Master’s Thesis – master Energy Science

The effective implementation of a PVT system

Reinier Derks (6285597)

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Utrecht University supervisor: Prof. dr. Wilfried van Sark
Second reader: Dr. Sara Mirbagheri Golroodbari
Smits van Burgst supervisor: Ing. Bas Rutgers
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Abstract

This thesis investigates the effective implementation of photovoltaic-thermal (PVT) systems in various building types to optimize energy use and reduce carbon dioxide (CO_2) emissions, aligning with global efforts to combat climate change. Conducted at Smits van Burgst, a medium-sized engineering firm in the Netherlands, this research responds to the increasing demand for sustainable building solutions. Although Smits van Burgst has extensive knowledge of installation technologies, its understanding of PVT systems remains underdeveloped. Therefore, this study aims to expand the company's capabilities in designing and implementing these systems effectively.

PVT systems combine the functions of photovoltaic (PV) panels and solar thermal collectors, allowing for the generation of both electricity and heat from a single installation. This dual functionality optimizes the use of available roof space and contributes to the reduction of a building's carbon footprint. While research has demonstrated that PVT systems are both efficient and cost-effective, there is still a need to explore their integration with other technologies to enhance performance and suitability for different building types.

To address these objectives, a MATLAB Simulink model was developed to simulate the performance of PVT systems across various building types, including office buildings, hospitals, medium-sized houses, and supermarkets. The model analyzed the electricity generation and demand, comparing these across different scenarios to identify when and where PVT systems are most effective. The findings were supplemented with an extensive literature review aimed at identifying complementary technologies that could further optimize PVT system performance.

The results indicate that office buildings can best use either smart EV charging stations or heat pumps to utilize excess energy. Conversely, residential buildings and supermarkets find greater benefit by combining PVT systems with long-term energy storage solutions, such as heat pumps with thermal energy storage systems or thermochemical storage systems. It is recommended for hospitals to not make use of additional technologies, as there is rarely any excess electricity to be utilized.

Based on the simulations and literature review, this thesis provides practical recommendations for implementing PVT systems in different contexts, emphasizing the importance of tailored solutions to maximize efficiency and sustainability. It also highlights the need for further research to refine these strategies, including the development of more comprehensive models that incorporate additional technologies. The insights gained from this research contribute to the advancement of sustainable building practices, supporting efforts to reduce carbon emissions and promote energy efficiency in the built environment.

Preface

This thesis represents the culmination of my efforts as a graduate student in the Energy Science master's program at Utrecht University. Throughout the past several months, I have investigated the potential of PVT systems as a sustainable means to reduce CO_2 emissions in buildings. This research was undertaken in partnership with Smits van Burgst, an engineering firm located in Zoetermeer, Netherlands. The objective of the project was to address a gap in existing research and to broaden the firm's knowledge in renewable energy technologies by focusing on the integration of PVT systems with other innovative solutions to enhance energy efficiency and sustainability across different types of buildings.

Contents

Introduction

The reduction of carbon dioxide (CO_2) emissions from buildings plays a vital role in the fight against climate change, and by making use of renewable energy technologies such as photovoltaic (PV) panels, this fight could potentially be won. PV panels can significantly reduce the building's carbon footprint by generating electricity from solar energy that can be used by the building itself. The same goes for solar heating systems, which make use of solar energy as well, but for heating purposes. As of 1 January 2021, all new constructions in the Netherlands, including residential and utility buildings, must comply with the BENG (Almost Energy Neutral Building) requirements. To become a BENG building, the building needs to reduce its primary fossil energy usage and make use of renewable energy (Rijksoverheid, 2021) By making use of PV panels and solar heating, buildings can fulfill these requirements to achieve a BENG certificate.

However, the limited space on buildings for such technologies can present a challenge. It is no longer allowed to have PV panels at a nearby location and count the generated electricity as part of your own (Harmelink, 2018). One solution to this challenge is to use photovoltaic-thermal (PVT) systems. First proposed in the 1970s (Kern and Russel, 1978), these hybrid systems offer two functions in one. Besides generating electricity through the PV panels, the system also collects heat from the PV panel that can be used to warm the building on which it is placed (Assoa, et al., 2007). This integration of systems can optimize the use of available roof space for buildings (Lamnatou, et al., 2017). Besides heating, PVT systems can also be used for applications such as desalination and crop drying (Kroiß, et al., 2014).

A typical PVT system operates by having PV panels collect solar radiation, which is converted to electrical energy via a silicon wafer (Calise, 2019). The efficiency of the conversion is highly dependent on the PV panel's operating temperature. As the temperature rises above the standard temperature at which solar panels are tested (25 degrees Celsius), the output voltage of the panel decreases, which leads to reduced power generation (Amelia, et al., 2016). To counteract this, PV panels can be cooled down by a fluid to the optimal efficiency of the panel. which is a large reason why floating PV farms are becoming increasingly popular as a source of renewable energy (Golroodbari, et al., 2023). Floating PV farms are placed on both freshwater bodies and offshore seas. By placing a working fluid, such as water, under a PV panel that transfers the heat generated by the PV panel to itself, the PV panel can remain cooled. A PVT system is essentially a PV panel with a heat transfer fluid, from here onwards referred to as a working fluid, allowing the captured heat to be utilized for various purposes.

Research has demonstrated that PVT systems are both efficient and cost-effective, and are worth additional research (Joshi, et al., 2018). Despite the promising findings, further research on integrating PVT systems with other technologies to optimize its usage needs to be done. The aim of this research is to fill an existing gap in the current research landscape regarding the usage of PVT panels with other technologies for different building types. This research seeks to answer the following central research question:

How can a PVT system be implemented most effectively in different building types?

