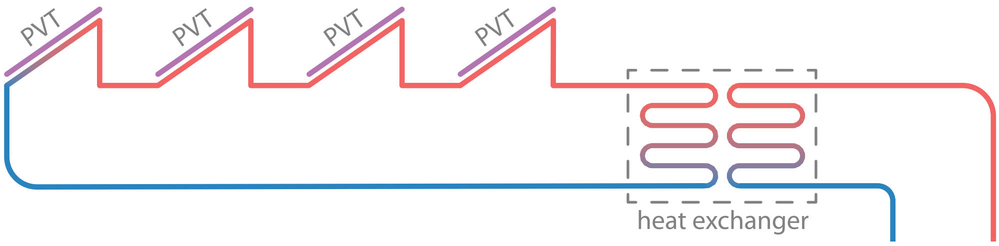


Figure 73. A proposed first part of the system configuration (own illustration).

From the heat exchanger, the water is distributed to the heat pump. However, the water that flows from the heat exchanger can also be directed to the aquifer thermal energy storage (ATES), in case there is no need to use it or in case the ATES needs to be regenerated. To keep the water circuit of the ATES separated from the rest of the system, there is also a heat exchanger needed there. Figure 74 shows the second part of the system:

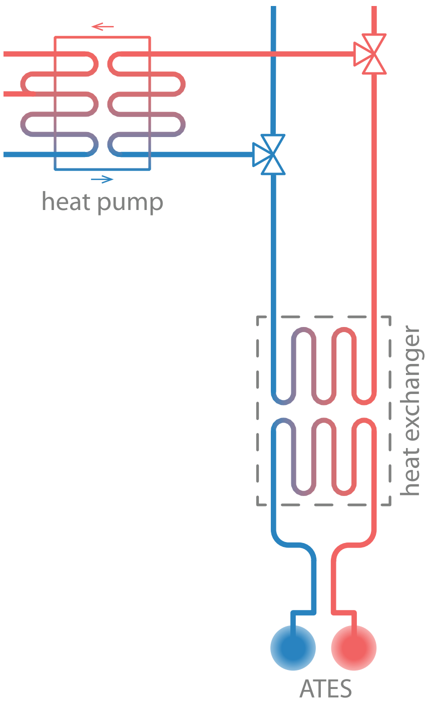


Figure 74. A proposed second part of the system configuration (own illustration).

If the water then exits the heat pump, a choice can be made if it will be used for low-temperature heat (LTH) or domestic hot water (DHW). For LTH, the input temperature of the water needs to be 30 to 35°C. Since Docklands is a relatively new building with proper insulation, 30°C is assumed. For DHW, the temperature needs to be a lot higher: 60°C. It is sometimes possible that the PVT collectors reach a temperature that is high enough for the water to be used for DHW, but most of the times the water temperature is too low. Because of that, a boiler tank is installed that makes sure that the heat is upgraded to 60°C. The 'end' of the DHW system can be a hot or cold water tap. In between the taps and the buffer tank, a heat exchanger is placed. Figure 75 shows the final part of the system:

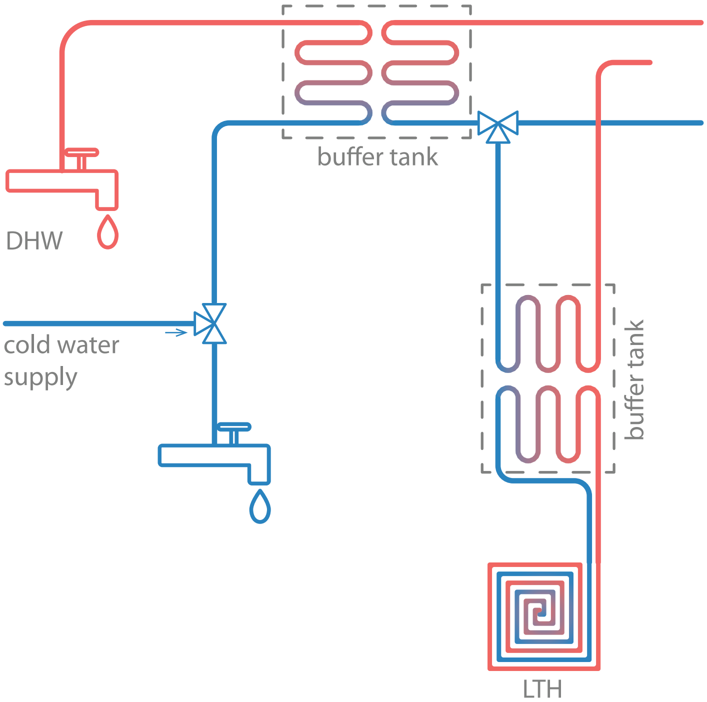


Figure 75. A proposed third part of the system configuration (own illustration).

What is not (completely) drawn in the three sketches are the pumps, valves and system control devices to keep the complete network up and running. They are considered as a separate field of study and are therefore not treated in detail in this report.

5.4 Operation modes of the system configuration

To grasp the exact working of the system configuration, all possible operation modes are considered and accompanying temperature ranges are indicated. It has to be made clear that different operation modes are linked to different temperatures and not necessarily the other way around. Moreover, the operation modes solely depend on the instantaneous energy need.

The first two variants are the direct-heating/storage modes, where the hot water runs from the collectors to a boiler. There can be made a distinction here between the boiler of the domestic hot water (DHW) and the buffer tank for the low-temperature heat (LTH). For the DHW boiler, the direct-heating/storage mode can take effect when the solar irradiation and the outside temperature are very high, resulting in a high PVT output temperature of about 60°C (for instance during summer). The hot water is directly lead to the boiler, where its heat can be extracted and be used for domestic hot water, or it can be stored. After that, the water is given off to the energy storage to cool down and is finally led back to the PVT collector. For the LTH buffer tank, the ideal season is mostly spring or autumn, with temperatures of 35-37°C.

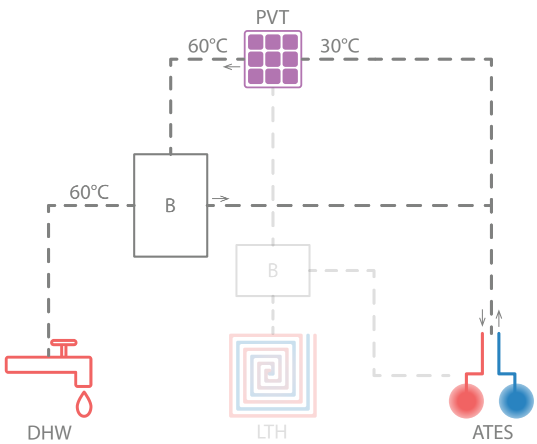
The third option is the heat pump mode: the hot water flows from the PVT collectors to the heat pump. In turn, the heat pump can direct the water to the buffer tank or the floor heating. Temperatures of about 10 to 20 degrees are needed now.

The fourth option involves a regeneration of the underground energy storage. Without interventions of the heat pump or boiler, the water is directly lead from the PVT modules to the storage. Temperatures of 5-10°C are necessary in this case, though this option solely depends on the need of regeneration.

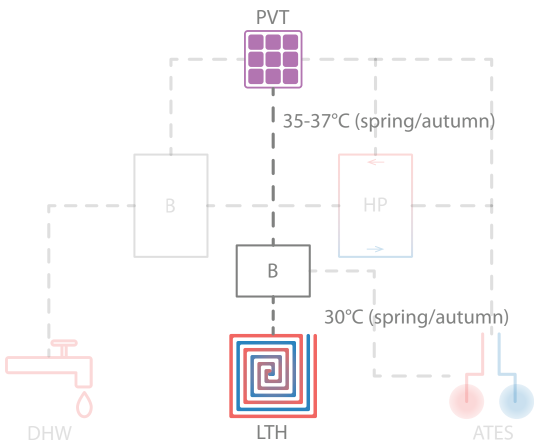
In case of the fifth variant, the underground energy storage provides the energy instead of the PVT system. During the summer, when the weather is mostly quite warm, the water provided by the collectors is too high for floor cooling. Using the heat pump to cool down the water costs a lot of energy. Therefore, water from the energy storage can directly be used for floor cooling.

The sixth option is similar to the one described before, but then for a different season. With unfavourable weather conditions, the PVT system cannot reasonable provide for the hot water. This means that reserves from the energy storage can be used for heating purposes. The heat pump can upgrade the temperatures now.

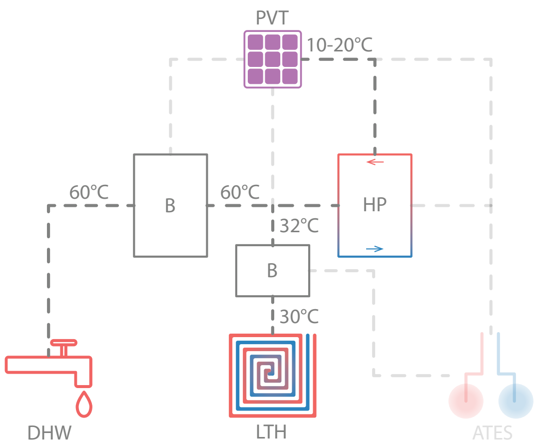
Figure 76 shows all six operation modes:



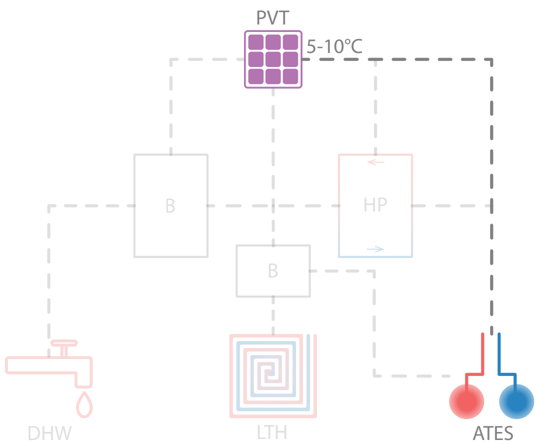
1. Direct-heating/storage mode DHW



2. Direct-heating/storage mode LTH



3. Heat pump mode



4. Regeneration mode

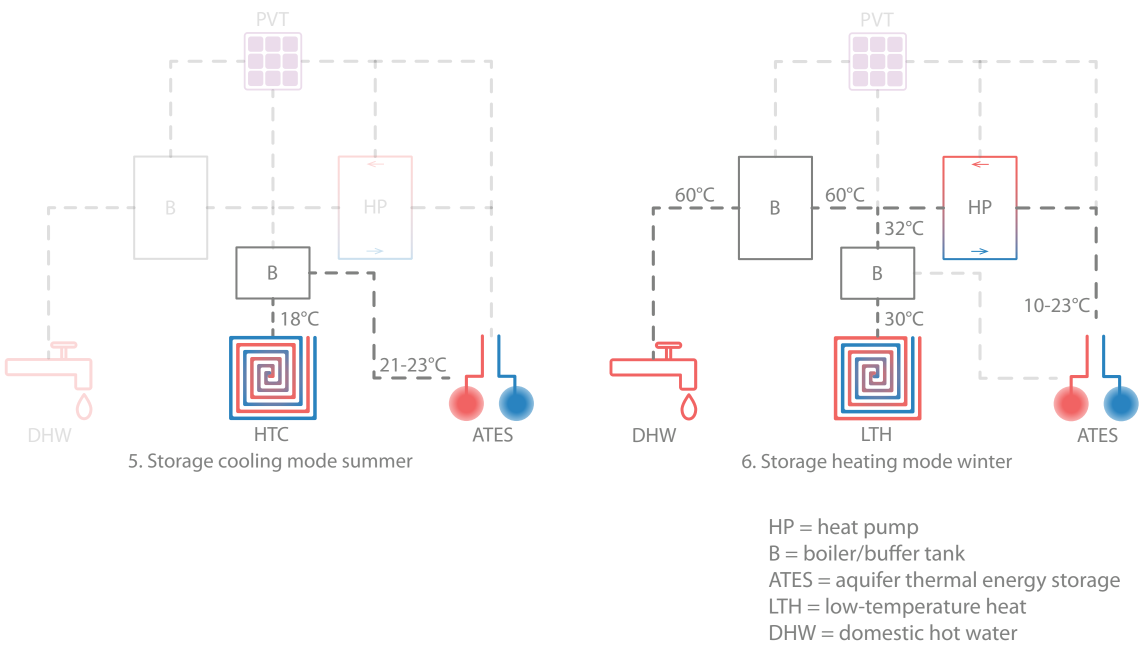


Figure 76. The six operation modes of the PVT system configuration (own illustration).

5.5 Thermal energy distribution

To get an even better understanding of the system configuration, its working per season will be described. The mean output temperature of the summer, the winter and the spring/autumn are taken. Also, the system configurations of these three 'seasons' are linked to one or more of the six operation modes described in the previous paragraph.

5.5.1 Summer situation

For the PVT temperature output in the summer, a flow velocity of 60 l/h is considered. This results in an output temperature of about 65°C. Depending on the length of the water pipes between the PVT collector and the heat exchanger, a temperature drop of about 1°C is assumed. Subsequently, the heat exchanger transfers the heat of the water to a different distribution system, causing a heat loss of about 3°C. The water now has a temperature of 61°C. This temperature is high enough to avoid Legionella, so it is not necessary to lead it directly to the heat pump. Moreover, doing this will cause the return temperature from that heat pump to be still high, which would induce energy losses. Therefore, the hot water can be given off to the buffer tank right away. This situation is comparable to operation mode 1. The remaining water is lead to the underground energy storage. The energy storage provides water for the high-temperature cooling of the floor, which corresponds to operation mode 5.

In this situation, the heat pump is switched off, since the PVT collectors together with the energy storage provides for the domestic hot water and the high-temperature cooling respectively.

Figure 77 shows the complete system configuration with the accompanying temperatures:

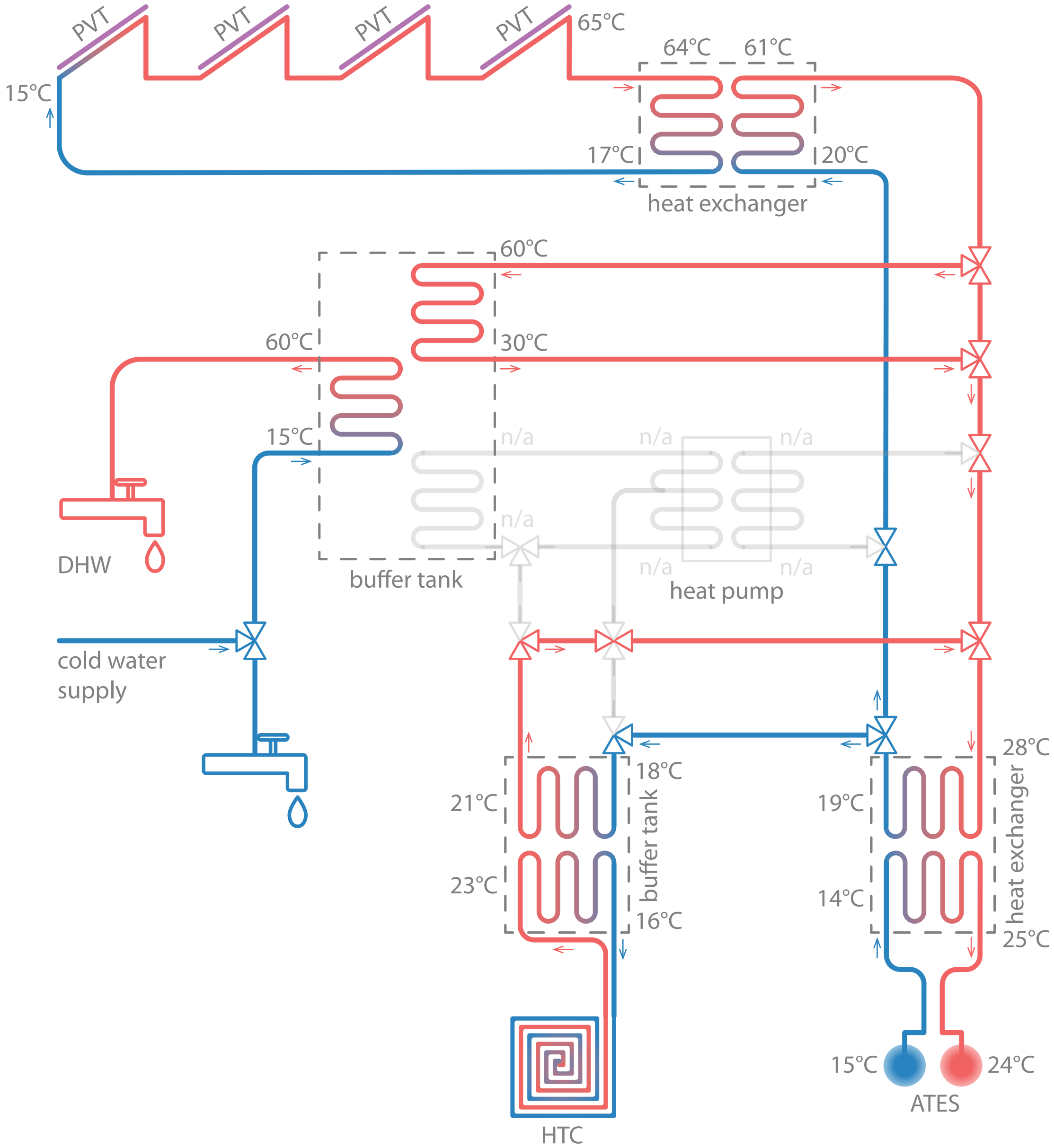


Figure 77. Proposal for the system configuration in summer. The temperatures are average values (own illustration).

5.5.2 Winter situation

Because there is more water needed for low-temperature heating in winter, the flow velocity that is assumed now is 120 l/h. The collector gives a temperature output of about 25°C. However, this temperature will in the end be lower than the maximum temperature than the underground storage (ATES) is allowed to store (which is 25°C), and because of that it makes sense to use the reserves of the ATES. Taking heat and conversion losses into account, the water from the ATES is expected to have a temperature of 20°C if it arrives at the heat pump. In fact, this situation is the same as operation mode 6.

A calculation example of a situation in winter is based on the amount of low-temperature floor heating that a family, living in an apartment in Docklands, needs on a cold Saturday in the middle of the winter. 140L of water is assumed to be needed. The temperature of the floor heating starts at 30°C, but since the water also needs to be transported to and exchanged by the heat exchanger in the buffer tank, 33°C is assumed. The energy that needs to be put in the heat pump - using formulas (4) and (2) - is 0.39 kWh. The calculation makes clear that floor heating in winter does not cost a lot of energy. However, if someone wants to shower (80L) in this situation, the water needs to be upgraded to 60°C first. Now, considerably more energy is needed: 0.69 kWh.

Figure 78 illustrates the system configuration for the winter:

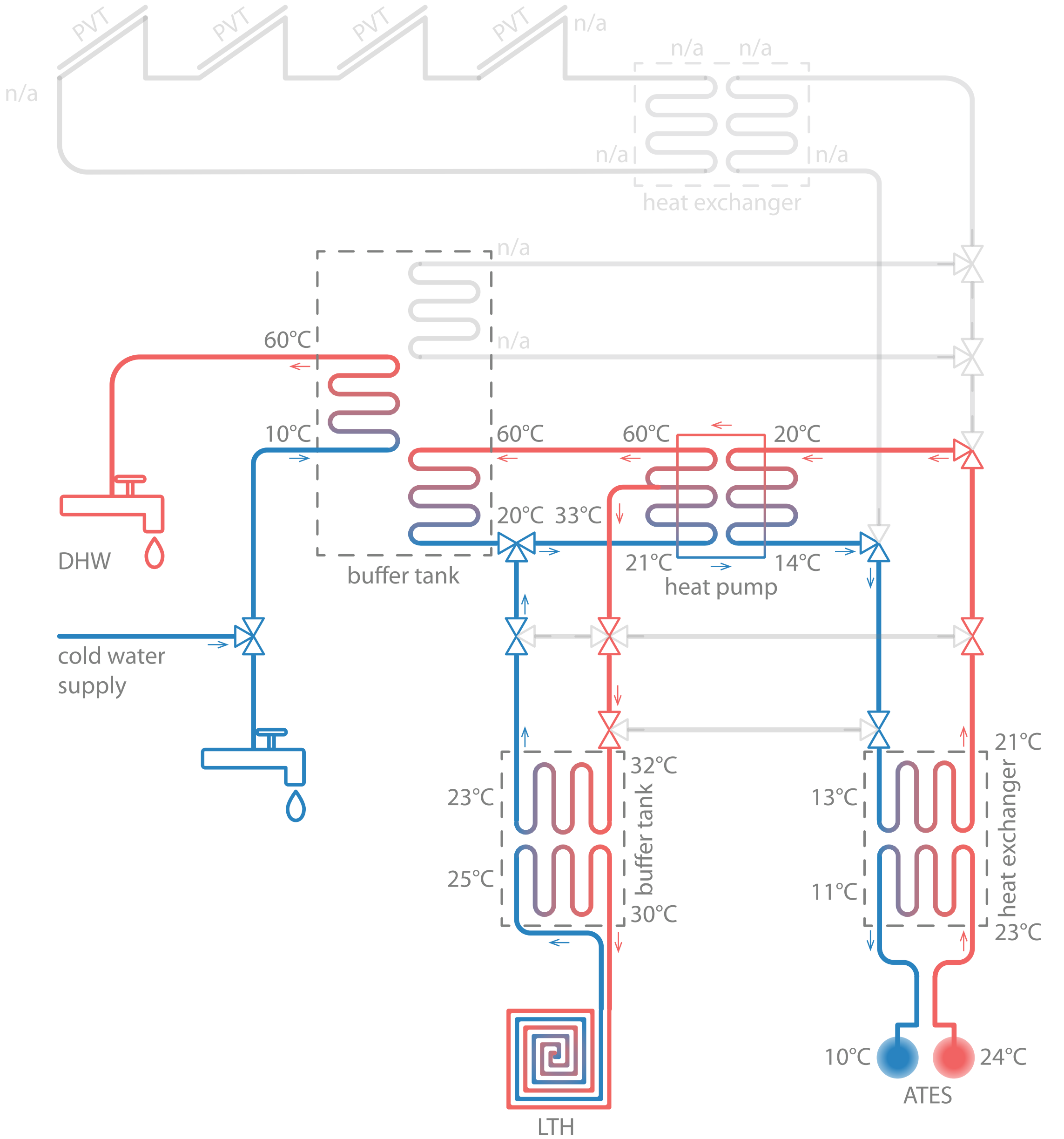


Figure 78. Proposal for the system configuration in winter. The temperatures are average values (own illustration).