To address this overarching question, the following sub-questions are formulated:

1) *How does the electricity supply of PVT relate to the demand for different buildings?*

2) *What technologies can help the effectiveness of PVT for different buildings?*

To answer these questions, a comprehensive study was carried out at Smits van Burgst. For the first sub-question, a MATLAB Simulink model was developed to simulate the performance of PVT technology across various building types, analyzing the electricity demand and supply case by case. Only the electricity generation and demand will be considered in this thesis. The second sub-question was explored through an extensive literature review aimed at identifying complementary technologies to enhance the PVT system's performance. After this, the data from the research was used together with the results from the model to see which technologies could be used. Using the results from the two sub-questions, the final research question was answered.

This thesis is structured into several key sections. First, the research background will provide vital information regarding the research. Next, the methodology section will outline how the research was conducted, how data were gathered and which methods were used to obtain results. This is followed by the results section, which presents all findings of the study. The implications of these results are analyzed in the discussion section, where the sub-questions will be answered. Finally, the conclusion summarizes the main insights of the research and will address the research question. This is followed by recommendations for future research.

Research background

Smits van Burgst was founded in 1946 and operates under two main branches that fall under the name Smits van Burgst. The first branch is a security company focused on security technology, whilst the second is an engineering company. The latter is specialized in installation technology, sustainability, and building maintenance. They strive to ensure that people, buildings and the environment are harmoniously aligned with each other. The company has a wide range of knowledge regarding various installation technologies. Sustainable building solutions are developing quickly and the demand for them is increasing, which is why it is essential for Smits van Burgst to consider making use of PVT systems. However, their knowledge of PVT systems has not yet been fully developed, which is why this research is being conducted.

PVT systems have been developed a significant amount since their introduction in the 1970s (Chow, 2018). There are several different types of PVT systems, including water-type PVT, air-type PVT, nanofluid PVT and Built-in PVT (BIPVT) systems (Tiwari, et al., 2023). These systems differ based on the different types of working fluids running below or above the PV panel to transfer the heat. A recent review of the current literature done by Tiwari et al, (2023), shows that most research has focused on water-type PVT and nanofluid PVT. These two categories are followed by BIPVT, air-type and other less common types.

Air-type PVT systems typically have air circulating below the PV panels, either with a fan or with natural circulation (Joshi, et al., 2018). Hegazy (2000) researched the performance of four different air-type PVT systems (Figure 2) and concluded that a system with the whole air channel above the PV panel has a lower performance than the other three systems, which all have similar performances. Among the designs studied, the third model was noted for its lower fan power usage.

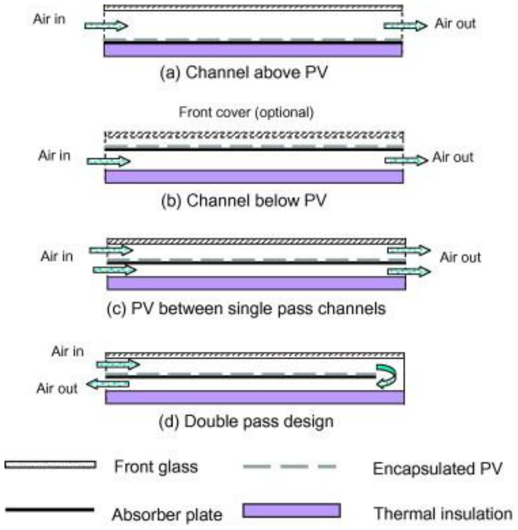

Figure 2: Chow, 2018. Cross sections of common air-type PVT designs.

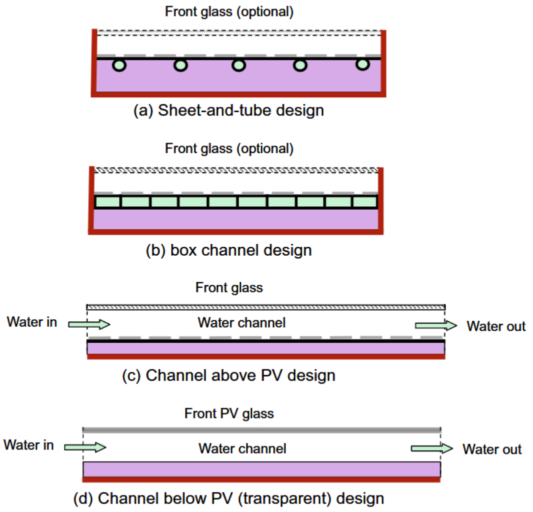

Figure 1: Chow, 2018. Cross sections of common water-type PVT designs.

PVT systems making use of water are often preferred due to their greater thermal efficiency. Four different water-type PVT modules can be seen in Figure 1. Through a combination of modeling and experiments it was found that the thermal efficiency of the channel above PV design was highest, followed by the channel below and the other two designs (Zondag, et al., 2002). The electrical performance is the highest for the channel below PV design however, while the other three designs lag behind. The sheet-and-tube design covered by single glass was recommended to be used due to its economical cost-effective nature. Through a literature review Sheikholeslami et al (2021) suggest that the thermal efficiency of water-type PVT is circa 72%, while the electrical efficiency is around 12,6%. The overall performance of water-type PVT systems is generally regarded as superior to that of air-based PVT systems (Sheikholeslami, et al., 2021).

Nanoparticles can be added to the base working fluid, making a nanofluid, to further enhance the thermal conductivity (Gangadevi, et al., 2019). Mahmood et al (2021) found that by utilizing nanofluids the thermal performance of the PVT system can be improved significantly. The electrical efficiency decreases slightly, but due to the significant optimization of the thermal performance the overall performance of the system improves. In recent research, Al_2O_3 (aluminum oxide) has been the most popular nanofluid used (Sheikholeslami, et al., 2021). The issues with using nanofluids include the high price of nano powders and their instability due to the increase in viscosity.

The integration of nanofluids together with phase change materials (PCMs) has become increasingly popular for researchers (Hamzat, et al., 2021). PCMs are cheaper than nanofluids but have the main drawback of being poor thermal conductors. By creating nano-PCMs this issue can be overcome. On top of that, excellent efficiencies were found in experiments (Al-Waeli, et al., 2017). However, more research is needed on this topic, before such systems can be adopted on a substantial scale.

BIPVT systems are a feasible approach for attaining net-zero emission buildings as they can be integrated into windows, roofs, facades and shadings (Yang, 2015). This allows them to be placed in all shapes and forms. Chow et al, (2007) found when integrating PVT systems in a vertical façade, the natural flow of the working fluid is preferred over a forced flow to improve overall performance. The main working fluids that are made use of are air, water and nanofluids (Maghrabie, et al., 2021). There are several constraints that need to be overcome before BIPVT systems can be regularly considered. These include high investment costs, aesthetical aspects, maintenance and social factors (Yang, et al., 2016).

Methodology

The main research question will be answered through the sub-questions, as can be seen in Figure 3. To answer the first sub-question, a MATLAB Simulink model will be made to simulate the amount of electricity generated by a PVT system for different buildings. Using an analysis of the results of this model and a literature study regarding the technologies, the second research question can be answered. By implementing different technologies with the results of the first model and seeing which are most complementary to these results, second research question will be answered. Using both sub-questions, the final research question will be answered, including future research recommendations.

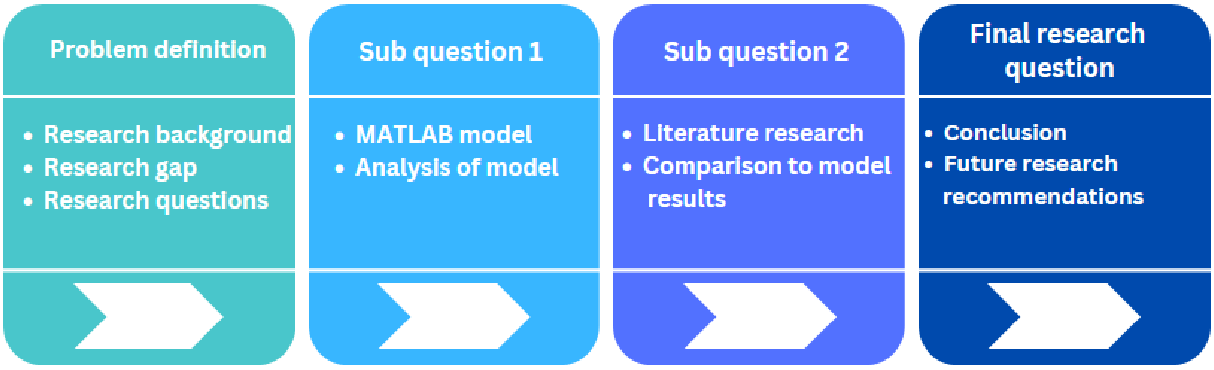

Figure 3: The methodology of this research visualized.

MATLAB Simulink is a versatile software package that can be used for the development and simulation of extensive dynamical models while being user-friendly (Tsai, et al., 2008). The choice of MATLAB Simulink was driven due its robust capabilities to handle complex simulations, while still being rather flexible. The program provides an intuitive graphical interface that allows users to build systems using a wide range of blocks that represent certain components. Due to this, the models built in Simulink are quite visual and can be understood rather quickly.

The amount of electricity generated by the PVT system was calculated per second for a whole year. The electricity demands of the corresponding buildings were then compared to the generated electricity through the charging and discharging of a battery. Using this, electricity deficits and surpluses were identified. The results generated came in the form of three graphs. These graphs represent the state of charge (SOC) of the battery in the system, the amount discharged from this battery and the amount the battery has been charged.

This research examined multiple cases, including an office building, a hospital, a medium-sized house and a supermarket building. For office buildings a case study was done of the Province Zuid-Holland (PZH) buildings. The separate case studies all differ in electricity demand and will therefore be simulated separately. By looking at these diverse cases a plan can be made for when PVT systems are most effective and what kind of technologies need to be complementary.

By synthesizing the results of the model and the answers from the two sub-questions, the final research question can be answered. This was done by looking at which technology can support the PVT system most effectively. The final research question will be presented as a brief overview of how PVT systems can be implemented most effectively and which technologies are needed for different cases.

Data

As input for the model, multiple data sources were accessed. First being the PVT specifications which were used. As there is currently no existing PVT module in MATLAB Simulink, a PV system was used with a heat transfer model surrounding it. This PV system is a solar cell module from Simulink. The parameters for this solar cell were determined by MATLAB with data from real life solar cells, with a maximum capacity of 1 kW per square meter under ideal conditions (MathWorks, n.d. -a). The battery block used makes use of data extracted from the Panasonic NiMH-HHR650D battery data sheet (MathWorks, n.d. -c).

To calculate the production from this system, solar data was used. This data was gathered via the Royal Netherlands Standardization Institute (NEN). The NEN 5060 contains representative reference climate data for determining the energy performance of buildings (NEN, 2021). The reference climate data is a climate year that is statistically representative of the climate from the past years. By making use of statistically average data, the model will be more accurate. The data collected will be in the form of Watt per square meter that fell onto the surface in the reference climate year in the Netherlands (NEN, 2021).