5.5.3 Spring/autumn situation

The final configuration is made for the spring/autumn, where a flow velocity of 90 l/h is considered. The temperature output of the collectors can rise to about 40°C. In that case, the PVT collectors take over the 'heat delivery' from the underground energy storage. If needed, the underground energy storage can be regenerated. This configuration is comparable to operation modes 3 and 4, and would result in the system configuration of figure 79:

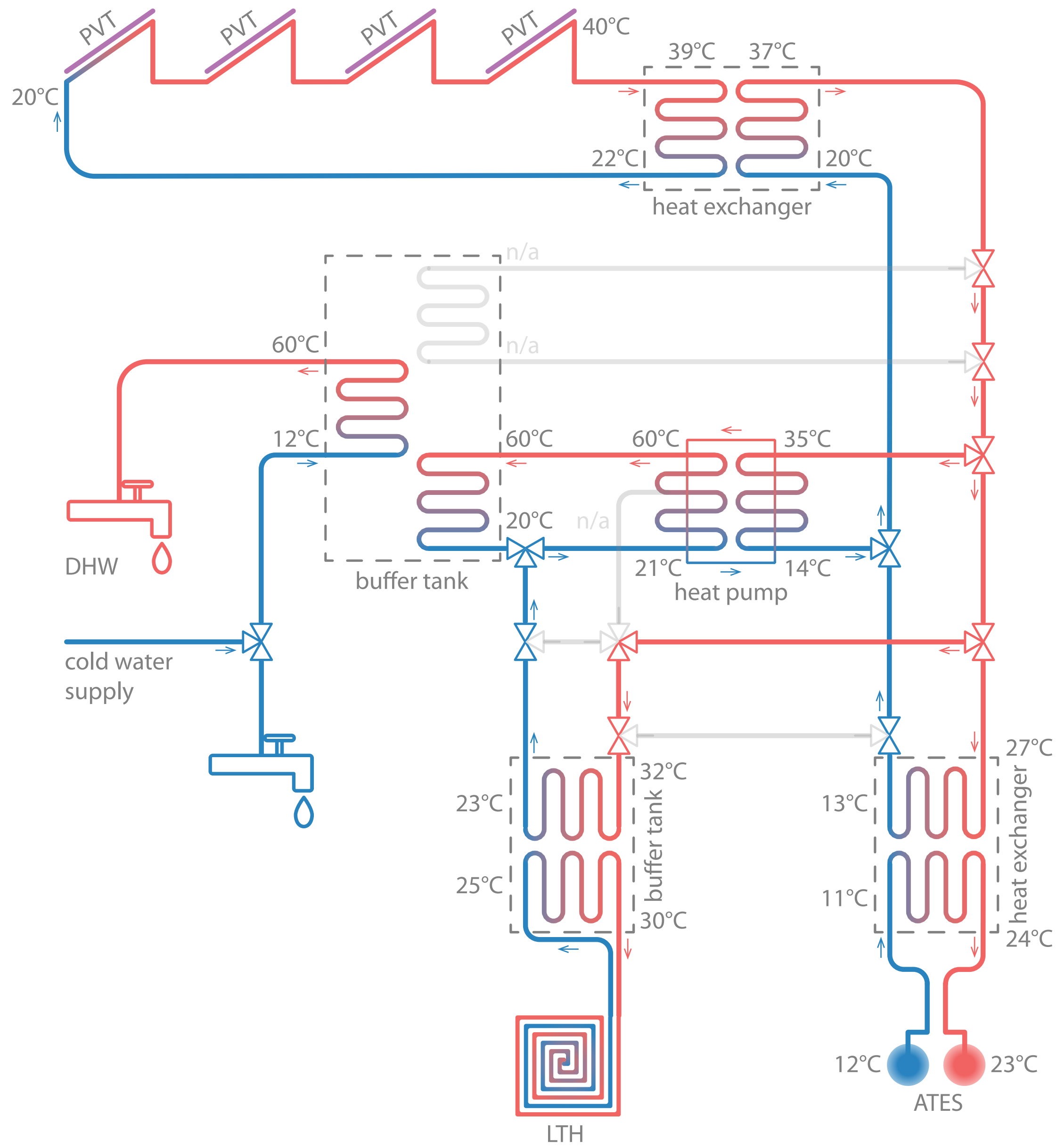


Figure 79. Proposal for the system configuration in spring/autumn. The temperatures are estimated values (own illustration).

5.6 Electrical energy distribution

An important component of the distribution of the energy that is generated by the PV cells, is the inverter. This device converts the electricity that arrives from the collectors to useable electricity. All the electrical equipment (heat pumps, flow controllers and other pumps) and power sockets are connected to the inverter. Unfortunately, the storage of electricity is not yet in a stage that it is deemed feasible for it to be applied in Docklands. There is the Tesla Powerwall, but given the costs to install those walls in Docklands, their application is considered impractical.

5.7 Evaluation in Polysun

To evaluate the chosen system configuration and the energy output calculations and graphs throughout this chapter, the simulation program Polysun will be used. However, since the PVT outputs in Polysun are partially dependent on the rest of the system configuration, together with the fact that during the development of this thesis there is little experience gained with the simulation program, the simulation procedures and results will be shown in the appendix.

5.8 Conclusion

This chapter described the system configuration of Docklands. This system comprises of PVT, a heat pump, two buffer tanks and an underground energy storage. Furthermore, six operation modes were developed. It may be clear that these operation modes are mainly dictated by the season. For example, during summer, if the temperature output of the PVT collectors is high enough, this hot water can practically directly be used for the domestic hot water. Moreover, the energy storage can provide for the high-temperature cooling. The heat pump can thus temporarily be switched off. However, during colder seasons, Docklands is mostly dependent on the underground energy storage. This confirms the importance of a proper interaction between the PVT collectors and the storage: during the warmer periods of the year, the storage is regenerated.

In the following chapter, the outputs of multiple PVT collectors are compared to the energy demand and energy use of Docklands. Also, the optimal placement of the total amount of collectors is discussed.

6. ENERGY BALANCE AND INFLUENCE OF DESIGN PARAMETERS

In addition to the previous chapter, this chapter presents the comparison of the PVT outputs to the energy requirements of the multi-family building. As a result, an energy balance should arise. Also, the influence of building design parameters on the quantity of PVT collectors is treated.

6.1 Introduction

The first part of this chapter will discuss the relationship between the energy outputs of the PVT collector and the energy demand and energy use of Docklands. In the most ideal situation, a specific quantity of PVT collectors should compensate for the energy demand and energy use of the multi-family building. In practice, it is somehow expected that an energy surplus is created, due to the fact that there are two types of energy in this case: heat and electricity. The surplus of energy is to be stored in the aquifer thermal energy storage. After this is treated, the calculated amount of PVT collectors is divided over the roof and accompanying facades of the multi-family building. Finally, the influence of various design parameters is discussed in order to find out how they affect the amount of PVT collectors that are needed for the energy balance.

6.2 Energy balance procedures

For the sake of clarity, the total thermal output Q_{coll} of all the building-added PVT (BAPVT) and the building-integrated (BIPVT) collectors is compared to the heat demand Q_{nd} of Docklands. This heat demand consists of the demand for the low-temperature heat (LTH), the domestic hot water (DHW) and the high-temperature cooling (HTC). Additionally, the electricity production E of the collectors is compared to the electricity use $E_{EPus;el}$ of the multi-family building. Also, it was mentioned earlier that fixed flow velocities would be chosen for the different seasons: 60 l/h during summer, 120 l/h during winter and 90 l/h for the spring and autumn. These flow velocities are included in the energy outputs of the PVT collectors.

6.2.1 Thermal output and energy demand

We start with the thermal output and the energy demand. The BAPVT elements have a total area of 285 m^2 (as shown in paragraph 3.2.3). This area is used to calculate the total thermal energy output. The same is done for the 1728 m^2 of possible BIPVT collectors. Figure 80 and 81 show the results of the comparison of the PVT energy output and the relevant energy requirements of Docklands, respectively:

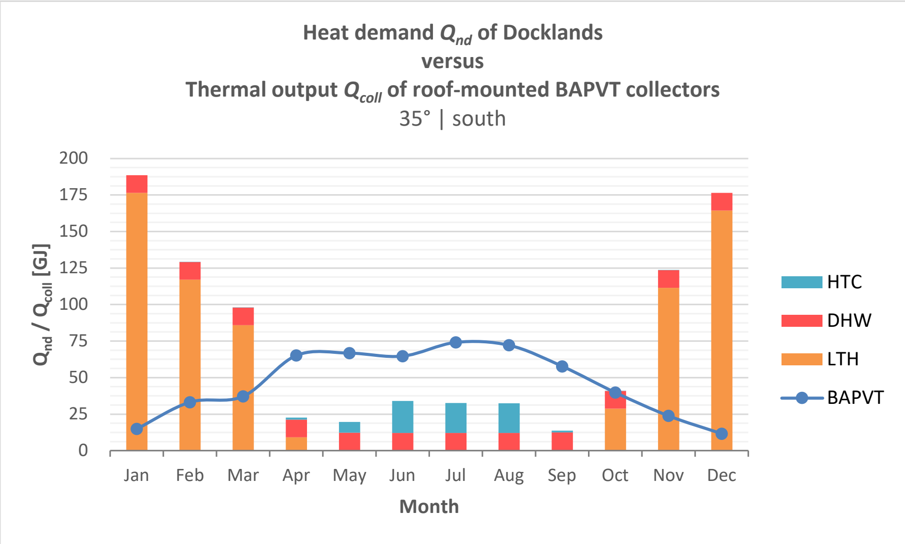


Figure 80. The heat demand of Docklands Q_{nd} versus the thermal output Q_{coll} of the BAPVT collectors (own illustration).

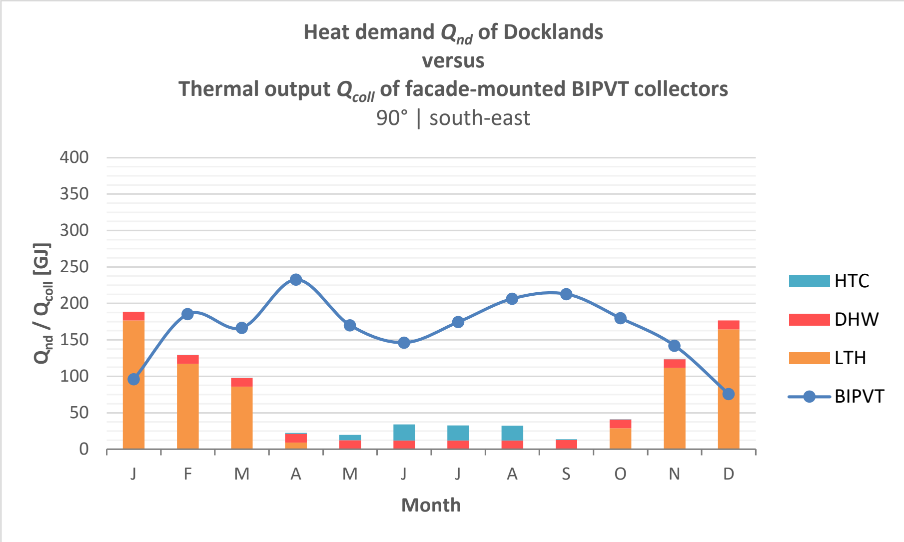


Figure 81. The heat demand of Docklands Q_{nd} versus the thermal output Q_{coll} of the BIPVT collectors (own illustration).

At first glance, figure 80 shows that the heat demand of Docklands seems quite higher than the energy that is generated by the roof collectors. Numerical values confirm this: the heat demand is 912 GJ, where the thermal output is 561 GJ, resulting in a difference of about 351 GJ. This means that there have to be applied PVT collectors into the facade to completely cover the demand. Filling both the south-east and the south-west facades fully with PVT modules obviously entails a gigantic surplus of energy, figure 81 shows. Therefore, an optimal value has to be found that should result in an energy balance. This optimal division of all the PVT collectors is calculated and discussed later on.

6.2.2 Electricity output and energy use

The electricity output and energy use for the roof-mounted and facade-integrated collectors are illustrated in figures 82 and 83:

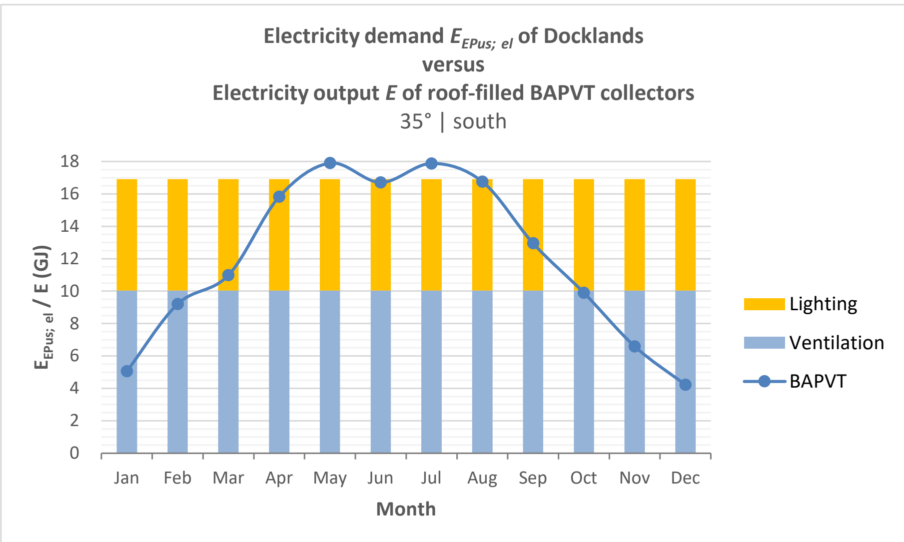


Figure 82. The electricity use of Docklands $E_{EPus;\ nd}$ versus the electricity output E of the BAPVT collectors (own illustration).

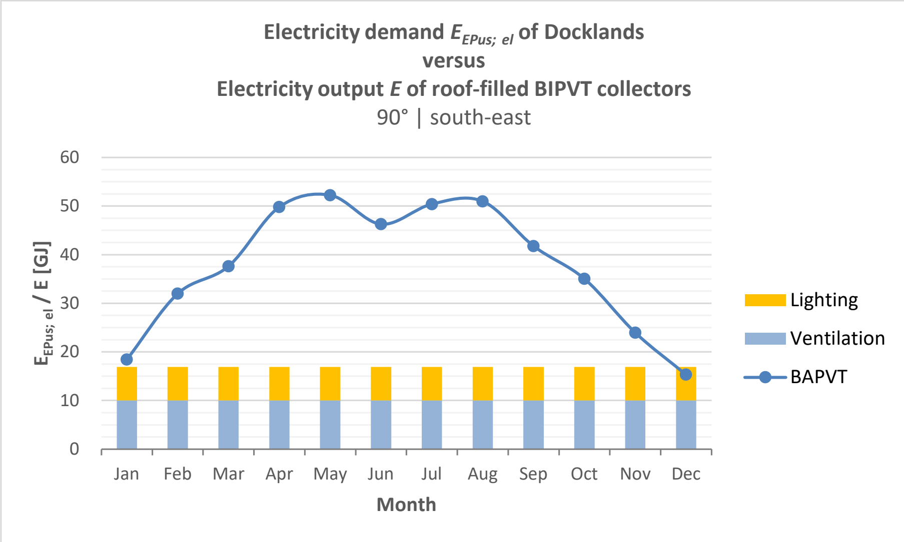


Figure 83. The electricity use of Docklands $E_{EPus;\,nd}$ versus the electricity output E of the BIPVT collectors (own illustration).

It may be evident that the amount of BIPVT collectors are not sufficient to cover the electricity use of Docklands: the total electricity use is 203 GJ and the total electricity yield is only 144 GJ, which gives a difference of about 59 GJ.

6.2.3 Yield difference between current and new situation

An interesting question that can be answered in this sub-paragraph is what the yield difference between the current situation (photovoltaic panels + solar thermal collectors) and new situation (roof-mounted PVT collectors) on the roof of Docklands will be. This comparison should confirm that PVT has a higher energy generation than the PV panels and solar thermal collectors. In order to compare both situations with each other, the current situation is explained first. Then, the total energy production of the new situation is calculated, after which the findings are compared to a reference example.

Since Docklands is imported in ENORM, the energy output of the photovoltaic panels and the solar collectors is known: 238 GJ. If the complete roof was to be filled with PVT modules, there would be generated 561 GJ for the thermal energy and 144 GJ for the electrical energy. This gives a total energy generation of 705 GJ. This is an increase of 296% more energy compared to the current situation.

"When a limited roof surface is available, the total yield of PVT will be considerably higher than the yield of the same roof surface with PV and solar collectors", according to Van Helden et al. (2013). The researchers claim that in their research, PVT has a 317% higher output than PV and solar thermal combined. This is even a bit higher than what was calculated, though it is still similar and realistic. It does show that PVT results in a significant energy improvement.

6.3 Energy balance

For an energy balance, it is again necessary to distinguish the heat demand from the electricity use, just as the thermal output needs to be separated from the electricity output. In the end, the amount of PVT collectors has to be rounded up to the output value that it can maximally cover. It was already known that the total energy demand of Docklands is 1,115 GJ: a heat demand of 912 GJ and an electricity demand of 203 GJ. The total thermal energy quantity that can be collected per year is 2,549 GJ: 561 GJ for a total of 285 m^2 BAPVT collectors and 1,988 GJ for a total of 1,728 m^2 BIPVT collectors. The total electrical energy quantity that can annually be generated is 598 GJ: 144 GJ for the BAPVT collectors and 454 GJ for the BIPVT collectors. Dividing these values by their area, gives a BAPVT thermal energy production of 2.0 GJ/m², a BAPVT electrical energy production of 0.51 GJ/m², a BIPVT thermal energy production of 1.2 GJ/m² and a BIPVT electrical energy production of 0.27 GJ/m². All this is summarised in figure 84:

	Q_{nd} [GJ/year] heat demand	$E_{EPus;nd}$ [GJ/year] electricity use	$Q_{nd} + E_{EPus;nd}$ [GJ/year] heat demand + electricity use	
Docklands	912	203	1,115	
	Q_{tot} [GJ/year] total heat output	Q_{coll} [GJ/m²/year] heat output	E_{tot} [GJ/year] total electricity output	E [GJ/m²/year] electricity output
BAPVT	561	2.0	144	0.51
BIPVT	1,988	1.2	454	0.27
BAPVT + BIPVT	2,549	n/a	598	n/a

Figure 84. Energy data of Docklands and the collectors (own illustration).

To find an optimal way of spreading the PVT collectors over the building, the total energy demand of Docklands and the thermal and electrical outcomes of the building-added (BAPVT) and building-integrated (BIPVT) collectors need to be matched in such a way that an energy balance arises. Since there are three parameters in this case - of which one is fixed and the other two can vary - multiple situations can be created, depending on what is desired. In order to not make it too complicated, two distribution methods of the PVT collectors are suggested:

- the BAPVT collectors completely cover the roof (as the PV panels and solar thermal collectors do in the current situation) and the facade is covered with BIPVT until the energy demand is met;

- the BAPVT modules cover the roof by half and the facade is covered with BIPVT until the energy demand is met. In this way, the part of the roof that is left uncovered, can be used for other purposes. Reasons for doing this can also be related to time and financial aspects.