The data for the PZH building case study was accessed from energy calculations done by Smits van Burgst in June of 2024. The data included detailed annual electricity usage of the year 2023. This was first processed and segmented into monthly, daily and hourly consumption patterns to fit the models parameters. The electricity used for a whole year was divided to the monthly usage using the percentages which can be seen in appendix A.2. This was then converted to the daily electricity usage, where only a difference between weekdays and weekends is made. The data was finally converted to hourly energy usage (A.1). These percentages are estimations that were made in consultation with colleagues. Figure 4 shows the hourly energy usage of the PZH buildings for Monday, January 1st.

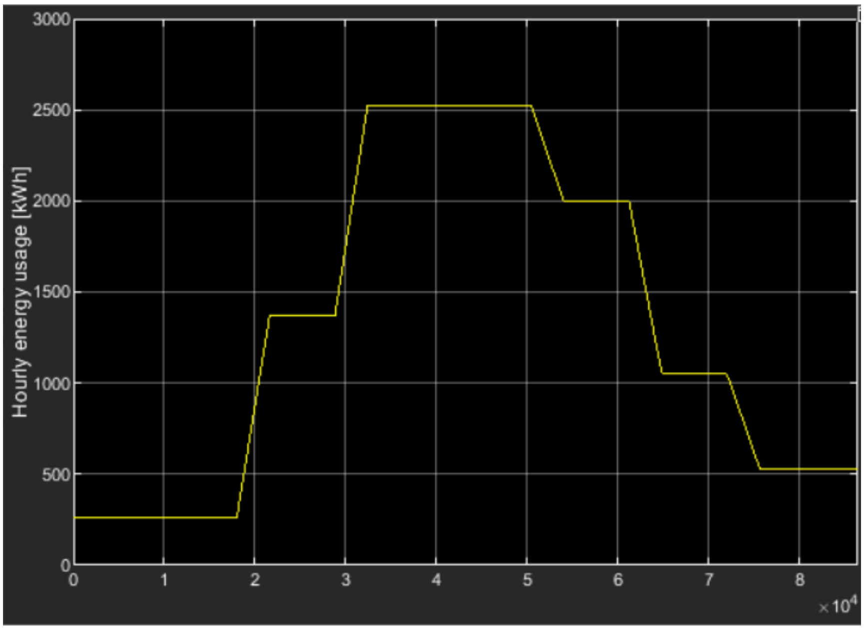

Figure 4: The hourly energy usage in kWh of the PZH building per second for a whole day (January 1st).

The data for the second case, a hospital building, was taken from the Catherina Hospital in Eindhoven (Catherina Ziekenhuis, 2022). Similar to the PZH case, this data was collected in total yearly electricity consumed. This was then divided into months, days and hours. For the third case, data for a medium-sized house was used. This data was retrieved from Vattenfall and was provided in monthly electricity usage, which only required it to be divided into days and hours (Vattenfall, n.d.). For the final case, data from a small supermarket was taken from CBS (CBS, n.d.). This was retrieved in kWh per year and was once again broken down to kWh per hour. The division into monthly and hourly energy usage can be found in appendix A.1 and A.2. The possible technologies that are mentioned were found via a literature research. The amount of panels used per building for the last three cases were based on estimates as to how many would fit per case. For the PZH case, calculations were conducted by Smits van Burgst to determine the number of panels that could be accommodated on all the buildings.

Model

To maintain a high level of accuracy, the model was configurated to run at a time step of 1 second. This ensures the system calculates many steps and allows for graphs and components to interact in between every input data point. The model used for this research covered a whole year of operation; thus the stop time added up to 31,536,000, with a start time of 0. The data points only ever changed every 3,600 seconds, so every hour. A variable-step solver is used together with ode23t solver algorithm. To ensure the results from the model were realistic and reliable, they were discussed with colleagues who gave insights on the results using their experience and thorough knowledge.

The MATLAB model developed for this researched is designed around a main PVT system with a multitude of subsystems as depicted in Figure 5. Each subsystem is structured to simulate an aspect of the model. The core of the model is a PVT system based on ‘sscv_hybrid_solar_panel’, an example system (MathWorks, n.d. -b). This example system provides a working PVT model. It was chosen due to there not being a PVT block in MATLAB Simulink and it being relevant for my research. In this system, inputs for solar irradiance and solar inclination are provided in the ‘Solar Inputs’ sub section. The ‘Pump Flow Inputs’ sub-system provides input areas for the internal flow, the demand and the supply of water of the tank. In the ‘load’ subsystem the electrical load can be seen. The sub system named ‘electrical load’ consists of a large system including a lithium-ion battery, the grid and a dynamical load. In the ‘optical model’ subsystem, the reflection, transmission and absorption of the glass are used to compute the heat absorbed by the PVT glass, the irradiance on the PVT panel and the radiative power absorbed by the PVT panel.

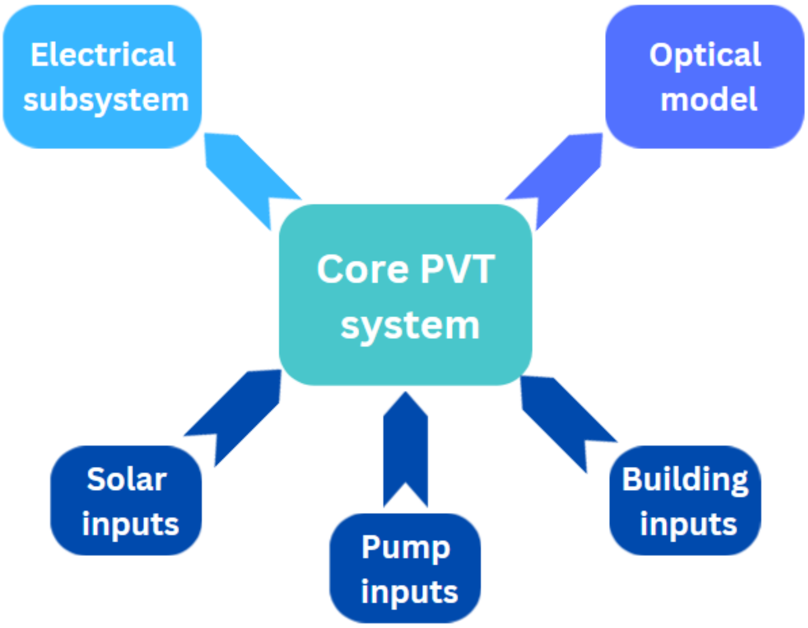

Figure 5: The MATLAB model simplified

The ‘optical model’ model makes use of use of the Fresnel equations with the inputs solar inclination and solar irradiance. There are two boundaries due to the glass covering the solar panel. The first being the air-glass boundary and the second being the glass-air boundary. Below you can see the Fresnel equations which lead to the transmittance t and the reflection r of the former boundary, where r_p and r_s stand for the P- and S-polarization, $\theta_{i,1}$ for the inclination angle and n_{rel} for the refracted index. The total reflection of this boundary is the average of both.

$$r_p = \left(\frac{n_{rel}^2 \cos(\theta_{i,1}) - \sqrt{n_{rel}^2 - \sin(\theta_{i,1})^2}}{n_{rel}^2 \cos(\theta_{i,1}) + \sqrt{n_{rel}^2 - \sin(\theta_{i,1})^2}} \right)^2 \ (Equation\ 1)$$

$$r_s = \left(\frac{\cos(\theta_{i,1}) - \sqrt{n_{rel}^2 - \sin(\theta_{i,1})^2}}{\cos(\theta_{i,1}) + \sqrt{n_{rel}^2 - \sin(\theta_{i,1})^2}} \right) \ (Equation\ 2)$$

$$r = \frac{1}{2}(r_p + r_s) \ (Equation\ 3)$$

$$t = 1 - r \ (Equation\ 4)$$

Between the first and second boundary, the light travels through the glass. Inside the glass some of the light is absorbed, which is the transmission coefficient τ_g. Here the α_g represents the absorption coefficient of the glass while d_g represents the thickness of the glass.

$$\tau_g = e^{\left(\frac{-\alpha_g d_g}{\cos(\theta_2)}\right)} \ (Equation\ 5)$$

For the second boundary, the angle of incidence ($\theta_{i,2}$) can be found by using Snell's law (equation 6). n_1 and n_2 being the refracted indexes of the glass and air, the ratio being 1.52. The inclination angles of the first day of the year and the yearly inclination angles can be seen in Figure 6 and Figure 7.

$$n_1(\sin(\theta_{i,1}) = n_2(\sin(\theta_{i,2}) \ (Equation\ 6)$$

After going through the Fresnel equations once again, the total transmission, reflection and absorption coefficients can be calculated in the following equations.

$$T_g = \frac{t_1 t_2 \tau_g}{1 - t_1 t_2 \tau_g^2} \ (Equation\ 7)$$

$$R_g = r_1 + \frac{t_1^2 r_2 \tau_g^2}{1 - r_1 r_2 \tau_g^2} \ (Equation\ 8)$$

$$A_g = 1 - T_g - R_g \ (Equation\ 9)$$

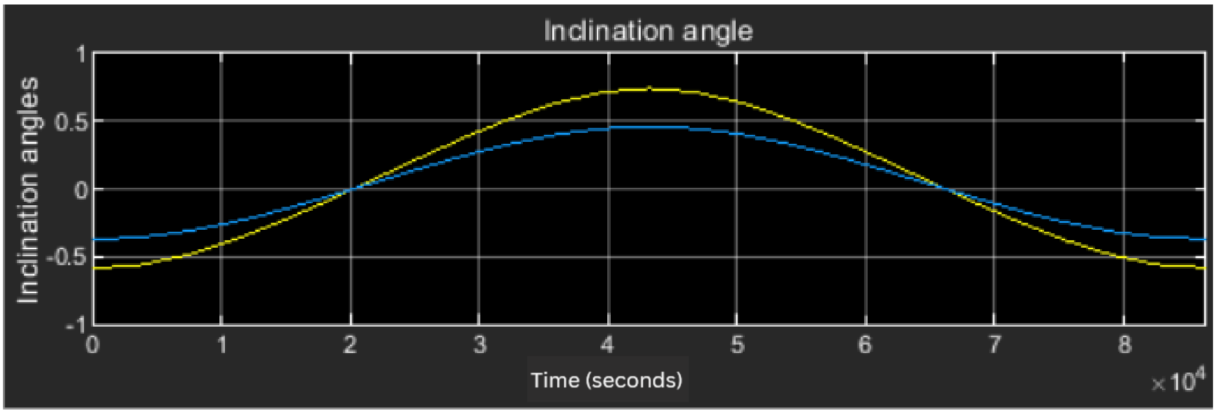

Figure 6: The inclination angles per second for a day (January 1st). The yellow line represents the inclination angle for the first boundary, while the blue line depicts the inclination angle of the second boundary.