For the two placement methods, this means the following:

- for the heat demand: 912 - 561 = 351 GJ is left over if the roof was to be fully covered. Dividing this output by the BIPVT heat production gives 293 m² of BIPVT area;

- for the heat demand: 912 - 281 = 631 GJ is left over if the roof was to be half-covered. This results in 527 m² of facade-integrated PVT elements;

- for the electricity use: 203 - 144 = 59 GJ is left over if the roof was to be fully covered. Dividing this output by the BIPVT electricity production gives 219 m² of BIPVT area;

- for the electricity use: 203 - 72 = 131 GJ is left over if the roof was to be half-covered. This results in 486 m² of facade-integrated PVT elements.

Knowing that the thermal demand dictates the amount of BIPVT collectors, 293 m² is needed when the roof is fully covered and 527 m² is needed when the roof is half-covered. However, in any case, too much electricity is produced. This amount can be determined by subtracting the electricity use from the total electricity output of the roof-mounted and facade-integrated collectors: 224 - 203 = 21 GJ per year. Since electricity storage is dismissed, there are two option possible: sell the electricity back to the grid (net metering) or convert it to heat and subsequently store it in the underground energy storage.

6.4 Influence of design parameters on the PVT quantity

Now that the energy balance and the (small) surplus of energy are known, it can be useful to know how various design parameters influence the quantity of PVT collectors and thus the energy balance. This accounts not only for Docklands, but also for similar buildings with different parameters. In this way, a guideline can be created where other buildings can be tested on. ENORM will be used to find out correlation between the amount of PVT collectors and some design parameters. Then, this correlation is passed on to the calculated areas of the PVT collectors.

First, a situation is created where the roof is completely covered with PVT modules, thus replacing the current panels and collectors. The total surface area of the facade-integrated elements should ensure that the EPC becomes 0. It has to be kept in mind that the PV cell type of the facade modules is dye-sensitised, so that the solar cell appearance can be dictated. Installing them in the south-east or south-west facade does not make a big difference, figure 48 showed. Besides this, the output power of a dye-sensitised PV cell is also important for the energy output. According to Meyer et al. (2009), the output power of a dye-sensitised solar cell with a module efficiency of 7% is 50 Wp/m^2 (pp. 18, 19). Since this was back in 2009, the output power of the type of cell in this report can be extrapolated. This means that a cell with an efficiency of 12% should have an output power of about 86 Wp/m^2. This output power will therefore be used to determine the amount of PVT collectors that are needed to get an EPC of 0. However, some restraint must be exercised since the application of extrapolation does not necessarily mean that this output power is precisely correct.

It should be kept in mind that the calculated PVT distribution applies for the design parameters that are characteristic for the building in its current state. Design parameters that are interesting for their influence on the amount of PVT collectors for similar buildings are:

- the window-to-wall ratio (WRR);
- the available roof area of the building that can be covered with PVT;
- the orientation of the building;
- the thermal resistance of the building.

The window-to-wall ratio is 0.28, according to ENORM and through the drawings of the architect.

6.4.1 Window-to-wall ratio (WWR)

To find out what the effect of the WWR is on the area *A* of the PVT collectors, the following methodology is selected. First, the WWR values are set from 0.10 to 0.80 (not taking into account building regulations, but solely to see what this ratio does). Second, the amount of facade-integrated PVT elements is proportionally compared to a complete roof full of BAPVT collectors, and a half-full roof covered with these collectors. In this way, the emphasis is more placed on relationship between the facade-integrated elements and the WWR. From this relationship, the amount of roof-based collectors can be extrapolated. Figure 85 shows the outcome:

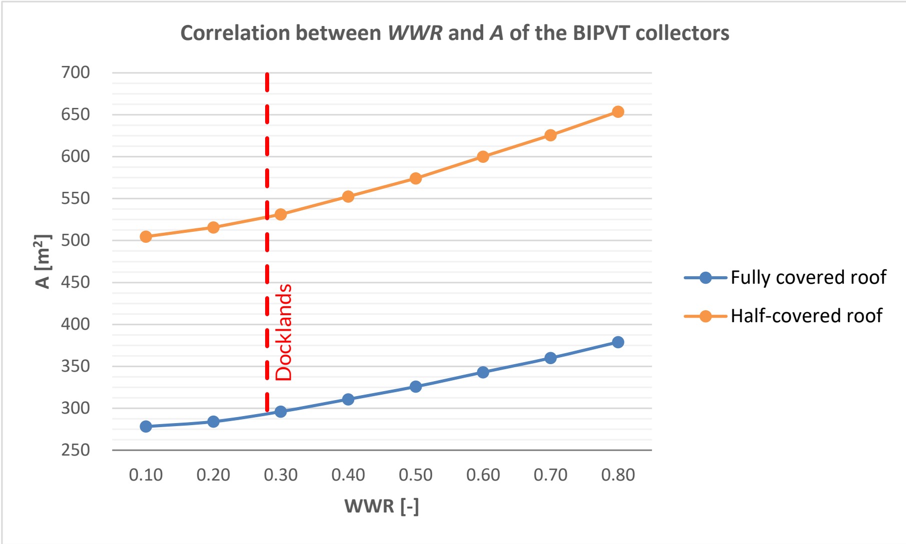


Figure 85. Influence of the WWR on the BIPVT area (own illustration).

The red dotted line indicates the WWR level (0.28) of Docklands. Figure 85 shows a rather flattened version of a quadratic function. Although this can somehow be expected - since glass is the weakest part of the building when it comes to heat control, and increasing the glass area asks more and more energy - the correlation visible in the figure is pretty flattened. Despite this, the figure clearly illustrates that, for instance, a building with a WRR of 0.60 needs 600 m^2 of PVT collectors in the facade (if the roof was to be half-covered) and 340 m^2 (for a fully covered roof). With 'building', a similar building compared to Docklands is meant, like a similar orientation, roof area and thermal resistance.

6.4.2 Roof area

Another interesting aspect that can be compared to the PVT quantity is the roof surface of a building. Here, the area of the roof-mounted PVT collectors is plotted against the area of the facade-integrated modules. The result is shown in figure 86:

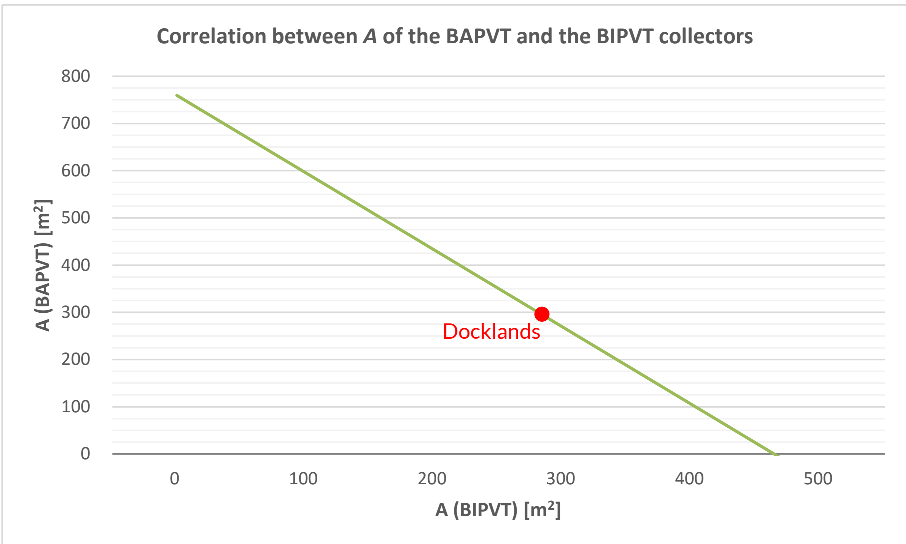


Figure 86. Correlation between the roof areas of the BAPVT and the BIPVT collectors (own illustration).

Out of the figure it can be found that if a roof surface of approximately 460 m^2 is available, that same roof filled with PVT collectors is - relatively seen - enough to cover the energy demand of the building. This could for example apply to an apartment building which is not that high, but has a floor plan that is spread over fewer floors.

6.4.3 Orientation

Evidently, the orientation of the building (or: facades) affects the number of PVT elements that are needed to cover the energy demand. This is not directly applicable on roof-mounted modules, as they are placed in the most optimal direction and inclination on a flat roof. For the facades, however, this is not always possible. For Docklands, only the facades that are the most favourable have PVT collectors integrated in them. Nevertheless, it is relevant for other buildings to find out how their orientation determines the quantity of facade-integrated PVT collectors. Just as for the window-to-wall ratio, a roof completely filled and half-filled with PVT is considered. Figure 87 illustrates the results:

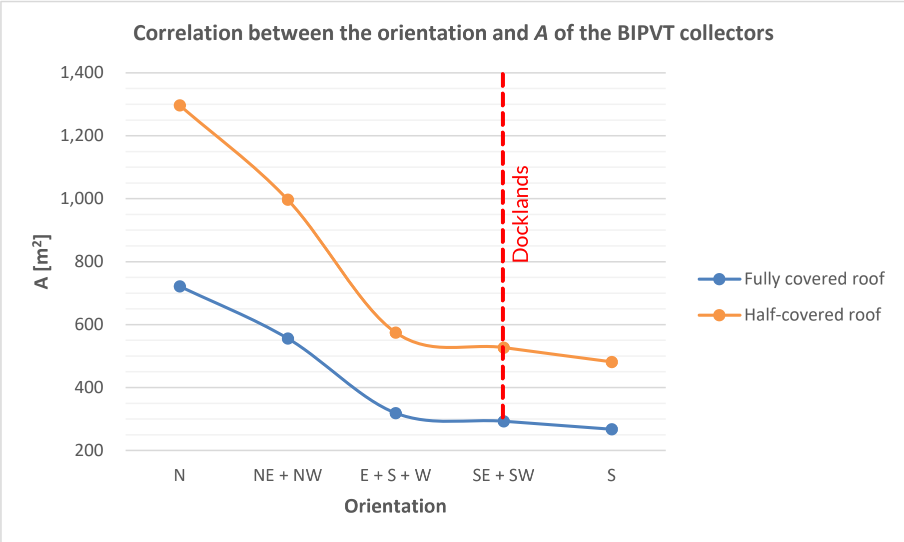


Figure 87. Correlation between the orientation and the area of the BIPVT collectors (own illustration).

Figure 87 is basically a different interpretation and direct proof of figure 48: it does not really matter if the PVT elements are integrated in and spread over the south, the south-west and south-east, or the east, south and west facades, although the south facade is the best choice. Basically every orientation where the word 'north' is present in, results directly in much higher losses. This is especially the case when the roof is not fully covered: differences between the various orientations tend to rise much more when less PVT collectors are situated on the roof.

6.4.4 Thermal resistance

The thermal resistance of a building can be divided in the resistance of the floor, the facades and the roof. Although the facades have the most surface area that comes into contact with the outside, the thermal resistance of the floor and the roof can also be relevant for their effect on the amount of BIPVT collectors. The bottom limits of the R-values that will be tested, are the ones that are currently applicable. Subsequently, six different R-values with an interval of 0.5 are used to see their effect on the number of collectors. Figure 88 shows how changing the thermal resistance of the different building parts influences the quantity of the BIPVT elements:

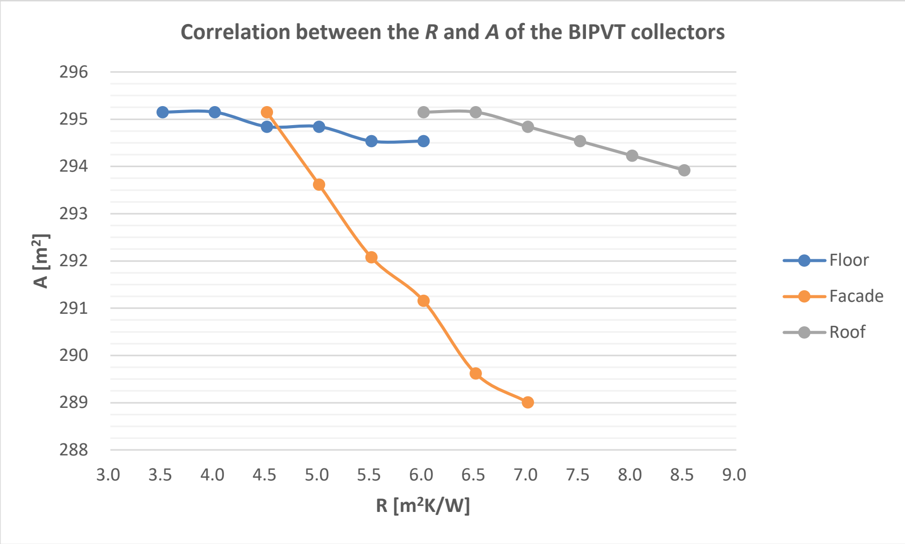


Figure 88. Correlation between the thermal resistance and the area of the BIPVT collectors (own illustration).

Raising the thermal resistance of the facade results in a steeper downfall compared to that of the floor and the roof. Additionally, the amount of collectors are slightly more affected by R-value changes of the roof than the floor.

6.5 Conclusion

In this chapter, the thermal and electrical outputs of the roof-mounted and facade-integrated PVT collectors were compared to the energy demand and energy use of Docklands. The comparison made clear that the maximum quantity of roof-mounted PVT collectors were not sufficient to cover the whole demand of Docklands. Additionally, if the south-west and the south-east facades of the building would then be integrated with PVT modules, this would generate way too much energy. This meant that an optimal area of the modules should be calculated, which was done later on. Additionally, it can be concluded that PVT collectors indeed have a higher thermal and electrical output per m^2 than photovoltaic panels and solar thermal collectors. The calculations point out that PVT gives a three times higher energy yield, which is almost similar to a practical research example.

For the optimal division of PVT collectors on the roof and in the facade of the multi-family building, two scenarios were proposed: a fully covered roof and a half-covered roof. The rest of the PVT modules have to be integrated in the facade. However, in both cases, an energy surplus of 21 GJ arises, which can be sold back to the grid or can be converted to heat and subsequently stored.

Finally, the roof-mounted and facade-integrated PVT collectors were subjected to various design parameters. The reason why this is done, is to bring the collectors in a broader perspective. That is, investigating how parameters like the window-to-wall ratio and the orientation of a building affect the quantity of PVT modules that need to be applied in order to meet the energy demand of that same building. In this way, a reasonable amount of collectors can be given for buildings with different design parameters.

The next chapter treats the development of the division and integration of the PVT collectors in the facade of the multi-family building.

7. FACADE-INTEGRATION ASPECTS OF PVT

The final chapter of this thesis describes the integration of the PVT collectors in the facade of the multi-family building. This will include facade details and eventual three-dimensional views to show the mutual placement and installation of the collectors. This chapter concludes with the division of the collectors over the roof and in the facade as an addition to area values from the previous chapter.

7.1 Introduction

The first part of this chapter will talk about the focus areas of integrating PVT collectors into a building. After that, various facade typologies are presented in which PVT modules can be integrated in. The reason why this is done is to expound how PVT can be integrated into various types of facades. Three typologies are selected: a traditional cavity wall, an aluminium-cladded facade and a curtain wall. After this, the focus will be on Docklands - which actually has a traditional cavity wall facade - where three-dimensional views are presented with attention for the connection and installation aspects of the PVT modules and the surrounding facade elements like windows. Finally, the roof and the representative facades of the multi-family building are shown, added and integrated with the PVT collectors. Various sketches of the facade-integration of PVT are added as an appendix to this report.

7.2 Focus areas of PVT integration

Before the actual facade typologies are discussed, it is important to emphasise some focus areas when it comes to PVT integration. These focus areas can be taken into account when integrating PVT modules into various facade typologies later on.

7.2.1 Partial substitution of facade elements

It was already discussed in paragraph 2.5 that an integration is not the same as an addition. This means that in case of an integration, a part of the outer leaf or facade cladding is to be substituted by - in this case - PVT modules. By applying this substitution, several facade properties like insulation, water-tightness, air-tightness and structural integrity can be affected.

The first property is mostly not present in the outer part of the facade, except in the case of sandwich panels. This makes it difficult to integrate PVT collectors into this facade type. One option is to apply thicker insulation to the collectors. Anyhow, this situation is neglected in this report; only facades with the insulation located in the inner part are treated.

The outer part of the facade also has an important function when it comes to the air- and water-tightness. It can be seen as the ‘first line of defence’. Although damp-proof membranes are mostly applied as a ‘second line of defence’ to protect the insulation, it is still wise to connect the PVT collectors as air- and water-tight as possible. This can be done by creating overlaps between the collectors. An exception would be for the transition from a collector to outer cavity leafs, cladding or windows: some adjustment space needs to ensure cavity ventilation.

The last important facade property is the structural integrity. In general, the inner (cavity) wall transfers the load from the floors and roofs to the ground. The outer part of the facade is mostly mechanically fixed to the inner wall. In case of the facade-integration of PVT, it thus is relevant to connect or suspend the PVT collectors effectively to the structural part of the building.

7.2.2 Piping system

The first focus area is the placement of the incoming and outgoing water pipes. Each collector needs to be attached to a pipe that supplies (cold) water as well as a pipe that takes back the heated water. The distribution of the water is partly comparable to an irrigation system in agriculture: water is distributed per pipe and flows to a point where it is spread onto the land.

One of the differences with this 'irrigation' system on the facade is the angle, and thus it requires more pumping energy. Nevertheless, a way should be found to develop a centralised piping system that is as simple and effective as possible.

To keep the system centralised, there should be various groups of horizontal or vertical distribution pipes - an incoming and an outgoing pipe - located on the facade, having an equal distance between them. In-between these distribution pipes, a group of five collectors is placed. This number is based on the amount of PVT elements connected in series as determined earlier. Finally, the distribution pipes are brought indoors per floor by applying a wall and floor recess locally. Figures 89 shows a proposal of the piping system on a fictional facade, with horizontally connected PVT collectors. Figure 90 illustrates the system with vertically placed modules:

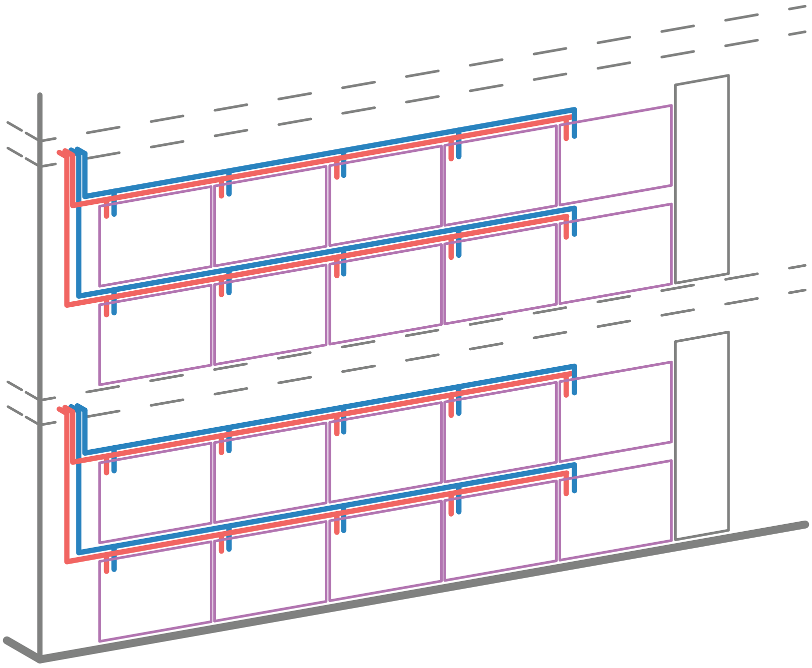


Figure 89. Proposed piping system for horizontally arranged facade-integrated PVT collectors (own illustration).

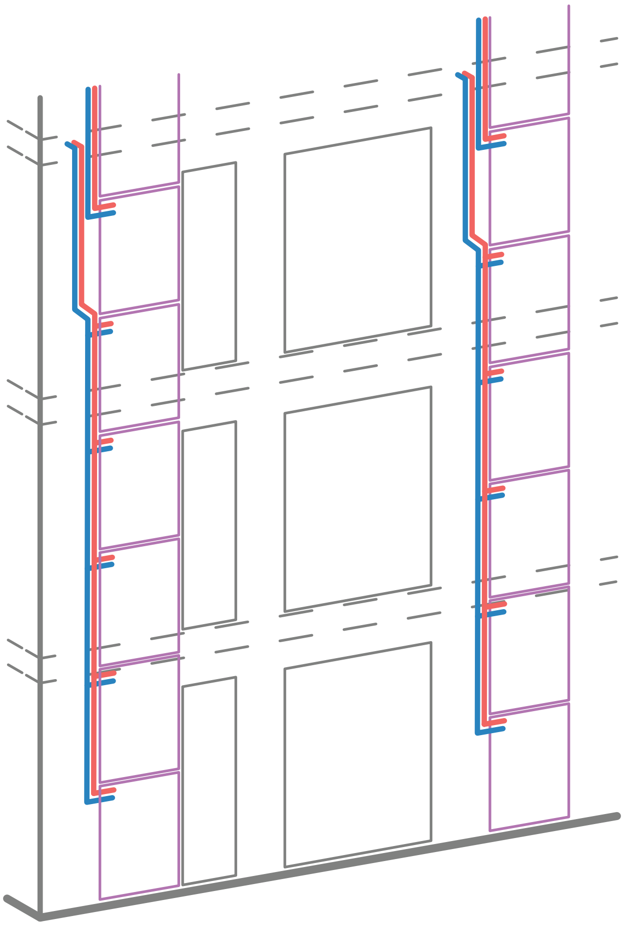


Figure 90. Proposed piping system for vertically arranged facade-integrated PVT collectors (own illustration).

Besides the proposals shown in the previous figures, it is also possible to move the piping system to the inside of the building. In that case, space for the pipes on the outer part of the facade does not have to be taken into account, thus improving the design freedom. A downside of the relocation of the distribution pipes to the inner part of the building is the fact that for every PVT collector, a recess has to be made in the wall and/or floor in order to bring the pipes indoors. This will result in an increase of the amount of thermal bridges and also requires serious thinking about the load-bearing aspects of the wall. However, since there are more distribution pipes located indoors, the thermal losses over the pipes will be significantly less. Figures 91 and 92 show the described proposal for a horizontally and vertically arranged system:

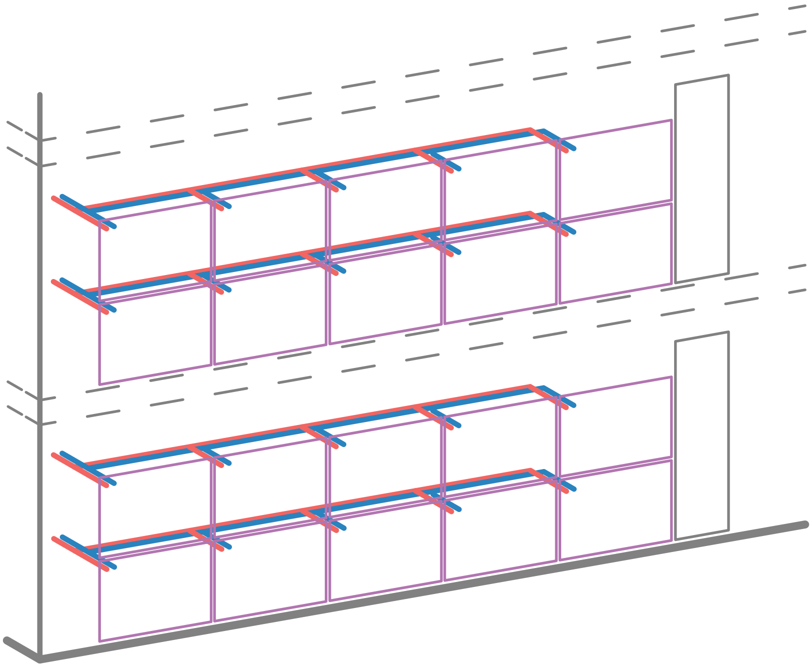


Figure 91. Proposed indoor piping system for horizontally arranged facade-integrated PVT collectors (own illustration).

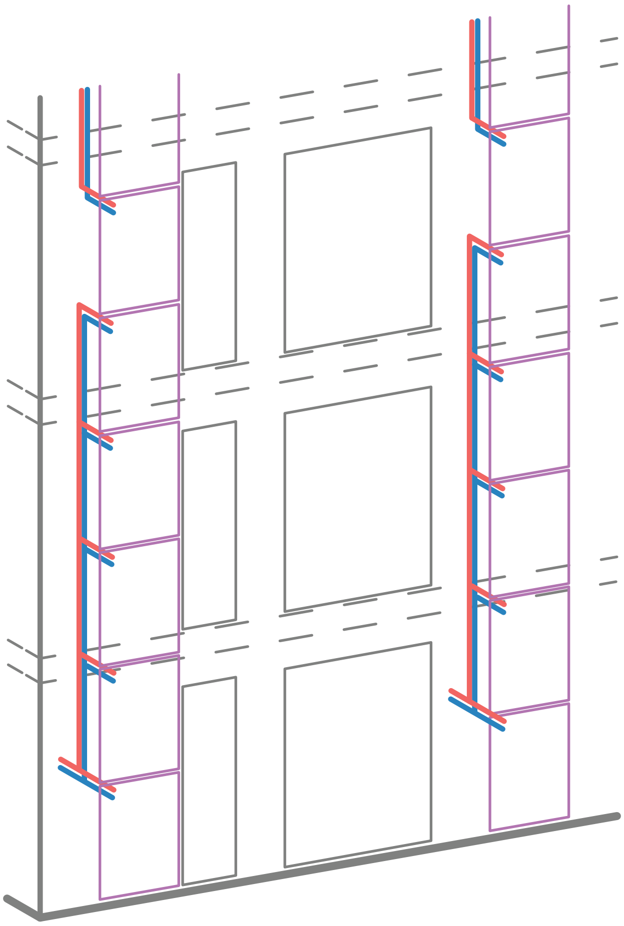


Figure 92. Proposed indoor piping system for vertically arranged facade-integrated PVT collectors (own illustration).

7.2.3 Maintenance

Another important point of attention is the possibility for maintenance services. The attachment of the PVT modules to the distribution system, but also the distribution system itself should be reachable by service technicians. In the case of installing the pipes on the outside of the facade, maintenance can be done by covering the pipes it with lockable small doors or locks. The appearance of these panels can in turn be dictated by the client or the architect. Conversely, when the pipes are placed indoors, maintenance can be done there.

7.2.4 Dimension flexibility

The final focus area is the dimension flexibility. The limitation of the collector size is clearly visible in figures 89 to 92. Generally, every solar panel or collector comes in a limited amount of types. If we take a look at the PVT modules sold by Brandoni Solare, it appears that they all have recurring widths of 991/997 mm and lengths of 1,655/1,661 mm - though the absorber area is only 1.44 m^2 (Brandonia Solar S.p.A., n.d.). This means that the design freedom of an architect is extremely restricted when applying these types of PVT modules in a facade. In order to have this design freedom, the PVT market should broaden the dimensions of their products. It would even be better to have a so-called PVT wall system, where the (wall-integrated) PVT collectors can be produced in almost any dimension desired. In this way, the producer can adjust his product to the wish of the architect. However, this also implies major financial consequences, possibly more complex calculations and an introduction of PVT integration early in the construction progress. Figure 93 shows how an improved design freedom can be related to the dimension flexibility of a PVT collector: the more sizes, the more buildings that are qualified for application possibilities:

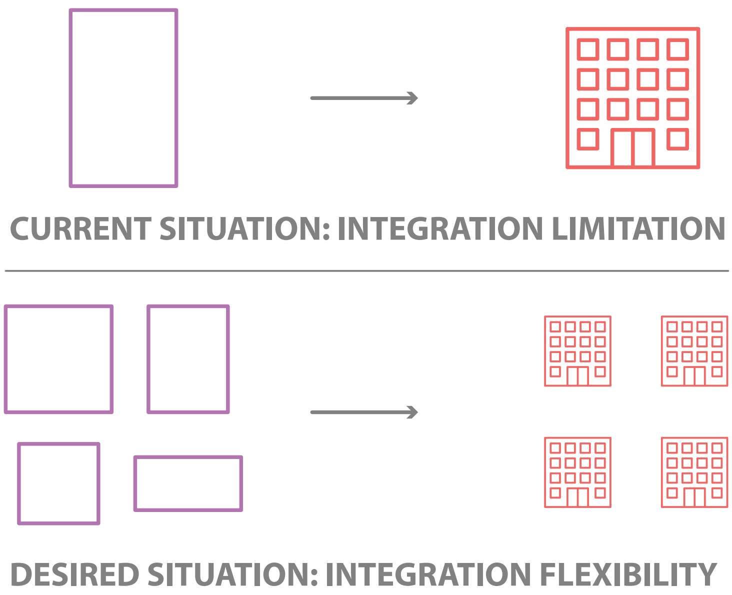


Figure 93. Relation between dimension flexibility and design freedom (own illustration)

7.2.5 Conclusion

In this sub-paragraph, it can be concluded that there are two main solutions when it comes to the piping system of the PVT collectors. There are a couple of decisive factors when making a choice between those two solutions. Locating the distribution pipes on the outer part of the facade limits design freedom and has comparatively higher thermal losses, though it results in less thermal bridges and less recesses in the walls and floors. A piping system that is placed mostly inside the building increases the design freedom and has less thermal losses, but the amount of thermal bridges and recesses is higher. In any case, it is essential to introduce PVT integration early in the building process in order to achieve a most effective result. Figure 97 gives an overview of the consequences of the main integration solutions:

PIPING SYSTEM IN OUTER PART OF FACADE:

- (+) less thermal bridges
- (+) less recesses
- (−) less design freedom
- (−) higher thermal losses

PIPING SYSTEM IN INNER PART OF FACADE:

- (+) more design freedom
- (+) less thermal losses
- (−) more thermal bridges
- (−) more recesses

Figure 94. Consequences of integrating the piping system in the inner or outer part of the facade (own illustration).

7.3 Integration in various facade typologies

7.3.1 Traditional cavity wall

A cavity wall has been applied for many decades in Dutch buildings. Traditionally, this type of wall is constructed of a brickwork outer leaf, a cavity, insulation material (although this was not common in the earliest cavity walls) and an inner leaf of sand-lime stone, concrete or a timber-frame wall. In this thesis, an inner leaf of concrete is chosen. We consider a random apartment building with windows, arranged in a structured grid:

Figure 95. Facade example of a cavity wall (unscaled; own illustration).

What can be noticed regarding the facade of figure 95 is that there is little space for integrating a PVT collector used in this research. Although there are many facades where the collector and the accompanying piping system can be integrated in, it is again emphasised that dimension flexibility is an important issue in case PVT collectors evolves to a wall-integrated concept. Additionally, integrating a PVT module in the facade of figure 95 requires a methodology to connect the PVT module to the construction behind - which would be the concrete. To minimalise the thermal bridge to as little as possible, some reference material by the Dutch company Plastica is consulted. Plastica (2017) is a supplier of building materials such as cassette panels that can be used as facade cladding. These cassette panels are mounted on a load-bearing construction behind with the use of aluminium brackets. Although they run through the insulation layer, between the coupling of the brackets and the construction behind, a plastic thermal bridge interruptor ensures that only the connection bolt forms a thermal bridge (p. 57). In this way, conduction is limited as much as possible. A detail of this solution is shown in figure 96. The aluminium brackets that are used for the cassette panels can in turn be connected to the metal thermal absorber plate of a PVT collector.

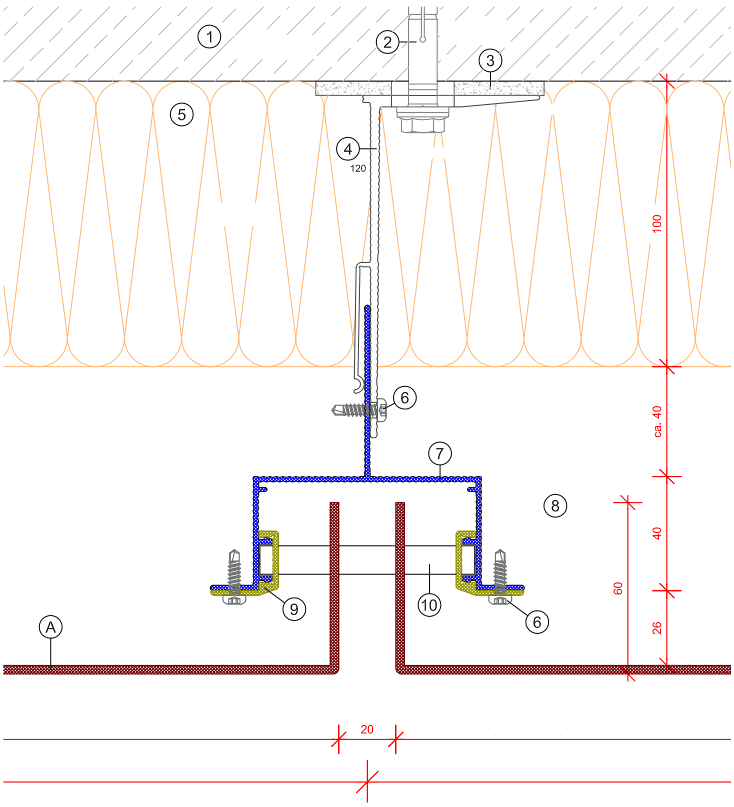


Figure 96. Cassette panels mounting with thermal bridge interruption (Plastica, p. 57, 2017).

There is, however, a downside to the attachment method of figure 96: it seems inconvenient to provide maintenance services. The cassette panels seem to be mounted 'permanently'. In case of the integration of PVT collectors, a facade suspension is preferred. This would mean that various profiles have to be fixed to the constructional part, where the module can be suspended on. In this way, a collector can be temporarily removed from the facade in case it is broken.

Besides the connection between a PVT collector and the underlying construction, there are some other connection types left to define: the connection between a module and the brickwork or window frame, and the mutual module connection. In an attempt to tackle these problems, some sketches are made, which are shown in the appendix of this report.

The focus should therefore be replaced from the central areas to the edge areas of the PVT collectors. Curtain walls are also (mostly) fixed on the edge - whether this is done with or without a frame - to the underlying structure. It would therefore be wise to know how this curtain wall fixation could be done. Figure 97 shows a detail:

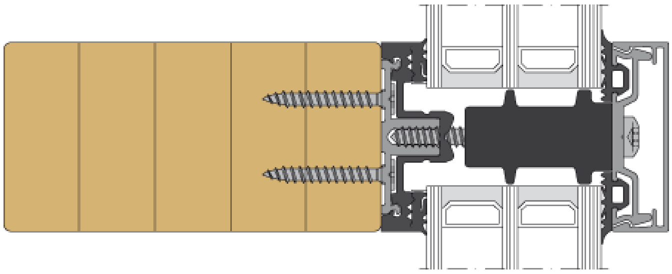


Figure 97. Curtain wall profile on a timber construction (Raico Bautechnik GmbH, n.d.).

The profile and glazing depicted in figure 97 can be substituted by PVT elements. The location of the three glass panes can be replaced by one outer glass pane, PV cells and the thermal absorber plate. However, this replacement is just the first step. It is essential to design a detail that guarantees a certain degree of removability of the elements, taking into consideration an appropriate mutual connection of the profiles that also makes it possible to remove the elements. This can be an aluminium angle bar (with slotted holes), which is fixed to the structural wall. This angle bar is provided with welded, protruded edges in which the PVT elements can be slid in.

For the elaboration of the details for a traditional cavity wall, we stick to one of the proposed piping systems and not to the facade example of a cavity wall. The reason for this is that the concept of integrating a PVT module has to be made clear here; the actual integration into the facade of Docklands - where also the facade composition is taken into account - is discussed later on in this chapter. Anyway, to clarify the integration, there have been made four different horizontal details: one detail where the PVT element joins the brickwork (HA), one where the PVT element joins a window frame (HB), one where a collector is connected to the vertical distribution pipes (HC) and one detail that shows the mutual connection between two PVT collectors (HD). Furthermore, one vertical detail is shown, in which the mutual connection between two PVT collectors including the horizontal distribution pipes are drawn (VA). The details are shown in figures 99 till 103. First, figure 98 illustrates the piping system again, but now with the locations of the details. Besides, it has to be made clear that only the cavity wall with a concrete inner leaf is shown here. For the cavity wall with a timber-frame inner leaf, there is referred to the appendix.

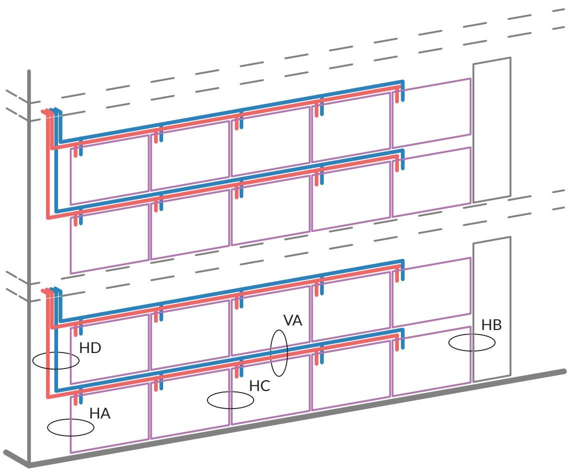


Figure 98. A proposed piping system with detail locations (own illustration).

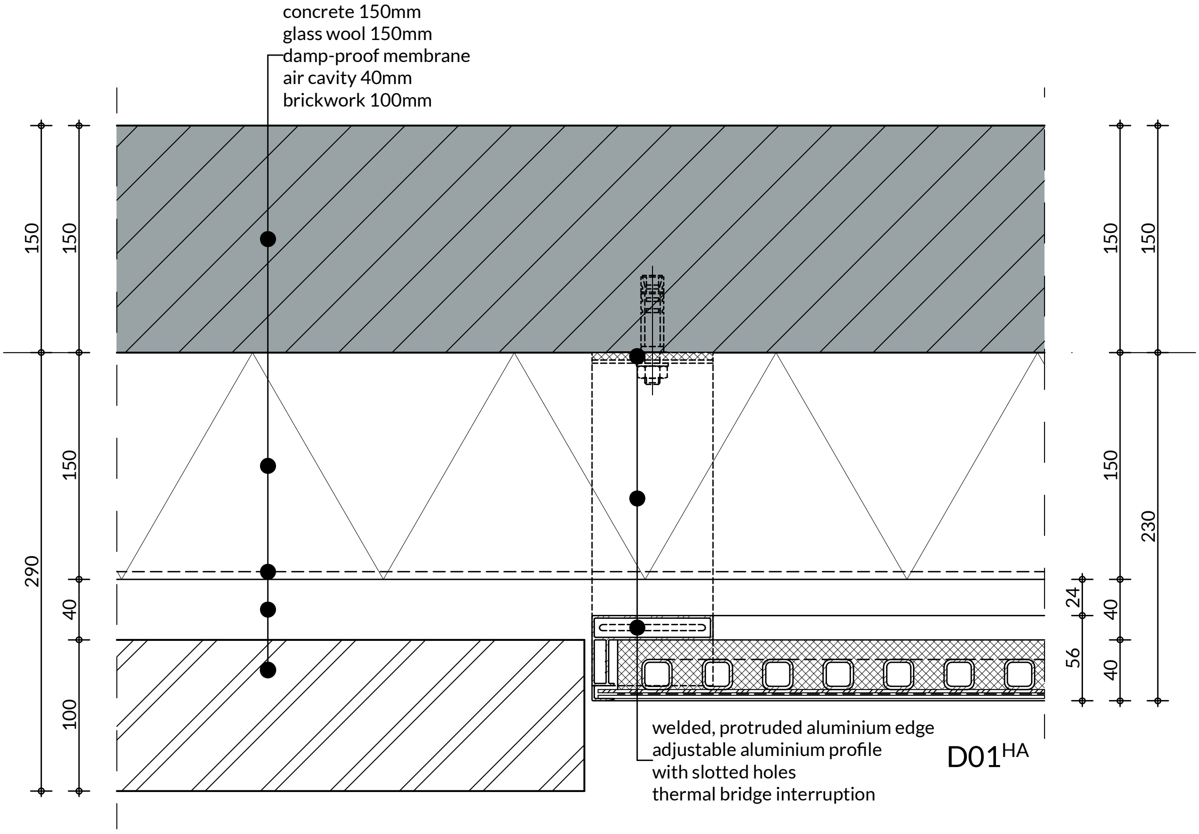


Figure 99. Cavity wall detail D01^{HA}, where the brickwork meets the PVT module (scale 1:5; own illustration).