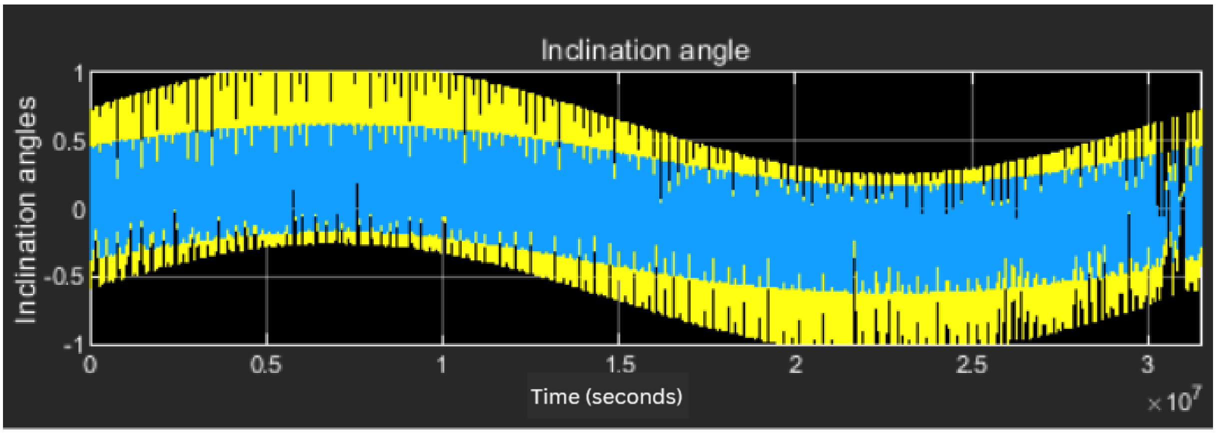

Figure 7: The inclination angles per second for the whole year. The yellow line represents the inclination angle for the first boundary, while the blue line depicts the inclination angle of the second boundary.

The irradiance on the PVT panel is used to calculate the electricity generated with a separate solar cell block. This solar cell block converts the irradiance to electricity while taking the temperature of the cell into consideration. The current and voltage can then be measured from this solar cell block by making use of the current sensor and voltage sensor blocks. The electricity generated from the solar cell is used in the 'Electrical Load' subsystem for further calculations. By multiplying the current and voltage the power generated by this solar cell block can be calculated as can be seen in equation 10. The temperature on the cell is calculated by a controlled heat flow rate source block. This block uses power as an input. The power input is computed by subtracting the power generated of the solar cell from the power absorbed by the optical model.

$$P = V * A \ (Equation\ 10)$$

Electrical subsystem

In this subsystem, the battery block is charged by the electricity generated by the PVT-panel. This battery block is simultaneously being discharged by a dynamical load block, which represents the building. The dynamical load block makes use of power as an input to ensure the system does not stop running when the battery is fully discharged, a switch is put in place that allows the battery to be deactivated and recharge until it has enough power to be used again. This switch activates when the battery is below 20%. This happens through a compare to constant block, which checks the state of charge (SOC) of the battery and activates when it is below 20%.

When this switch is activated, electricity from the grid is used to ensure the load can keep on running. A transport delay block is added between the switch and the compare to constant block to allow the battery to recharge after it has been switched off from the load. The transport delay block is set to 100 seconds. This ensures that the battery does not constantly switch on and off if it reaches below 20% and shortly after above 20%, which causes the model to stop working. The transport delay block only functions when the input consists of the data type double. The compare to constant block outputs the data type boolean. To allow these two blocks to interact properly, a data type conversion block is added to convert the data from boolean to double.

Water-heat subsystem

This model provides a fully working subsystem for the water pipes running below the PV panels. It includes a heat exchanger, multiple pumps, pipes and a tank. This tank has multiple inlets and it is filled and emptied due to three pump inputs. These are, the demand, the supply and the internal flow. The internal flow determines how much water is running through the pipes, the supply determines how much warm water comes in and the demand how much water goes out of the tank. All these variables need to coordinate well with each other for the subsystem to work. The temperature of the water is dependent on the heat coming in from the PVT system which passes through the exchanger. In the top graph of Figure 8, the thermal power output of the panels can be seen. In the bottom graph, the temperature of the water represents the yellow line, while the temperature of the exchanger is shown with the blue line. These graphs depict the first seven days of the year.

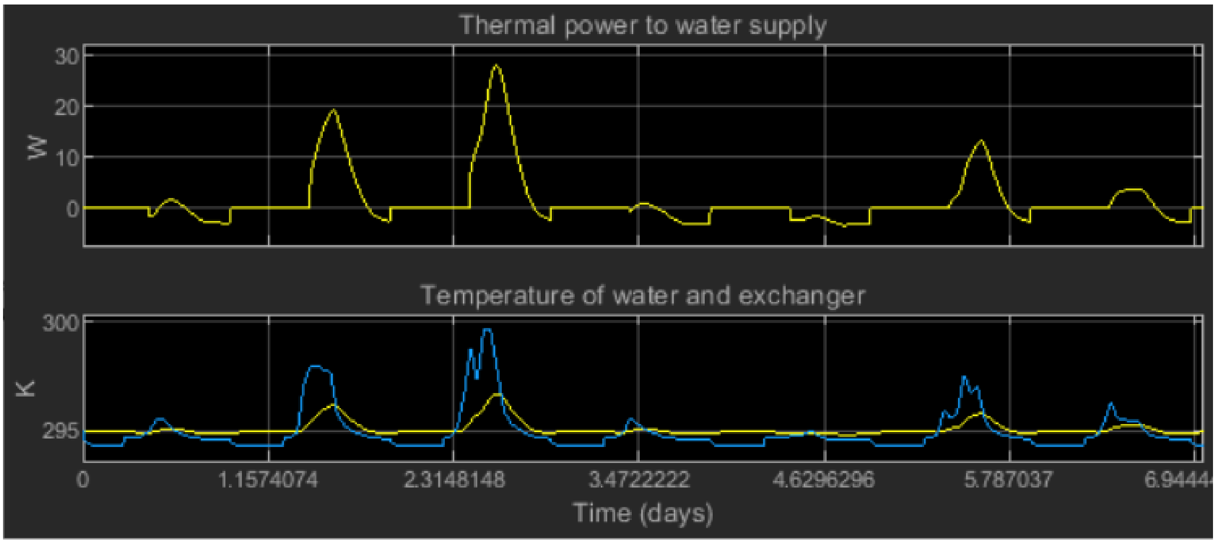

Figure 8: Graphs regarding the thermal system per second for a whole week. The top graph represents the thermal power output to water supply. The bottom graph depicts the temperature of water (yellow line) and the temperature of the exchanger (blue line).