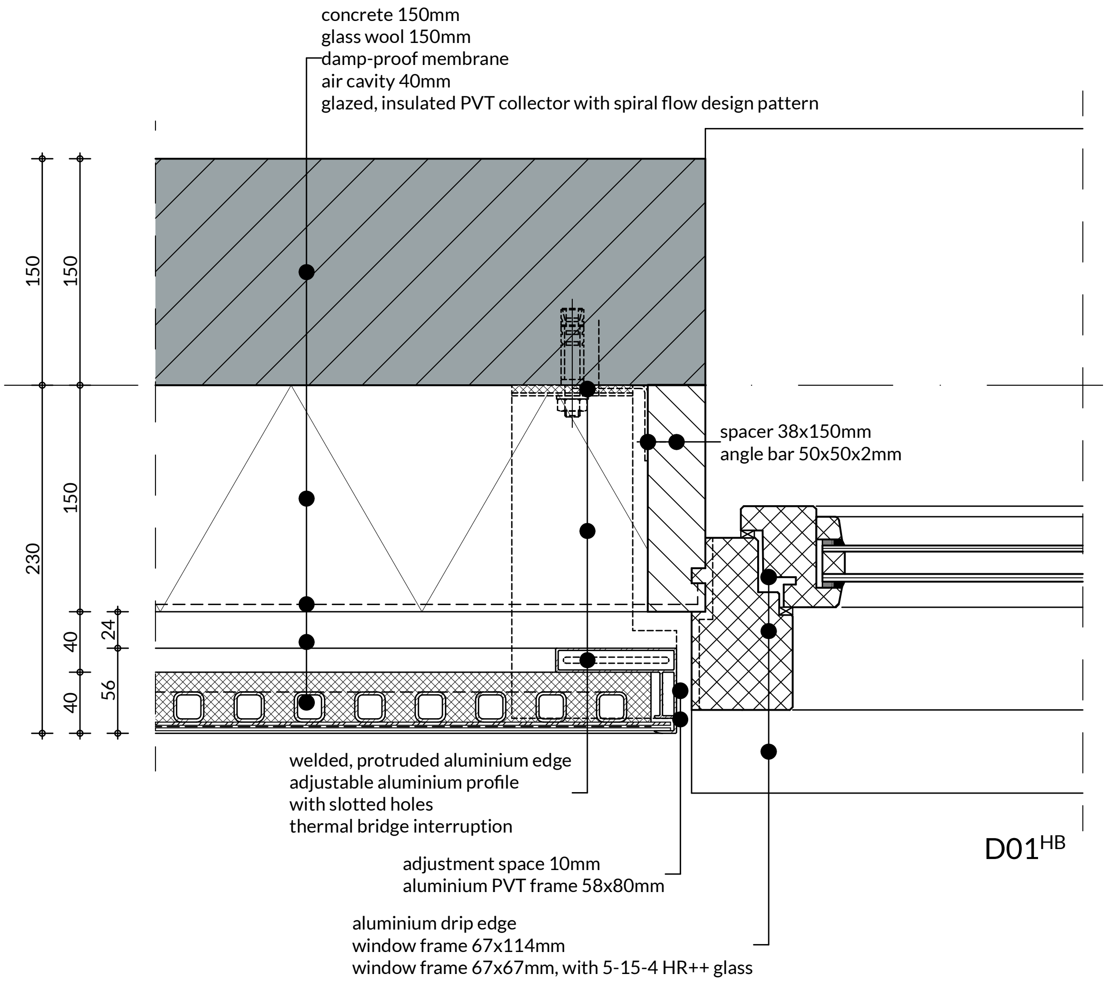


Figure 100. Cavity wall detail D01^{HB}, with the connection between PVT and the window (scale 1:5; own illustration).

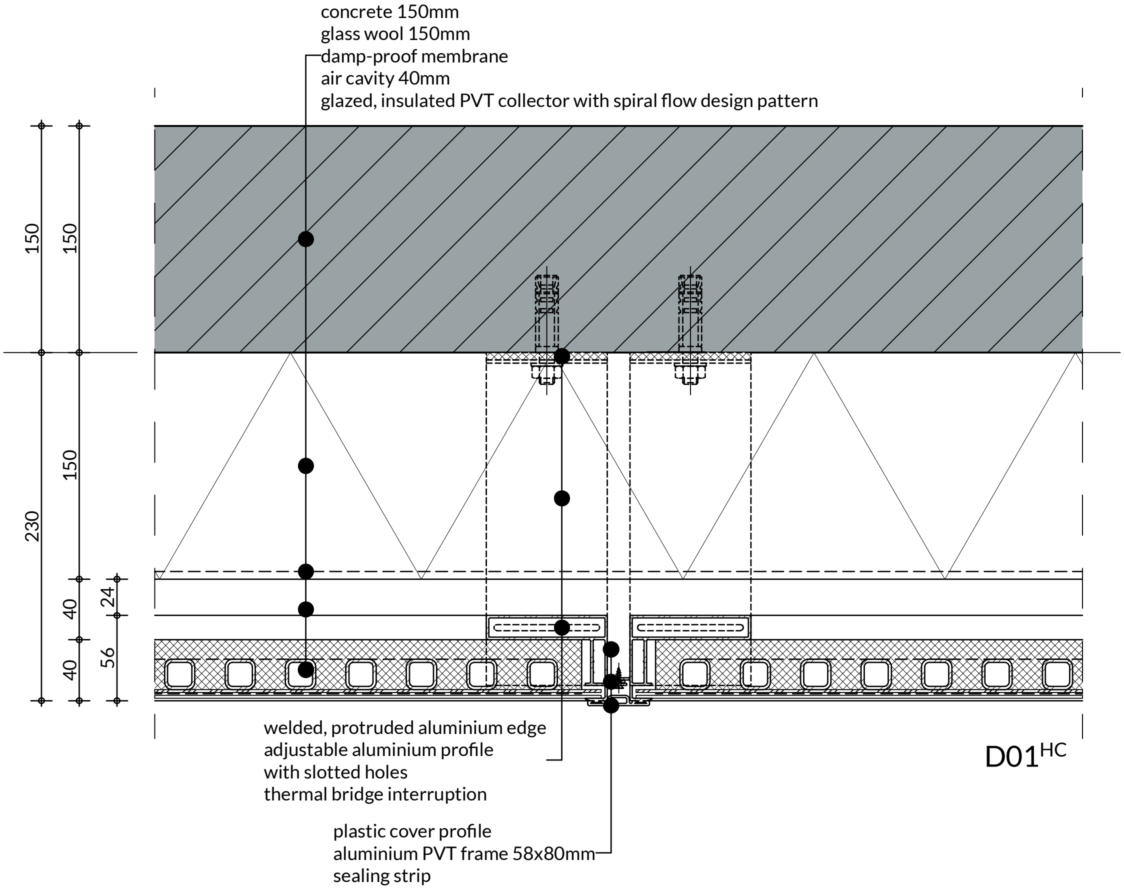


Figure 101. Cavity wall detail D01^{HC}, with the mutual PVT connection (scale 1:5; own illustration).

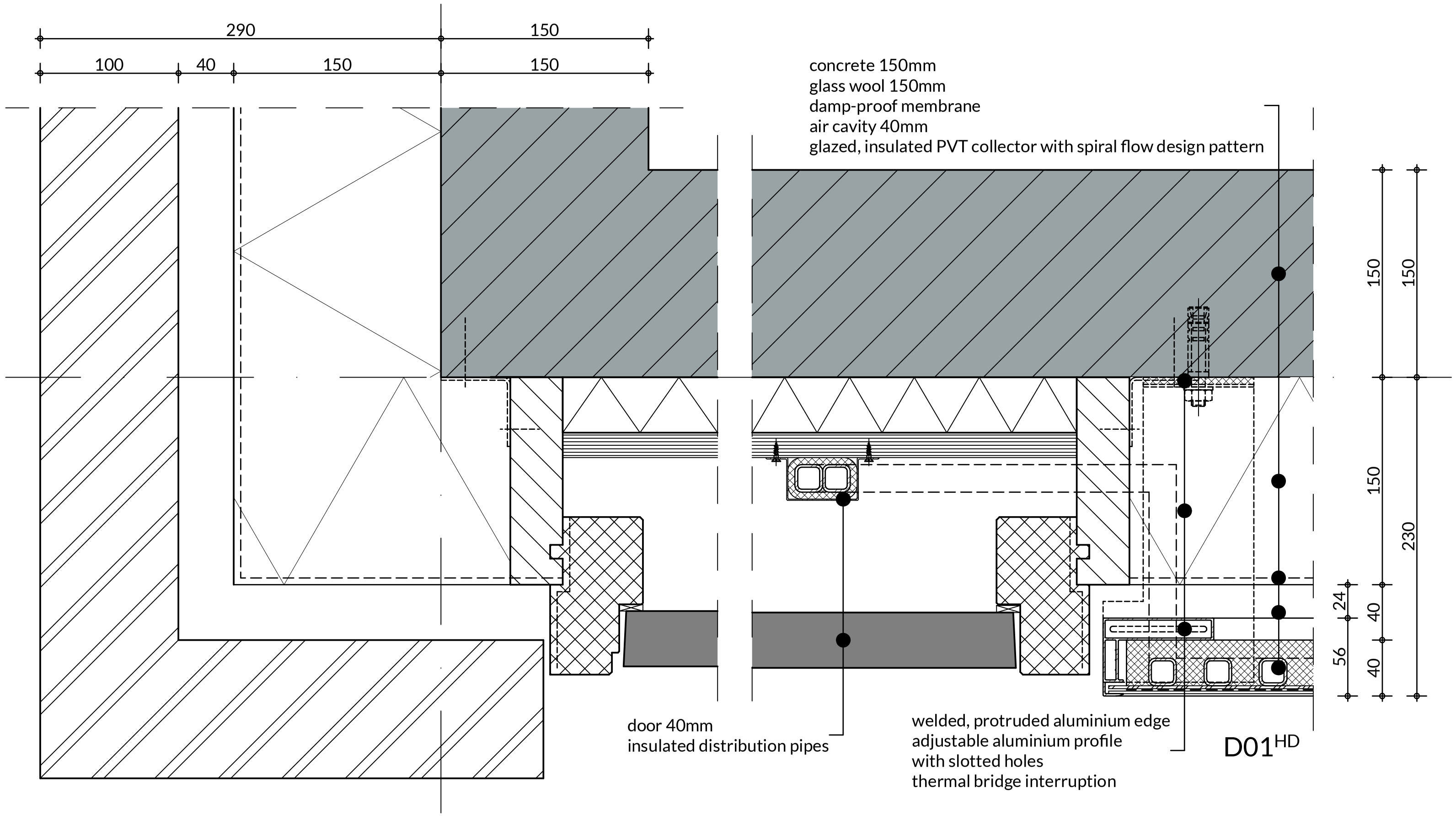


Figure 102. Cavity wall detail D01^{HC}, with the connection between PVT and the distribution pipes (scale 1:5; own illustration).

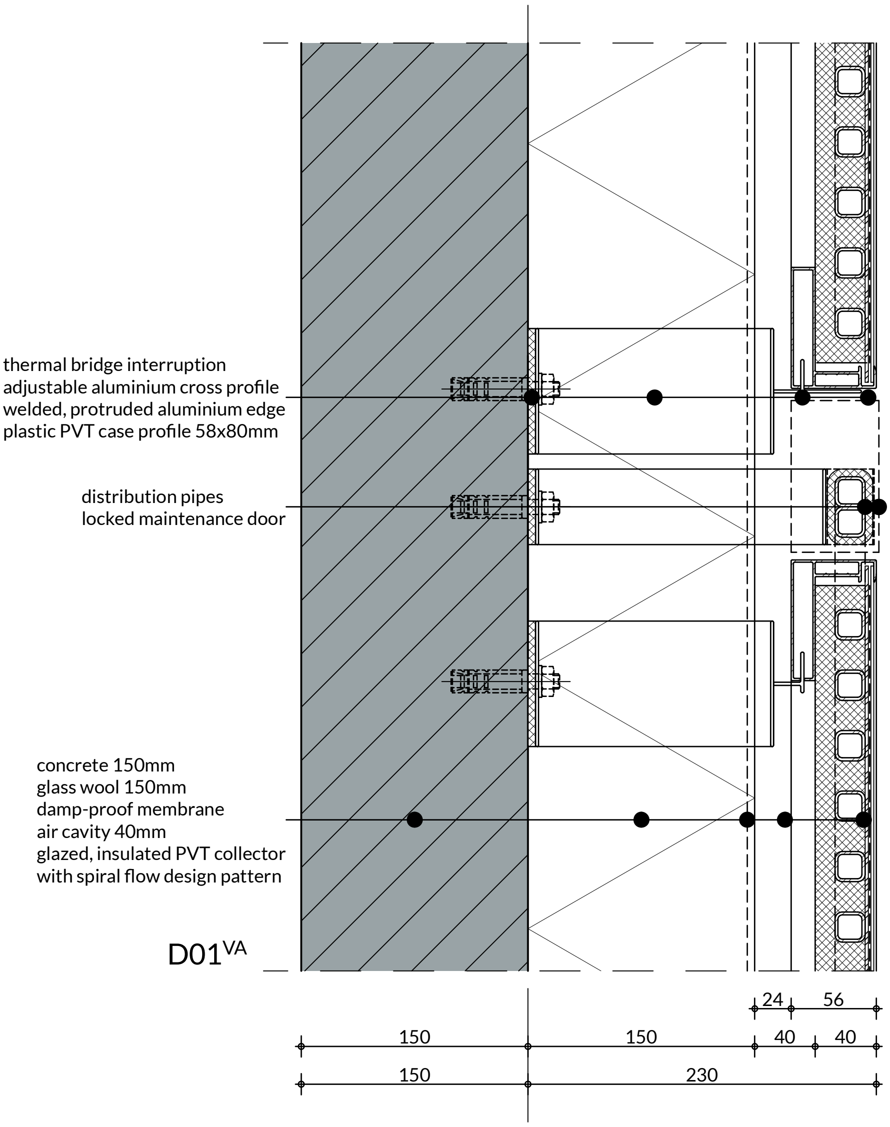


Figure 103. Cavity wall detail D01[VA], with the mutual PVT element connection and distribution pipes (scale 1:5; own illustration).

7.3.2 Aluminium cladding

Previous details have made clear that the mounting of the PVT elements largely depends on the structural wall. This makes it irrelevant to show the elements when they replace aluminium cladding. However, the mutual connection between a PVT collector and a cladding element is still interesting. That is why only a horizontal section of this connection will be shown in the appendix. Also, the facade view is shown there.

7.3.3 Curtain wall

The facade view and a horizontal detail of the connection between a curtain wall and a PVT collector is shown in the appendix.

7.3.4 Integration in balconies

The integration of PVT collectors in the balconies is theoretically possible. In case of Docklands, the glass balustrades can be replaced by collectors. However, this integration is considered too dangerous, for relatively high temperatures can be reached. A solution for this problem would be the development of additional, protective casings or fences around the collectors.

7.4 Division, integration and visualisation for Docklands

For the division and visualisation, various and renders are presented to show the eventual effect of applying roof-mounted and facade-integrated PVT collectors to Docklands. It has to be noted that a situation will be shown with flexibly dimensioned PVT collectors, in order to show an aesthetical building appearance of the (near) future.

7.4.1 Division for a fully covered roof

If the roof is completely filled with PVT collectors, the amount of facade modules would be 293 m^2. However, since the dimension flexibility of the collectors entail different outputs per collector, the amount of modules that need to be connected in series can vary. This is neglected in this paragraph, though, as this takes a lot of time to redefine. Anyway, a large part of the south-west facade and a small part of the south-east facade are used to integrate PVT elements of various dimensions. Although there are many layouts possible, in this case there is chosen to place the collectors between the windows in order to show the potentials of the PVT modules. In the end, 113 collectors are integrated, with a total area of 296 m^2. This results in a small energy surplus of 4.2 GJ/m^2/year of thermal energy and 0.81 GJ/m^2/year of electrical energy, on top of the existing surplus of electrical energy as discussed in chapter 6.

7.4.2 Division for a half-covered roof

For a half-covered roof, 527 m^2 of PVT collectors should be integrated in the facades. However, it turns out that there is not enough (useful) space. If the south-west facade was to be utilised maximum, this would give 331 m^2 of modules. The south-east facade, conversely, has much less effective space; the lower part lies in the shadow most of the times due to a neighbouring building close to Docklands. The amount of space that is available in this facade is about 100 m^2. This means that about 100 m^2 is needed to meet the energy requirements of Docklands.

7.4.3 Integration approach

The integration itself can be approached in the two ways described in sub-paragraph 7.2.2: placing the pipes on the outside or locating them on the inside. For each approach, the outside appearance can practically be the same, since possible maintenance doors or locks can have the same 'image' as the brickwork. The integration of the PVT collectors in the facade of Docklands is visualised in figures xxx and xxx. Moreover, only visualisations for a fully covered roof are shown, because it is extremely hard and considered not very effective to show the situation with a half-covered roof.

Figure 104. Visualisation of the PVT integration in Docklands (own illustration).

Figure 105. Visualisation of the PVT integration in Docklands (own illustration).

7.5 Conclusion

This chapter made clear that for the integration of a PVT module, it can be wise to think of focus areas. The integration not only requires a proper connection between an element and a facade part, but also a proper mutual connection. In addition to this, a proper layout of the distribution pipes needs to be taken into account, as well as maintenance services. Two solutions for this problem are the placement of the pipes on the inside or on the outside of the facade, each with its own advantages and drawbacks.

Furthermore, the integration and the division of the PVT collectors showed that dimension flexibility is of great importance. It is therefore recommended to develop multiple collector sizes in order to meet the wish of architects and clients and to eventually increase the integration possibilities of PVT collectors.

8. CONCLUSION

The main purpose of this research is to propose and substantiate a PVT system configuration with the additional integration of PVT collectors into a facade, all this applied (in)to the multi-family building of Docklands in the Amsterdam neighbourhood of Buiksloterham. In this conclusion, the four sub-questions and finally the main research question will be answered, with the aim to endorse the main purpose of this research. Before this is done, the process for developing a PVT concept in the light of this thesis (figure 106) as well as a wider approach for developing a PVT concept are presented (figure 107).

The goal of figure 106 is to illustrate the linear progress chosen in this thesis: the maximisation of the PVT output and the optimisation of parameters for the PVT integration. This process starts by determining the energy demand and energy use of the case study building. The second step comprises of the calculation of the thermal, temperature and electricity output of a chosen PVT collector. This step includes the maximisation of the thermal and temperature output, which indicates that evaluation points are taken every time a possible maximisation is chosen. Important evaluation points here are the insulation capacities, mass flow rate, number of collectors in series and the total amount of PVT collectors. The third step is the development of a system configuration of which PVT is a part of. The penultimate step is the energy balance that needs to be created, where the amount of energy that is provided by a specific number of PVT collectors needs to match the energy requirements of the case study building. The previous three steps are crucial here, since they all affect the energy balance in their own way. Finally, all or some of the PVT modules have to be developed to a PVT product. This final step partly depends on the way the piping system is installed together with the dimension flexibility of the collectors. It can thus be seen as an optimisation step, since other parameters have to be sacrificed (as figure 94 for example showed).

The purpose of figure 107 is to show a number of parameters that can possibly be optimised during the process - and thus making the concept more generally applicable. As shown in the previous figure, the thermal and temperature output of the PVT collector is maximised and aspects of the PVT integration are optimised. However, there are a lot of additional parameters that can be optimised in order to implement a PVT concept into other buildings. Moreover, it does not need to be a linear process, as figure 107 shows, since there can be a constant feedback process present between various building-related, PVT-related and system configuration-related parameters. This means that every aspect of the concept is constantly affected by optimisation. In addition to this, optimisation means that there will be aimed for the most favourable result, where time and money are taken into account. In the end, the optimisation processes all influence the energy balance and the PVT integration.

To give examples of correlations between various parameters, two graphs are created. Figure 108 shows that for a higher insulation value of the building, the effect of adding more PVT collectors decreases - since less energy is needed/lost. The energy balance can be created on the basis of various limits like time, money, aesthetics and technology. Figure 109 shows that the (overall) thermal and temperature output of a PVT collector rise if its insulation capacities increase, but again, various limitations can influence the energy balance.

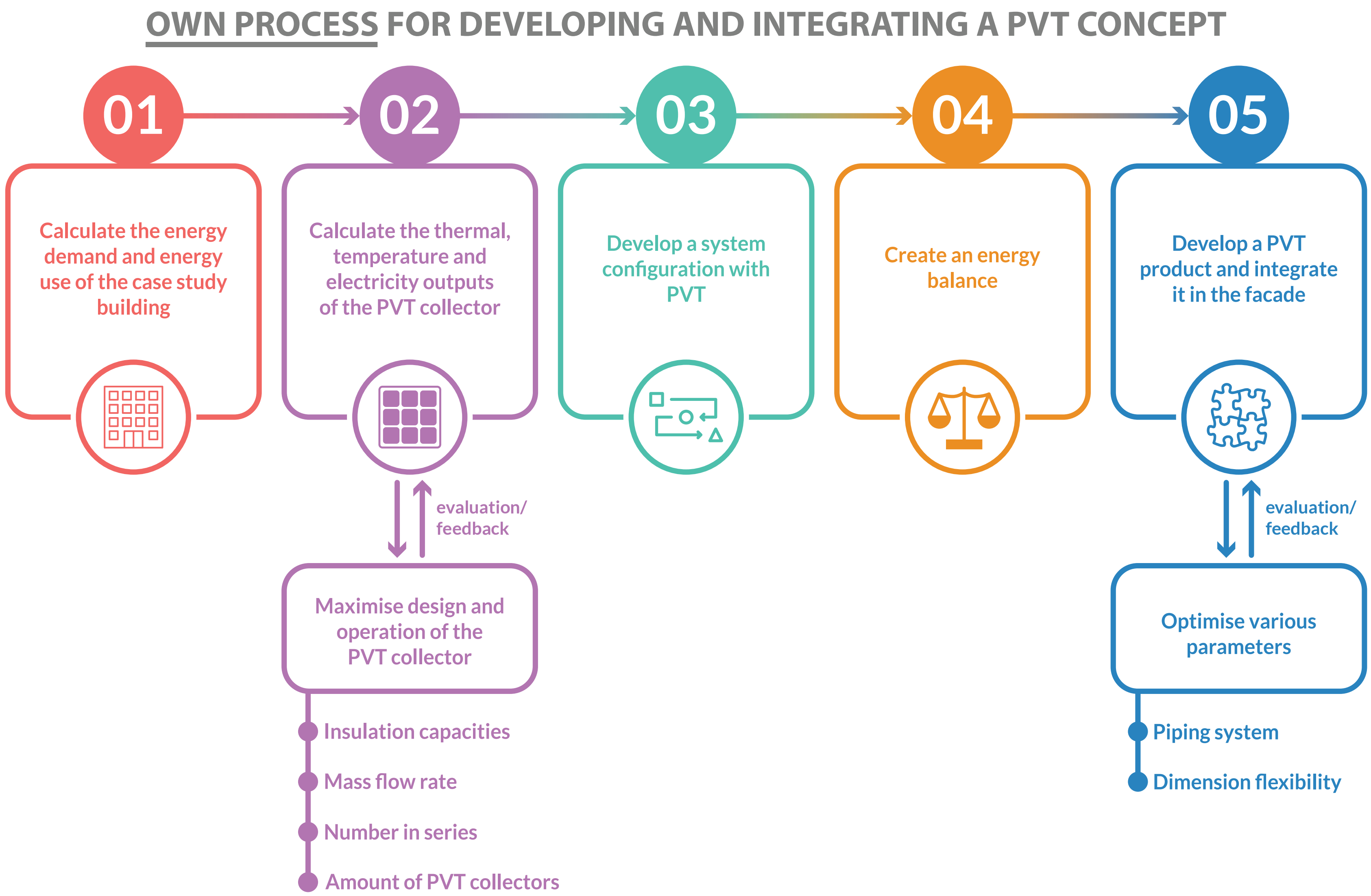


Figure 106. The own process for the PVT concept (own illustration).