In this research, we opted not to do any calculations with the water system. This is due to the complexity of it. If we were to do this, we would need to adjust all variables for every case to ensure the system is working, which would cost quite some time. However, by having a working water system, Smits van Burgst is able to gain insight into the real life implementation of PVT panels.

Altogether, a MATLAB model is made that runs for a whole year. This model revolves around a PVT system that includes multiple subsystems. These subsystems include an optical subsystem, an electrical system and a water-heat subsystem.

Results

The results of the MATLAB Simulink model are discussed in this section. This section will discuss the results of the model case by case, starting off with the case study, the office building of the PZH. After all cases have been presented, various options for complementary technologies are introduced.

These results are presented using graphs created in MATLAB. First, the SOC of the battery throughout the time is provided, to see when the battery is fully charged and when the battery switches off below 20% charge. This graph gives insight into if the correct battery size was used and if a battery is even necessary. Besides the SOC, the accumulated discharge electricity output and the accumulated charge electricity input of the battery across time will be shown. Using this the periods of time where the PVT panels in combination with the battery struggles to provide electricity for the buildings will be identified. Not only this, but also by identifying how often the battery is fully charged we can see if the battery has the correct size or not. A graph showing the power output per time of the battery is not shown due to it being difficult to read as the simulation has a large number of data points. It was therefore opted to use the accumulated charge and discharge power.

For every case, the battery used in the system has a rated capacity of 13,000 Ah. This was based on the estimate that the battery should be able to provide electricity for at least four hours during the buildings peak electricity usage. The formula to calculate the rated capacity in Ah is as follows:

$$Rated\ capacity\ [Ah] = \frac{Energy\ [kWh] * 1000}{Voltage\ [V]} (Equation\ 11)$$

The calculations for rated capacity were done using data from the PZH case and were applied to every case. For a weekday in January, the PZH office using around 31,572 kWh. The battery would need to supply 5,262 kWh to keep it running for four hours. With a system voltage running at 400 Volts, the battery would need to have a rated capacity of circa 13,000 Ah.

Cases

The initial case presented involves the PZH office buildings. In this scenario, the total annual electricity consumption of all buildings was calculated to be 7.7 million kWh. This was disaggregated into kWh used every hour as explained in the methodology. For this case, 1,147 PVT panels with a maximum capacity of 1 kW were used to generate electricity. This was based on a calculation made by Smits van Burgst regarding the amount of panels that could fit on all roofs. As depicted in Figure 9 and Figure 10, the simulation results show that the cumulative charge was approximately 1,900 kWh, whereas the cumulative discharging capacity reached about 1,250 kWh. The SOC exhibits seasonal variability as during the winter the battery charge seldomly reaches above 20%, while in summer months it consistently reaches 100% (Figure 11).

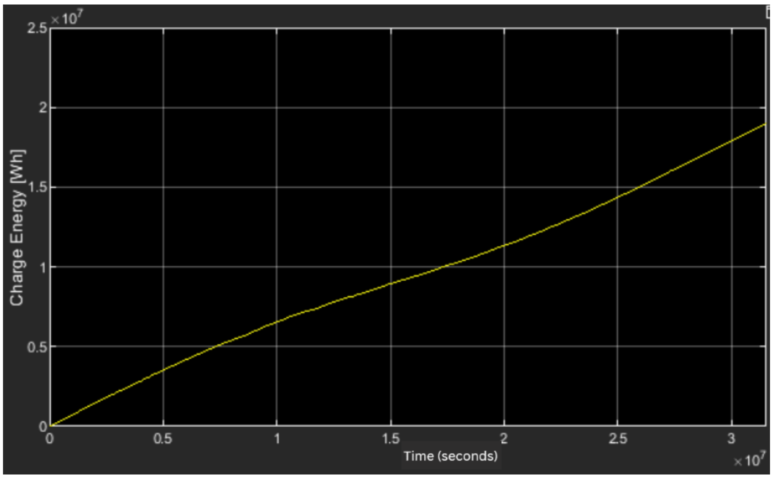

Figure 9: The accumulated charge electricity from the battery in Wh per second over the whole year for the PZH case.

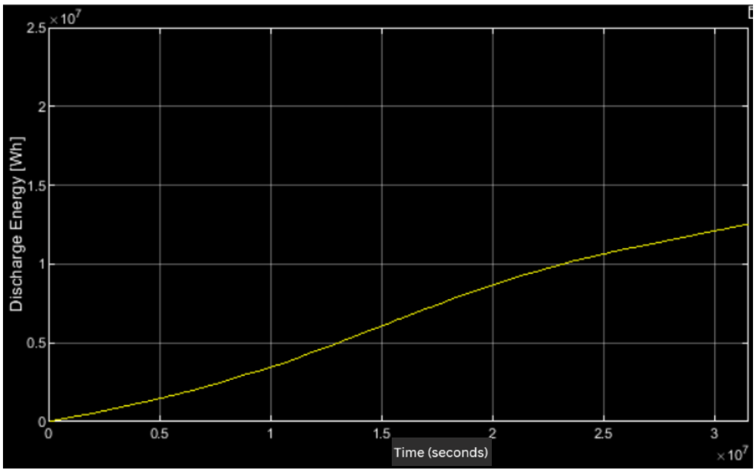

Figure 10: The accumulated discharge electricity from the battery in Wh per second over the whole year for the PZH case.