WIDER APPROACH FOR DEVELOPING AND INTEGRATING A PVT CONCEPT

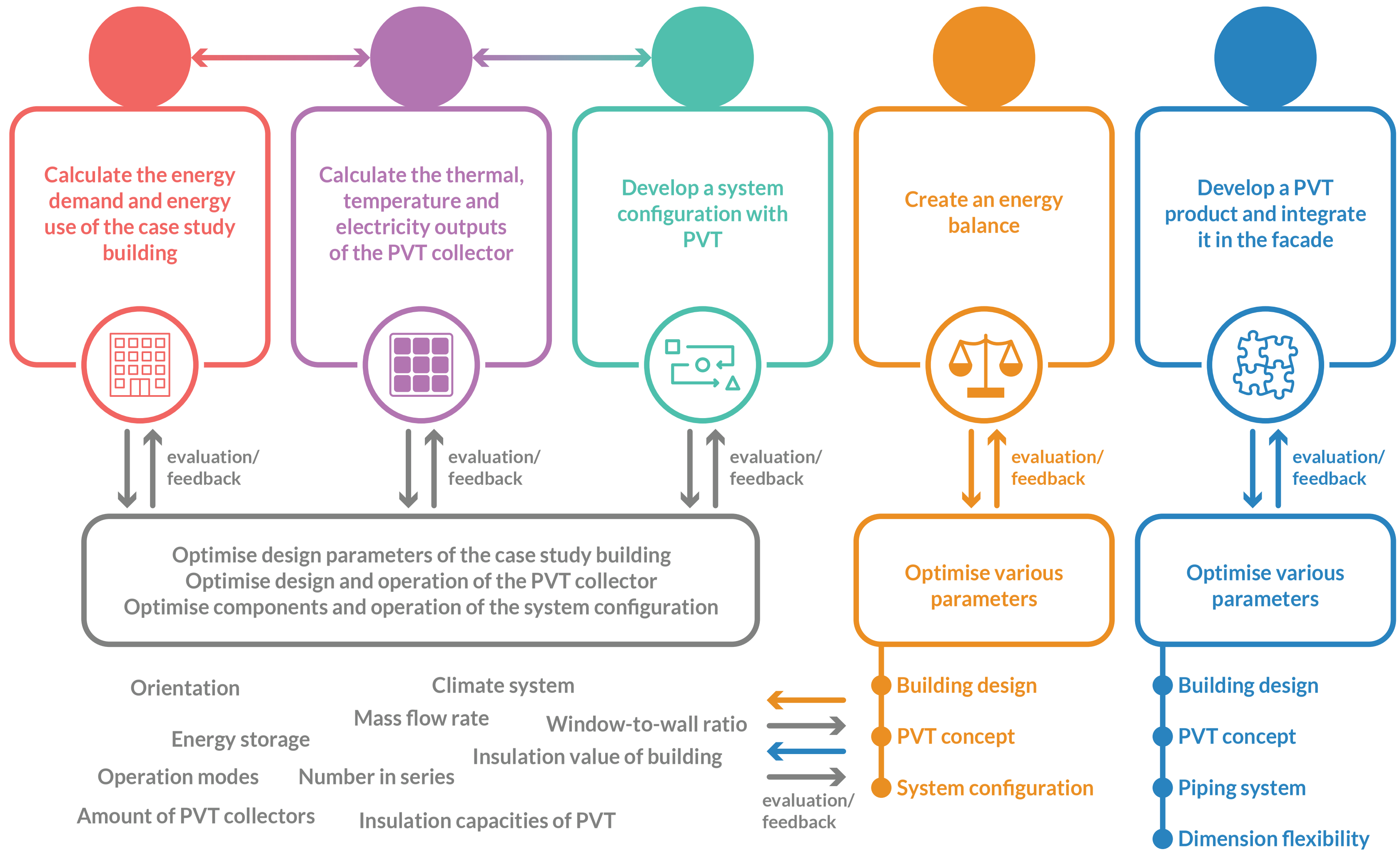


Figure 107. A wider approach for the PVT concept (own illustration).

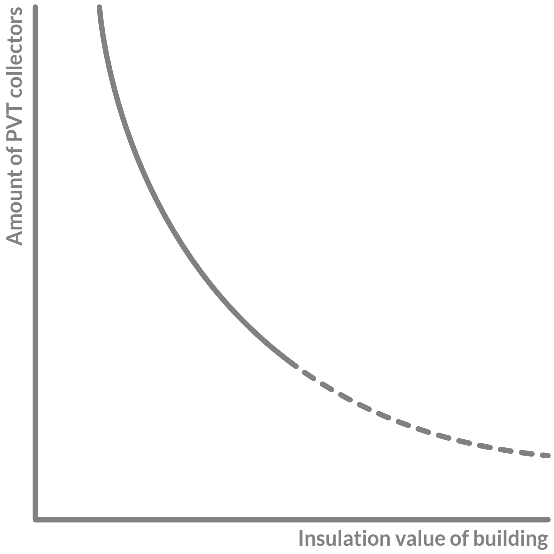


Figure 108. Correlation between the amount of PVT collectors and the insulation value of the building (own illustration).

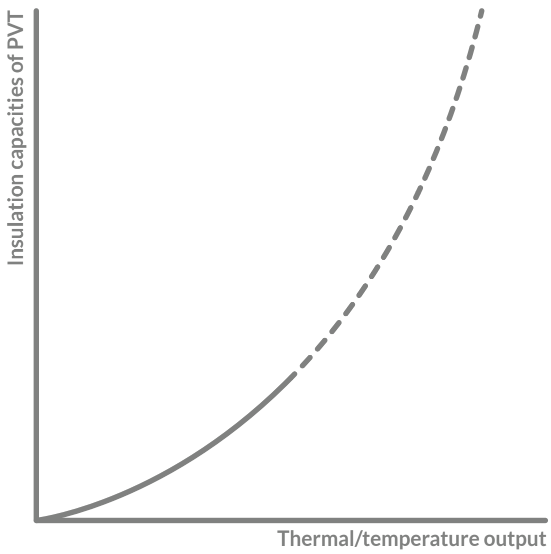


Figure 109. Correlation between the PVT insulation and the thermal and temperature output (own illustration).

Now that the progress and optimisation strategies of this thesis are summarised in a nutshell, it is time to answer the sub-questions and research questions. We start with the first sub-question:

"What is the current situation regarding PVT?"

A photovoltaic thermal collector is a combination of a photovoltaic panel and a solar thermal collector, which has the benefit of removing and utilising the heat from the PV cells in order to increase the cells' efficiency. Therefore, it has a dual output: electricity and heat is produced. The phenomenon of PVT has already been on the market since the 1970s. Research and development of this renewable energy technology has focused on all kinds of aspects, such as the application possibilities, design scenarios, cost-effectiveness and efficiency improvement. Over the past years, more and more interest can be seen in the quantity of PVT applications that are available in the market. In general, the thermal output of a PVT collector can be air-based, liquid-based or a combination of both. Due to the higher specific heat of water, the liquid-based PVT technology results in a better thermal efficiency. Moreover, glazing on top of the collector, insulation at the back and the use of squared pipes in a spiral flow design pattern equally increase the thermal or electrical output. Besides this, PVT modules can also become an integrated part of a building envelope, and therefore, many researches have focused on the development and testing of building-integrated PVT.

"*How can the energy output for PVT be calculated for different situations?"*

In the first place, the energy output for PVT can be sub-divided in three different types: thermal energy, temperature and electrical energy. The thermal yield of the collector depends on the one hand on the amount of heat that is provided by the sun. This parameters strongly depends on the time of year. The collector can also lose heat, which are called transmission losses. This parameter is related to the insulative capacities of the collector, as well as temperature-related parameters.

It may be clear that the temperature output of a PVT module also depends on its thermal performance. However, the flow velocity of the water, the temperature difference between the in- and outcoming water as well as the amount of collectors that are connected in series are similarly important factors here. The higher the flow velocity, the shorter the water is being exposed to the sunlight and the colder the output temperature is. If the velocity is decreased, the outgoing temperature will be higher, but less water is utilisable. Furthermore, the temperature output depends on the chosen mean inside temperature. This temperature will be higher in the summer, also resulting in a higher temperature difference between the in- and outcoming water. On top of that, if multiple collectors are connected in series, the water temperature of the last collector is significantly higher than the previous one(s). However, there is a limit: connecting too much collectors in series flattens the temperature output.

When it comes to the electricity output: a PVT collector has a higher so-called performance ratio than a PV panel, since more heat is removed from the solar cells. However, if the temperature inside the PVT collector becomes too high, this can result in a lower electric yield.

Besides the output types of a PVT module, the way of application also dictates the energy output. For facade-integrated PVT, in general, the yield will be significantly lower than for roof-mounted PVT elements.

> *"What is a common multi-family typology that can be used as a reference case for this study?"*

Since a PVT collector gives a higher yield per square meter than a photovoltaic panel and a solar thermal collector separately, it is wise to apply PVT collectors to multi-family building typologies that have a relatively high energy demand with a scarce roof area. This is therefore a common typology that can be used as a reference case for this study. Additionally, it is also an incentive to not only look at the application possibilities of PVT on a roof, but also integrating them into a facade in order to meet the energy demand.

> *"How can a PVT system configuration be optimised or maximised for renewable energy use?"*

A modern PVT system configuration generally can have three output uses: low-temperature heat, domestic hot water and high-temperature cooling. Applying these outputs in a well-insulated building can greatly reduce the energy demand compared to the more conventional, older buildings. Besides this, it is important to state that a collective system configuration with local, individual control and storage is deemed as being the most efficient, for this results in much less energy losses. Furthermore, an energy efficient device like a heat pump is considered indispensable for the configuration. However, a mutual, well-coordinated collaboration between the various elements of the system configuration is also essential, not least to bridge the energy mismatch. During the summer, the PVT collectors can mostly provide for the energy demand. Excess heat is stored in the underground energy storage, which can also deliver colder temperatures to the heat pump if high-temperature cooling is needed. During the winter, the energy storage mostly delivers heat to the heat pump, as the temperature inside the PVT modules is often too low. It is therefore important to consider multiple operation modes of the system configuration and apply a specific mode depending on the time of year and the desired energy output.

The aspects of optimisation and maximisation strongly relate to the desired outcome and the way an energy balance is reached. The optimisation of a system configuration means that a situation is created where two or more parameters are the most favourable, taking into account limitations as time, money, aesthetics and technology. Maximisation, however, can also lead to a favourable output of one or more parameters, but this can be at the cost of other parameters or limitations.

> *"What does this multi-family typology offer when it comes to PVT building-integration possibilities?"*

First of all, there is the aspects of building-addition of PVT collectors on the roof of a multi-family building. Several so-called solar thermal roofs are available, which have an energy-generating layer on top of the constructional part of the roof. If PVT is to be integrated into the facade, there are a couple of focus areas that need to be taken into account: a partial substitution of facade elements, the piping system, maintenance services and the dimension flexibility. In general, the outer skin of the facade is replaced by PVT. This means that the PVT collectors need to have a proper and reliable connection to the inner, mostly structural element of the facade. This can be done by suspending the collectors like boxes or elements to the facade. In this way, there is also space for removing the elements in case one of them is broken. Besides this, it is also wise to take the mutual connection of a PVT collector and a facade cladding material or the outer leaf into account, in case a part of the facade is integrated with PVT. Furthermore, the integration of PVT requires proper thinking about the location of the distribution pipes. These pipes can be placed on the outer, but also on the inner part of the facade. Both solutions have their advantages and drawbacks. A final important observation is the lack of design freedom when integrating a PVT collector into the facade. Therefore, a recommendation would be that the dimensions of PVT collectors should be more flexible. Overall, the water-tightness and the ventilation possibilities of the facade are important. Also, to keep the appearance of a PVT collector in line with the appearance of the facade, one can choose to apply, for instance, dye-sensitised solar cells. However, doing this will slightly decrease the electric output.

> *"**How can an energy concept with PVT be optimised or maximised in terms of renewable energy and be integrated in the envelope of a multi-family building?"***

An energy concept with PVT can be optimised or maximised in terms of renewable energy by first looking at the multi-family building. This well-insulated multi-family building needs to have a collective, individually controlled energy system configuration which uses low-temperature heat, domestic hot water and high-temperature cooling. Furthermore, choosing a liquid-based, glazed, insulated PVT collector with squared pipes in a spiral-flow design pattern increases the thermal efficiency. The collector needs to be part of a series of collectors. On top of that, a proper mutual cooperation between the PVT collector and underground thermal energy storage is needed to pursuit and foster heating and cooling in a most optimal way. An optimisation or maximisation can be achieved by creating a most favourable situation, ensuring a proper interaction between multiple parameters. For the integration of a PVT collector into a facade, especially the inner constructive part of the facade needs to be taken into account as well as the placement of the distribution pipes. Also, the mutual connection between the PVT element and a facade element, the water-tightness and the ventilation of the facade is important. Finally, it is highly recommended to introduce multiple dimensions of PVT collectors in order to have more integration possibilities in a facade.

Although it is tried to answer the research questions as complete as possible, it may not be surprising that more research needs to be done into PVT - especially into the effect of dimension flexibility. Not least because PVT is highly promising and could most certainly become an essential renewable energy technology in the (near) future.

9. POSTFACE

9.1 Reflection

A subject that has triggered me more and more during my education in Building Technology, is the current transition between fossil fuels and renewable energy and what this means for the built environment. What kind of systems are possible and how can we implement renewable energy technologies in our buildings? The photovoltaic thermal (PVT) collector is a system that converts solar irradiation into electricity and heat. This system seemed an interesting graduation topic to me. Fortunately, interest was sparked as I approached one of the mentors of the research theme *Smart Energy Buildings*, Sabine Jansen. Sabine recently performed a feasibility study into a sustainable and integrated energy system for the Buiksloterham neighbourhood in Amsterdam. A part of the proposed energy systems was the recommendation to introduce PVT. However, there still was a demand for the way in which PVT could be applied on a more local scale, not least because it is known that PVT has a higher energy output per square meter than photovoltaic panels and solar thermal collectors separately. A multi-family building was interesting in this case, for such a typology has a relatively small roof area compared to the energy demand. Besides this, it is also interesting to find out how PVT can be integrated into a multi-family building, other than the more conventional way of adding it to a building. In this way, a PVT collector can become an integral aspect of a building. I approached Arie Bergsma to guide me in this process, which meant that Sabine and Arie would become my mentors. Although the exact outline of the research theme is aimed at energy storage, the research methodology is somewhat similar: performing a literature study, an energy concept development and an energy simulation.

The first part of the research was the literature study. This part should give an incentive of why we have to foster the switch-over from fossil fuels to renewable energy. That is why I talked about the aim of the Dutch government first. I continued, after a brief introduction about renewable energy systems, with PVT. For me, it was of great importance to grasp the phenomenon of PVT. I wanted to know how it exactly works, what kind of PVT types there are and how PVT can be applied in the built environment. Despite the fact that PVT is into existence for approximately four decennia, its research and development is still in its experimental phase because of the various aspects and complexities of PVT. The website ScienceDirect provides – after proper searching and reading – enough and endless information that could be used for the literature study. Various papers and data from distributors helped me to eventually make a choice for the PVT collector type with which I would continue.

At this point in the graduation process, my approach slightly changed. I had to move from scientific essays to a more practically-aimed strategy. Now that PVT was thoroughly examined, it had to be integrated into the facade of the multi-family building. Also, additional renewable energy technologies had to be discussed which – together with PVT – could form a system configuration concept for the multi-family building of my research. All this had to be substantiated with calculations and energy performance simulations. The knowledge that I gained during the seven years of my education was put to the test: what do I know and what do I have to know for this research? The work that I produced during those seven years, together with some books, hand-outs and – frankly – the internet, that all provide (basic) knowledge about the field of research, proved to be very useful at this point. However, it took quite a while to grasp the calculations of the thermal, temperature and electrical output of a PVT collector. Not only their parameters are intertwined, they also need to be properly substantiated and grasped. And frankly, I underestimated this. For example, a PVT or solar collector is usually connected in series in order to achieve a higher output temperature. Overall, it can be said that especially the calculations entailed into a lot of learning moments for me. For the facade integration, some details I produced during my education were helpful, as well as some standard details and reference cases of integrated solar energy systems. The parts of the system configuration are explained in various books about building physics. Simulating the proposals was quite difficult, as one has to understand how a simulation program exactly works. It has to be said that for a graduation process of this time span, only the basics of the simulation program can be unravelled. Anyway, it was up to me to gather all the information and to propose and clarify an integrated PVT system configuration. To be honest, all this was very complex and sometimes tending towards mechanical engineering, though this complexity made it very challenging and educational. It also showed that there is so much I do not know, but – putting things in perspective – that the basic knowledge that I have, proved to be of great importance.

With PVT – and to a lesser extent other renewable energy technologies – being the main topic of this research, the focus was more aimed at research. Nevertheless, integrating PVT collectors into a building and developing a system configuration also asked insight in my design qualities. However, creating a design by researching design possibilities showed that in the context of this thesis, research had the upper hand. Moreover, I also think that design by research fits my nature, as I like to use proven outcomes and methodologies on which I can build further and eventually can create something new. This being said, I think that my approach worked in this case, because the topic demands proper research. This does not alter the fact that there are various aspects that I underestimated.

A part of the conclusion of this research discussed the aspect of optimisation and maximisation. My process showed a number of PVT-related parameters that I maximised in order to achieve a higher thermal and temperature output together with the optimisation of the PVT integration to get a more practical facade-integration. Especially during the last part of my graduation process, I was advised by my mentors to thoroughly explain a more integral approach, which is not linear (like my process). This means that I had to look at the interaction between various parameters and see how they influence each other. It is important to take a look at how a PVT energy concept can be applied on other - similar - buildings.

In my opinion, this research could be an important contribution to the understanding and application of renewable energy technologies in the built environment. Energy harvesting systems that use solar irradiation should not be seen as a stand-alone element in the built environment, but more as an integral and coherent part. With this research, I did an attempt to offer more clarity when it comes to renewable energy systems and their integration into the built environment.

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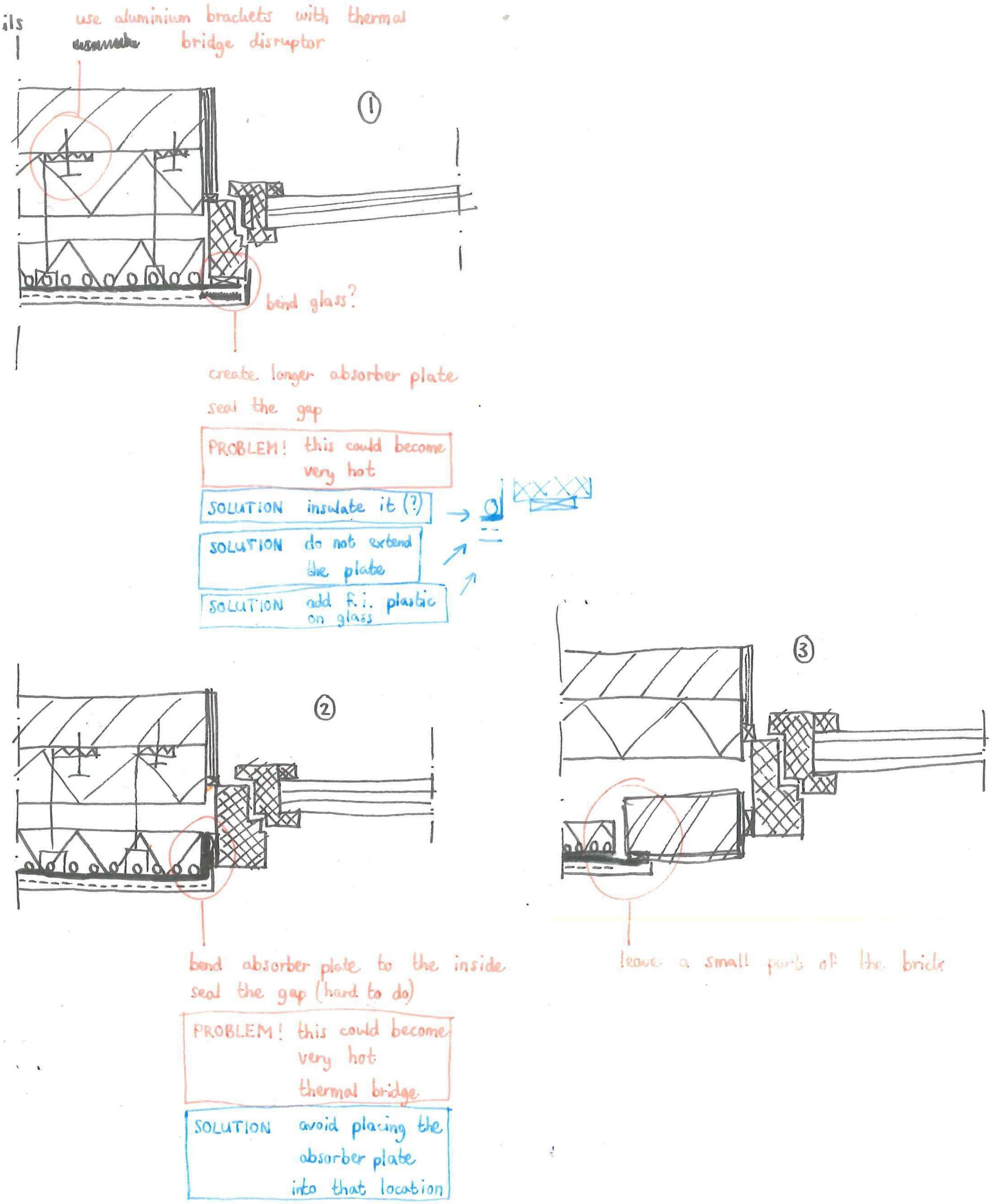
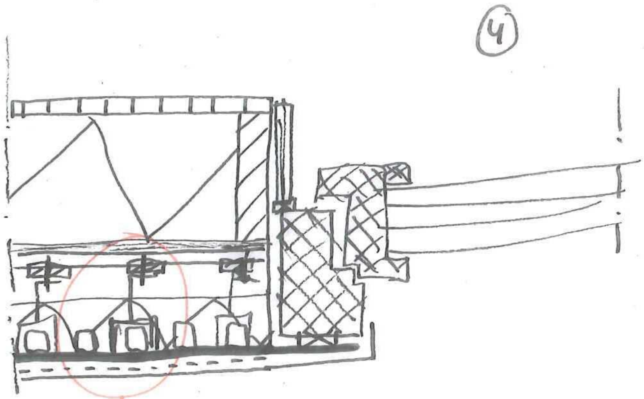
APPENDICES

***A1*. Sketches of various PVT module connections (own illustration).**

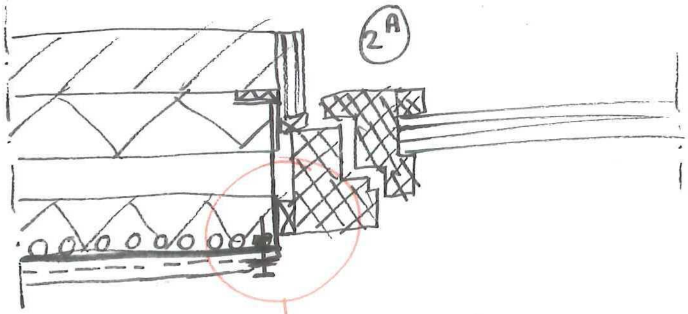




add OSB and horizontal + vertical timber framing

WHAT IS IMPORTANT HERE IS THE EDGE OF A PVT MODULE! THIS COULD BE PLASTIC

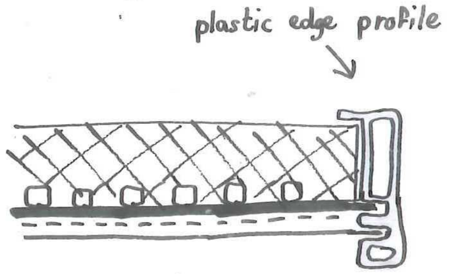
I FORGOT THE EDGE!



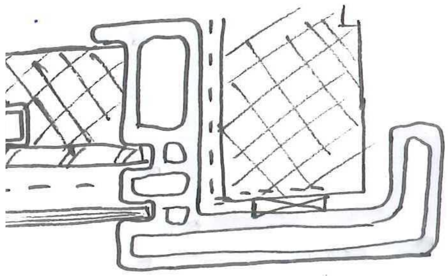
add 'clamp-side plate': clamp PVT inside and fix it

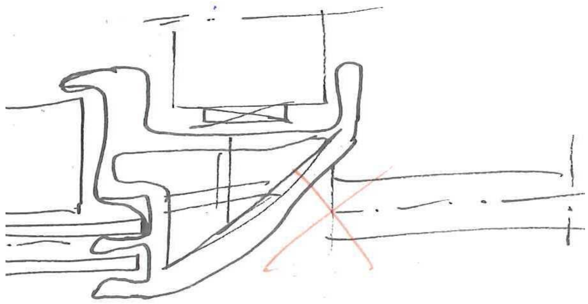
PROBLEM! the gap is not really different and changes in size (ΔT)

SOLUTION make the gap long-lasting and sustainable



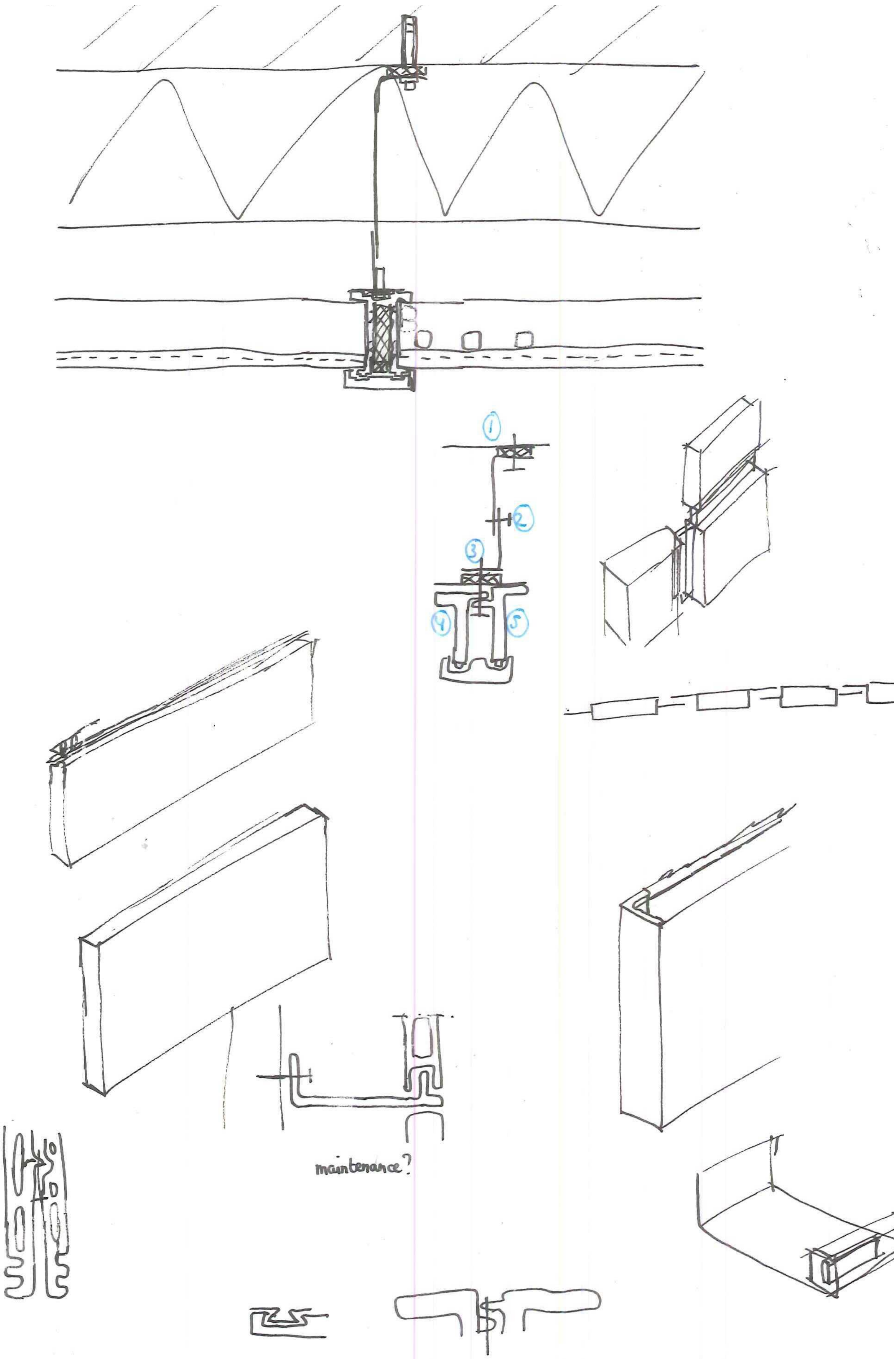
add an angle bar to this profile + a sealing strip (+ dpc) and the connection is solved



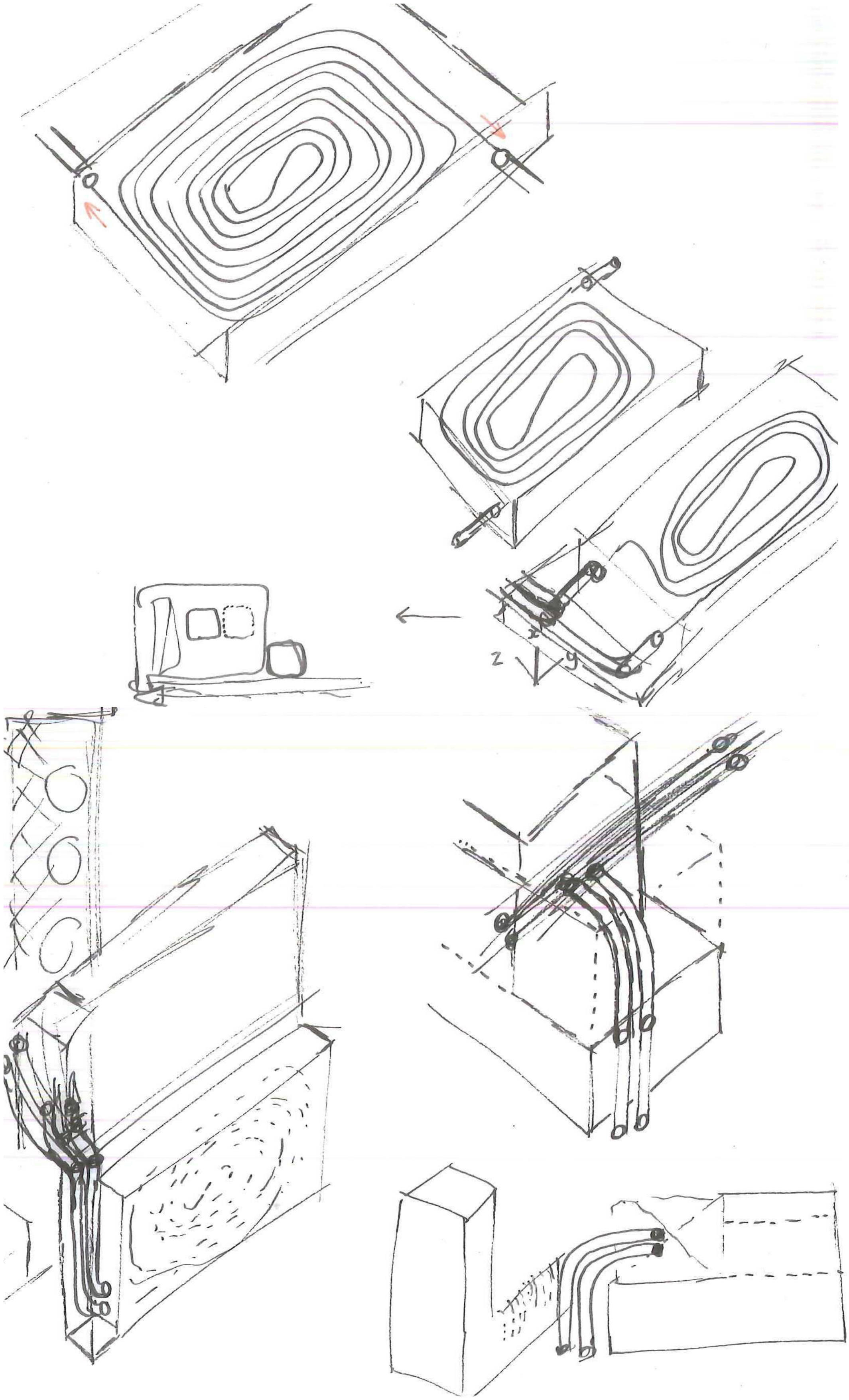


French balcony can only be maintained when bricks are partly kept

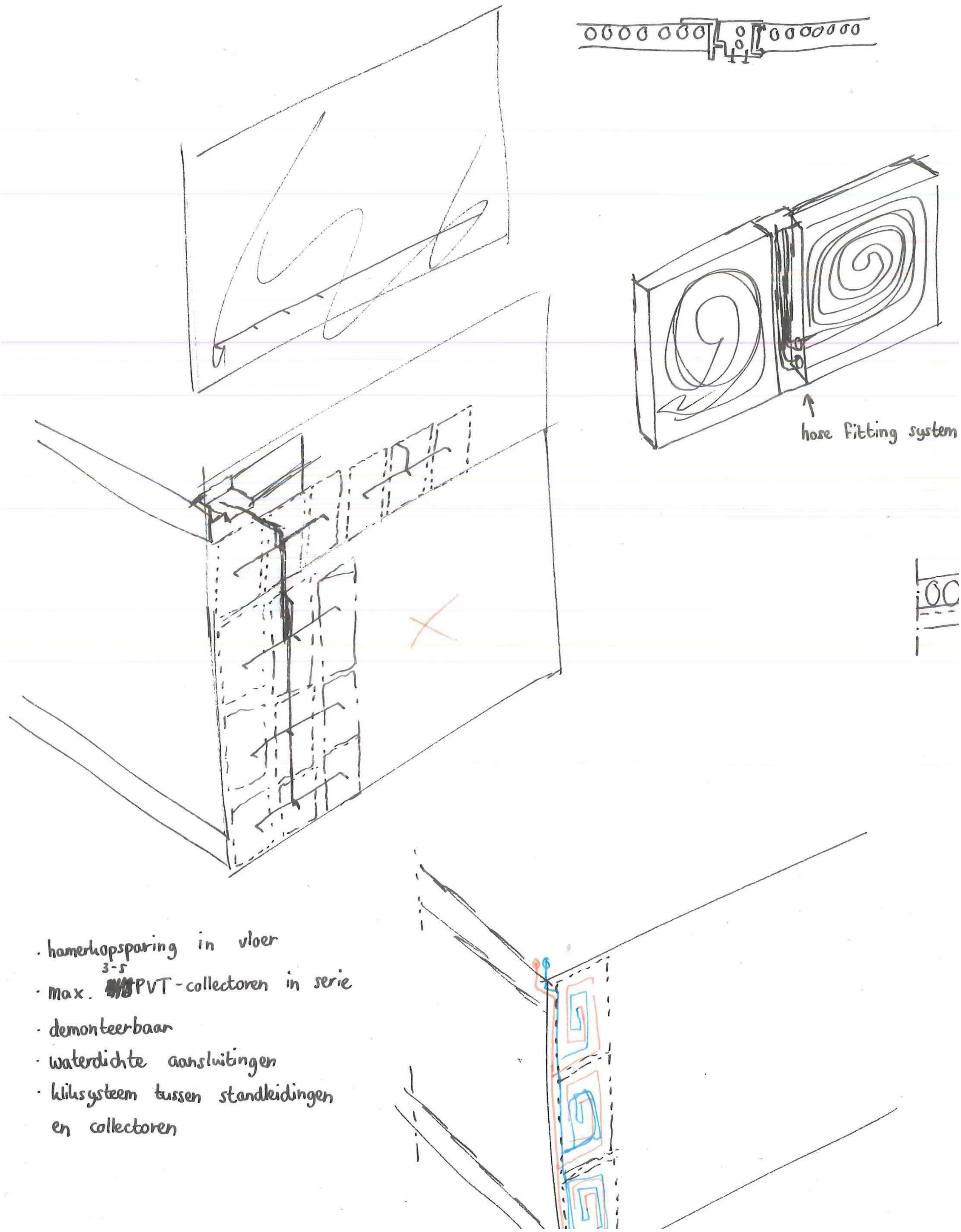
A2. **Sketches of various PVT module fixations (own illustration).**

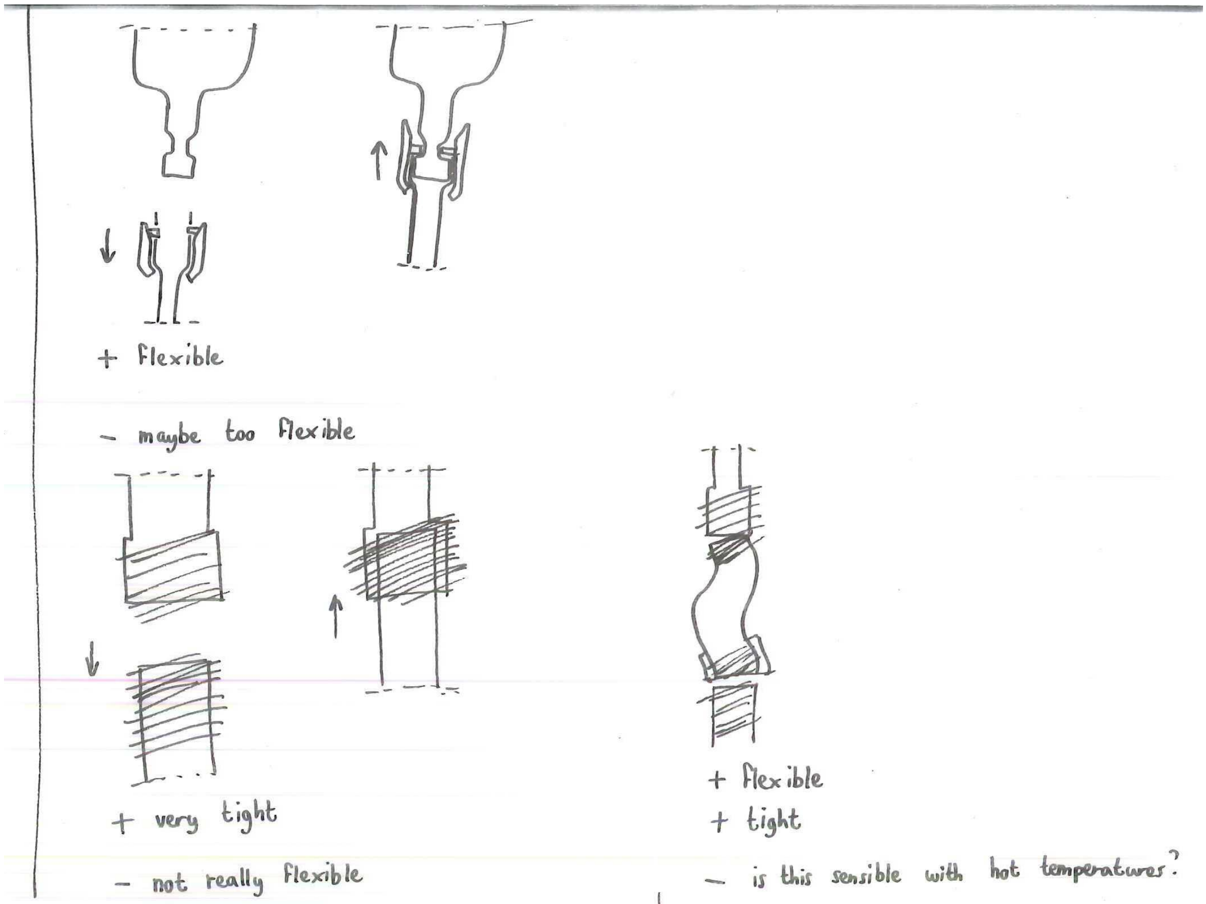


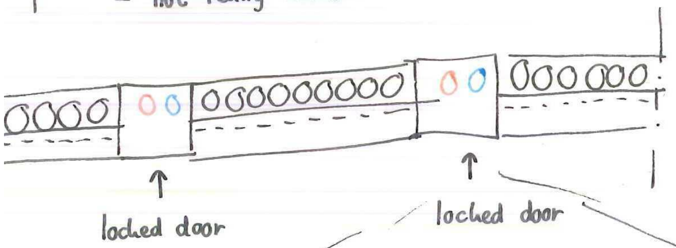
***A3.* Sketches of various PVT pipe layouts and distributions (own illustration).**

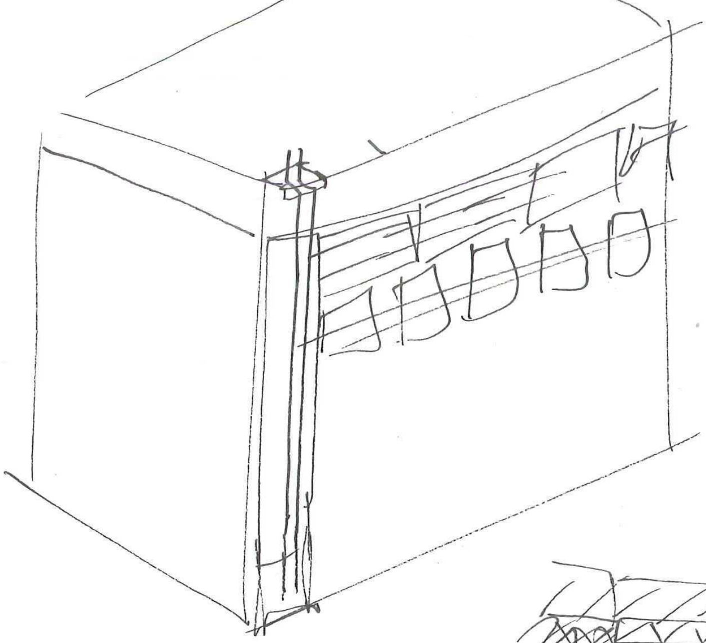


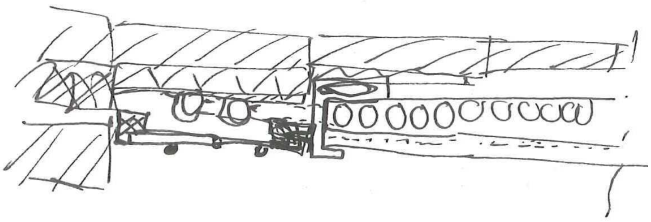
A4. **Sketches of various PVT pipe layouts and distributions (own illustration).**



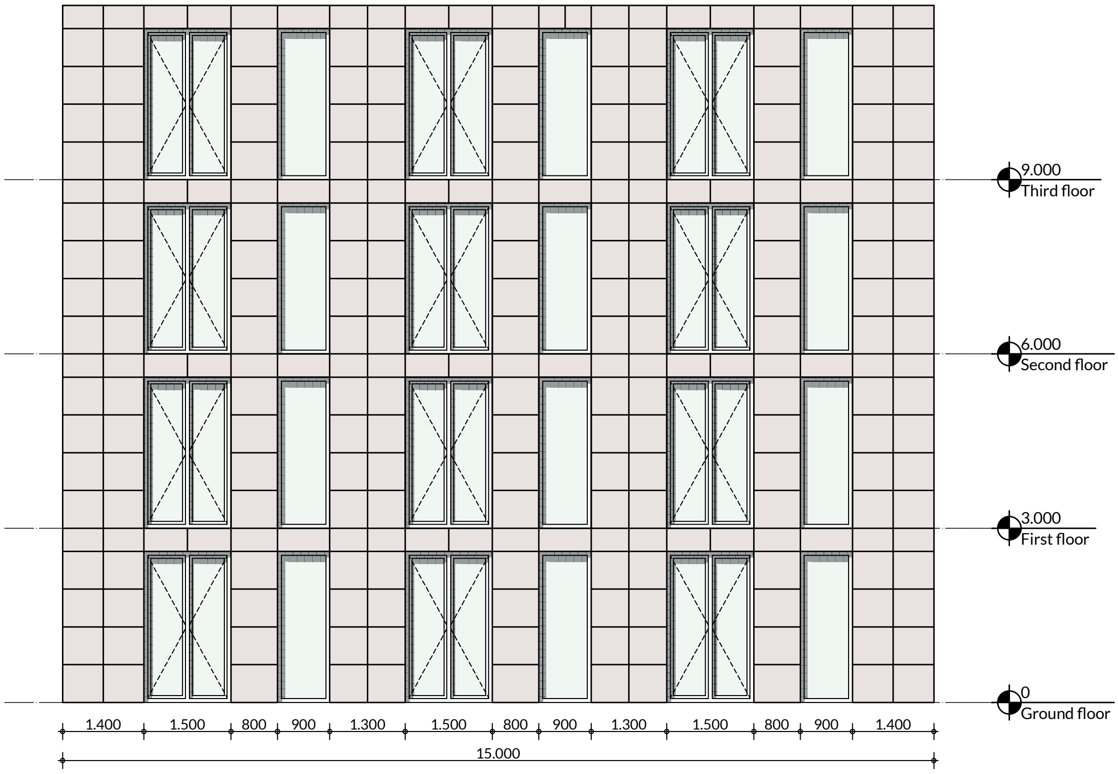

+ flexible
- maybe too flexible
+ very tight
- not really flexible
+ flexible
+ tight
- is this sensible with hot temperatures?


locked door
locked door

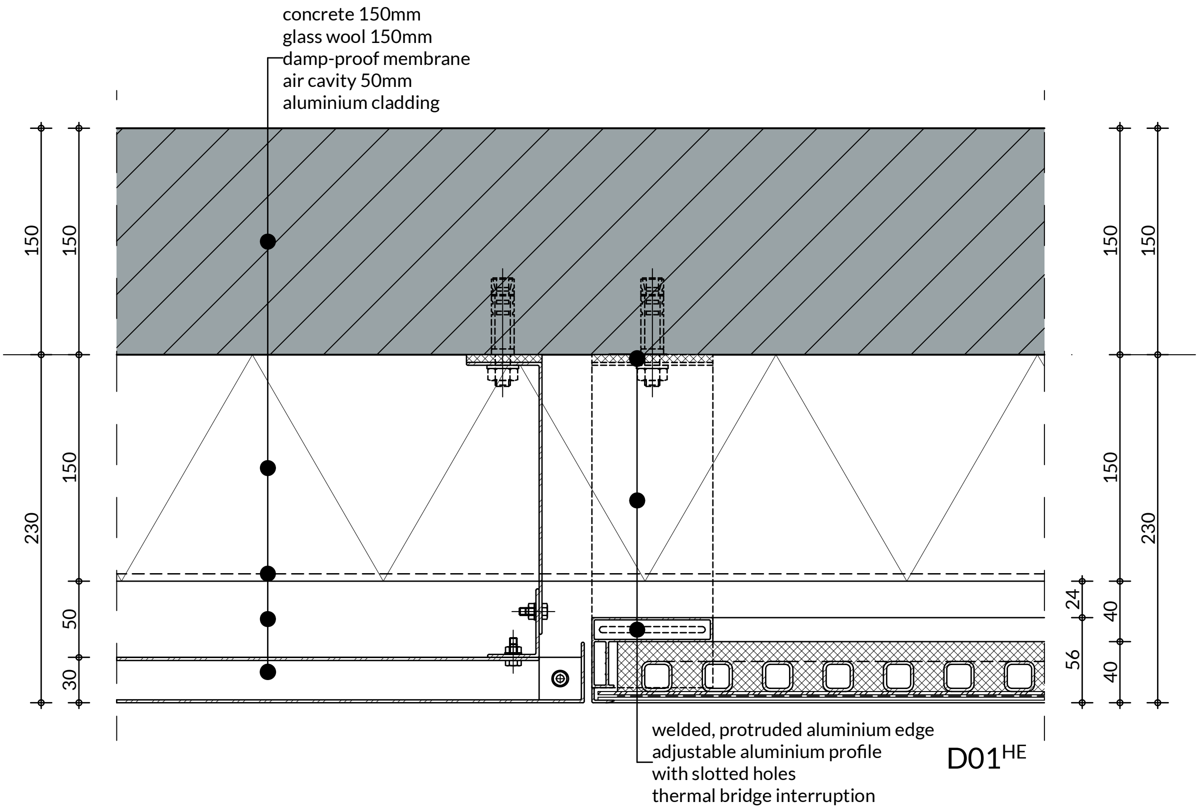




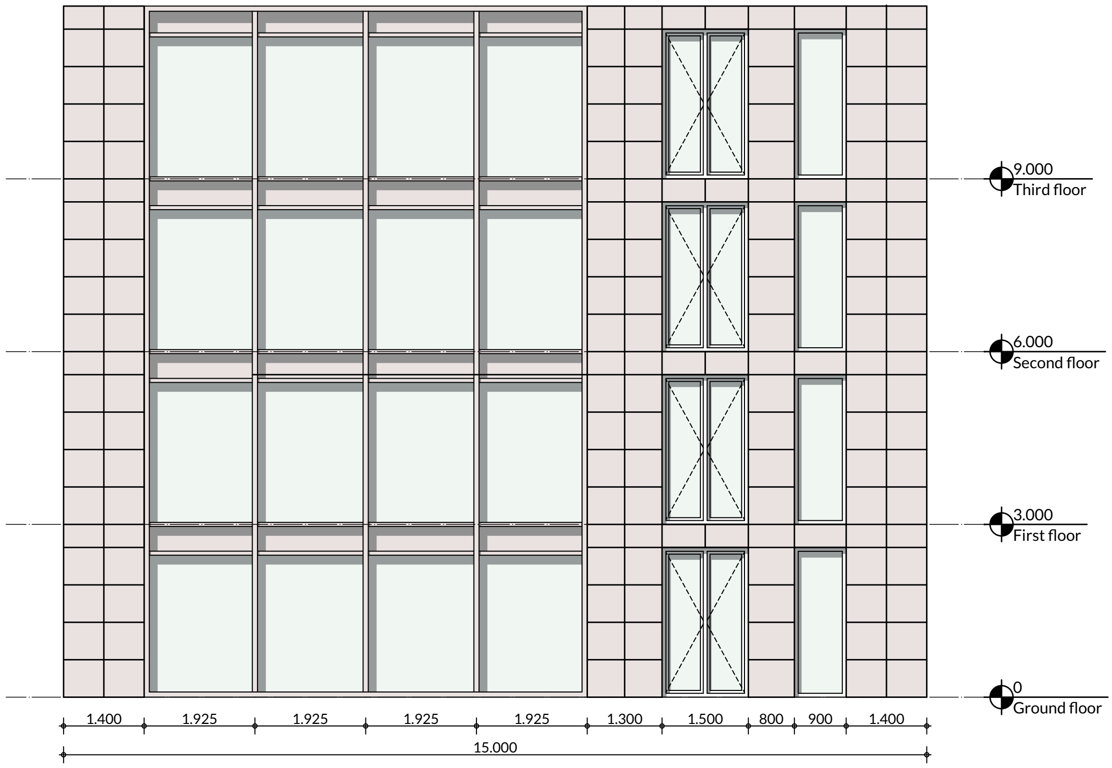
***A5.* Facade example with aluminium cladding (unscaled; own illustration).**



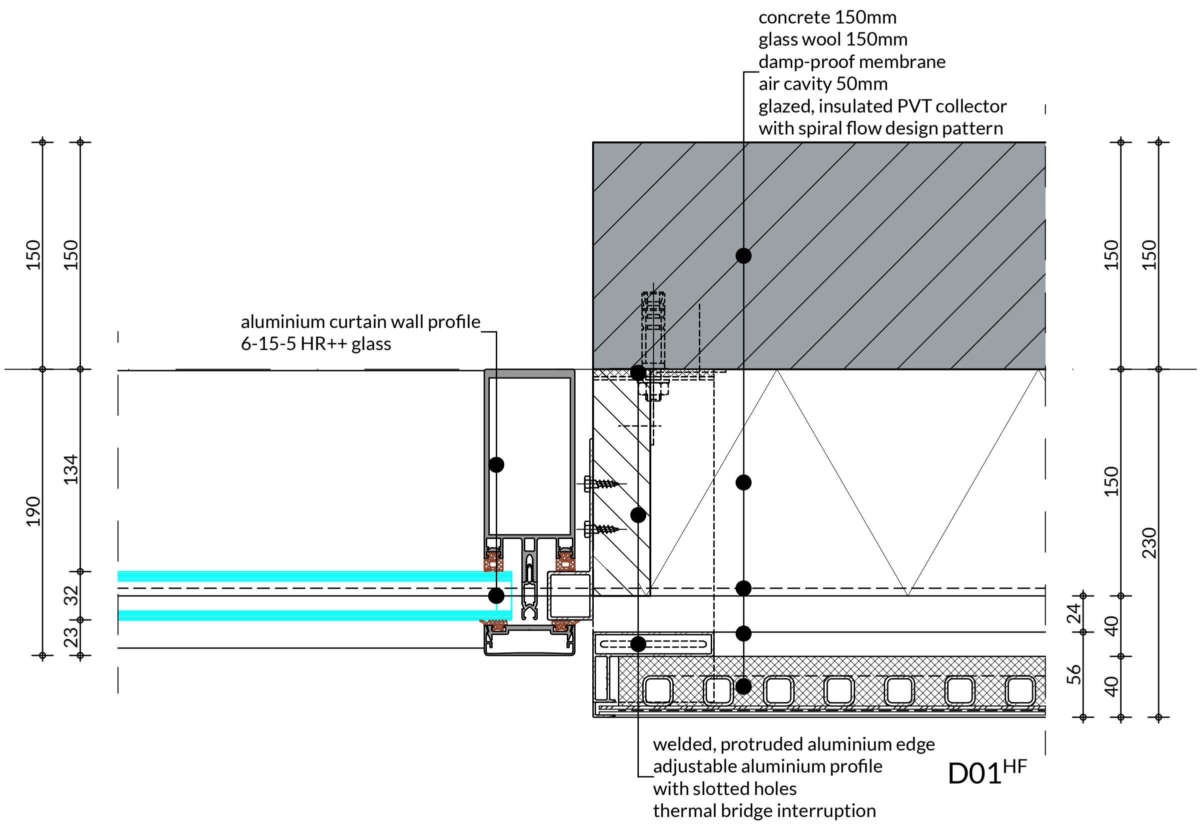
***A6.* Cavity wall detail D01HE, where the aluminium cladding meets the PVT module (scale 1:5; own illustration).**



A7. **Facade example with a curtain wall (unscaled; own illustration).**



A8. **Cavity wall detail D01HF, where the curtain wall meets the PVT module (scale 1:5; own illustration).**



A9. Simulation with Polysun.

This section describes how the system configuration can be created by and simulated in Polysun in order to evaluate the calculated and assumed thermal and electrical yields and output temperatures for the months and seasons as shown in the previous paragraphs. Note that, as mentioned in paragraph 5.7, that the PVT outputs in Polysun are dependent on the rest of the system configuration. For example, the mean inside water temperature is not fixed in this case. The flow velocity is, however. Also, for the sake of clearance, the PVT collector used in Polysun is the same as used for the calculations.

Creating the system

In the so-called 'Wizard' in Polysun, various kinds of system configurations are already predefined by the program. This is extremely helpful, since creating a system configuration from scratch - with all kinds of pumps and flow controllers - would cost a lot of time. The system that is applicable for Docklands can be found under 'Hybrid collector systems (PVT)' and then '59g: Ground source-loop regeneration by PVT'. To have a situation that is comparable to the configuration that was presented in the previous paragraph, only a system that is applicable to one apartment in Docklands is simulated. For the energy output, this apartment can be multiplied by the total number of apartments in Docklands (this number is 44 in reality, but for the model also the 13 working units were categorised as 'apartments', making the total number of apartments 57). Each apartment is given four roof-mounted collectors, connected in series. This means that the simulated outputs are to be compared with the calculated outputs for four collectors in series. Also, the apartment properties must be specified. In the drop-down menu of the 'Results' tab, various outputs can be simulated.

PVT thermal outputs

By choosing 'Component results' in the 'Results' drop-down menu, the energy outputs of all devices in the system configuration appear. One of those devices is the PVT collector, of which the total output Q_{coll} is compared to the calculated values from the previous chapter. In Polysun, this output value is called 'Collector field yield'. In principal, the values for Q_{coll} - and also the transmission losses Q_{trans} - are directly related to the flow velocity of the water, which is also shown in Polysun. Thus, by changing the flow velocity, the thermal output and the transmission losses also change. Since less water is needed in summer, a flow velocity of 60 l/h is considered. For the winter, this is 120 l/h. These two seasons are being compared. Figure A8[A] shows the simulated and calculated results for the thermal output. The difference is the result of subtracting the calculated output from the simulated output:

Month	v [l/h]	$T_{m; sim}$ [°C]	$T_{m; calc}$ [°C]	$Q_{coll; sim}$ [kWh]	$Q_{coll; calc}$ [kWh]	ΔQ_{coll} [kWh]
May	60	45.1	40	59	94	-35
June	60	44.7	40	86	91	-5
July	60	45.2	40	72	104	-32
August	60	45.6	40	92	101	-9
Month	**v [l/h]**	$T_{m; sim}$ [°C]	$T_{m; calc}$ [°C]	$Q_{coll; sim}$ [kWh]	$Q_{coll; calc}$ [kWh]	ΔQ_{coll} [kWh]
November	120	21.5	20	42	33	+9
December	120	18.6	20	18	16	+2
January	120	18.9	20	30	21	+9
February	120	20.4	20	49	47	+2

Figure A8[A]. Comparison of the simulated and calculated thermal outputs (own illustration).

The figure shows that the simulated mean inside temperature in summer is a bit higher than the one used for the calculation. It can be expected here that the simulated thermal outputs are therefore lower because of higher transmission losses. This is the case, but for May and July, the output differences are quite high. The situation in winter shows minor differences, but for May and July, they are considerably larger.

PVT temperature outputs
The temperature output is the 'Maximum value' for the 'Outflow temperature' in Polysun. This output is calculated for four collectors in series, which means that for the simulation, also four in series connected modules are chosen. Figure A8[B] shows the comparisons made for the temperature output:

Month	*v [l/h]*	*$T_{m; sim}$ [°C]*	*$T_{m; calc}$ [°C]*	*$T_{out; sim}$ [°C]*	*$T_{out; calc}$ [°C]*	*ΔT_{out} [°C]*
May	*60*	*45.1*	*40*	*50.6*	*60.2*	*-9.6*
June	*60*	*44.7*	*40*	*47.6*	*61.0*	*-13.4*
July	*60*	*45.2*	*40*	*51.7*	*62.0*	*-10.3*
August	*60*	*45.6*	*40*	*50.1*	*62.8*	*-12.7*
Month	*v [l/h]*	*$T_{m; sim}$ [°C]*	*$T_{m; calc}$ [°C]*	*$T_{out; sim}$ [°C]*	*$T_{out; calc}$ [°C]*	*ΔT_{out} [°C]*
November	*120*	*21.5*	*20*	*21.7*	*27.3*	*-5.6*
December	*120*	*18.6*	*20*	*21.2*	*25.7*	*-4.5*
January	*120*	*18.9*	*20*	*20.5*	*26.8*	*-6.3*
February	*120*	*20.4*	*20*	*22.5*	*29.1*	*-6.6*

Figure A8[B]. Comparison of the simulated and calculated temperature outputs (own illustration).

What is interesting to see here is that the calculated outputs are both too optimistic in summer and winter. This indicates that the simulated outputs are more flattened and more energy is lost through transmission.

PVT electricity outputs
'Energy production DC' is the value that Polysun has calculated. Since Polysun simulates the electrical output of all modules instead of one, it has to be divided by four. Figure A8[C] shows the simulated and calculated comparisons:

Month	v [l/h]	$T_{m; sim}$ [°C]	$T_{m; calc}$ [°C]	E_{sim} [kWh]	E_{calc} [kWh]	ΔE [kWh]
May	60	45.1	40	34	26	+8
June	60	44.7	40	32	24	+8
July	60	45.2	40	32	25	+7
August	60	45.6	40	31	24	+7
Month	v [l/h]	$T_{m; sim}$ [°C]	$T_{m; calc}$ [°C]	E_{sim} [kWh]	E_{calc} [kWh]	ΔE [kWh]
November	120	21.5	20	10	9	+1
December	120	18.6	20	7	6	+1
January	120	18.9	20	9	7	+2
February	120	20.4	20	14	13	+1

Figure A8^{C}. Comparison of the simulated and calculated electricity outputs (own illustration).

The differences are quite minimal here and can possibly be traced back to the performance factor. It is not known which performance factor Polysun uses, but the chance is considerable that this is of a higher value than the one used in the calculations.

The comparisons made on Polysun are a measure that can be taken to determine if the calculated outputs are somehow realistic. It must be said, however, that a simulation program like Polysun takes a significant amount of time to understand completely. Despite the fact that most of the differences were minor, the comparisons can be different when having more experience with the program.


TUDelft