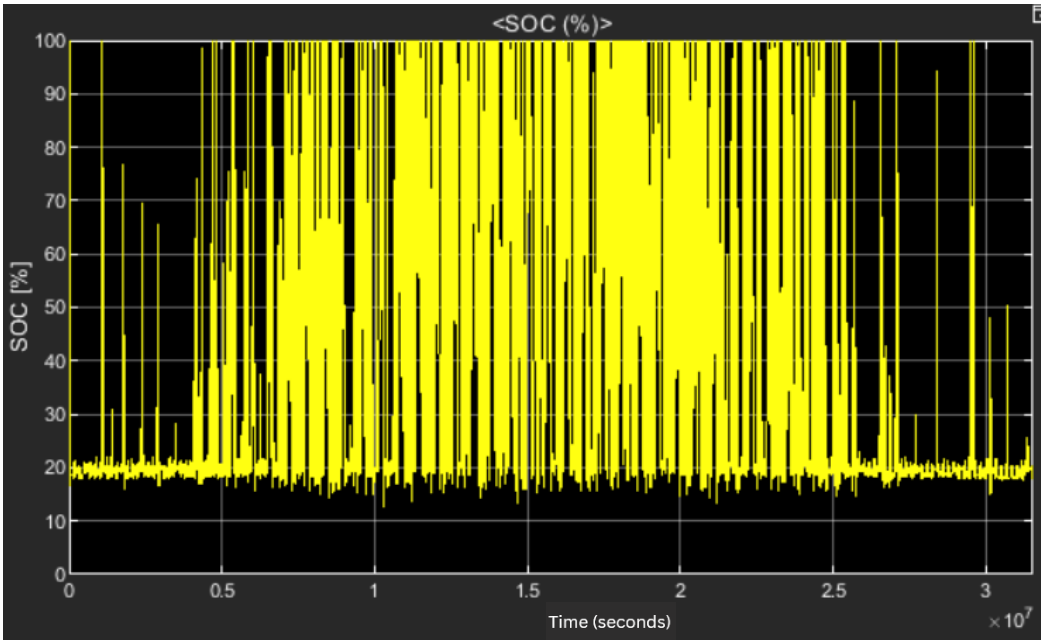

Figure 11: The SOC of the battery per second for a whole year for the PZH case.

The second case involves a hospital, specifically the Catharina Hospital in Eindhoven. The total annual electricity consumed for this facility is 21 million kWh (Catherina Ziekenhuis, 2022). This amount is divided into the months following the same percentages applied to the PZH office buildings. However, the daily division differs notably. While office buildings typically consume most energy throughout the weekdays, hospitals maintain a consistent energy usage pattern throughout the weekend and the week. Similarly, the hourly consumption is distributed more evenly over the entire day due to its continuous operations. This results in a relatively constant electricity consumption profile compared to other cases. For this simulation, 500 panels were used to generate electricity. The battery size was kept consistent with the PZH case to allow for comparison.

As can be seen in Figure 12, the simulation results show that the accumulated discharge electricity is 12,500 kWh. The accumulated charge is 19,000 kWh (Figure 13). The SOC of the battery does not exceed 20% often as observed in Figure 14. Merely during a short summer period does the battery fully charge.

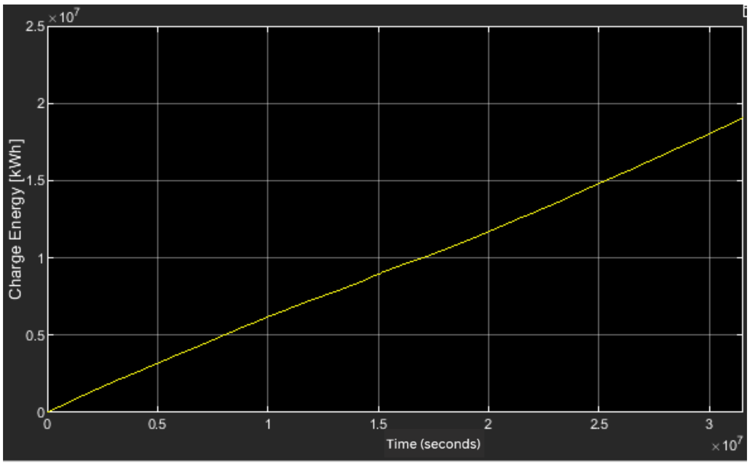

Figure 13: The accumulated charge electricity from the battery in Wh per second over the whole year for the hospital case.

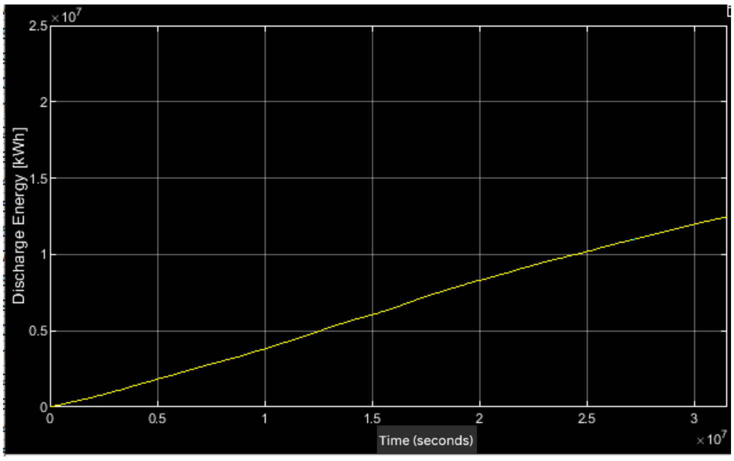

Figure 12: The accumulated discharge electricity from the battery in Wh per second over the whole year for the hospital case.

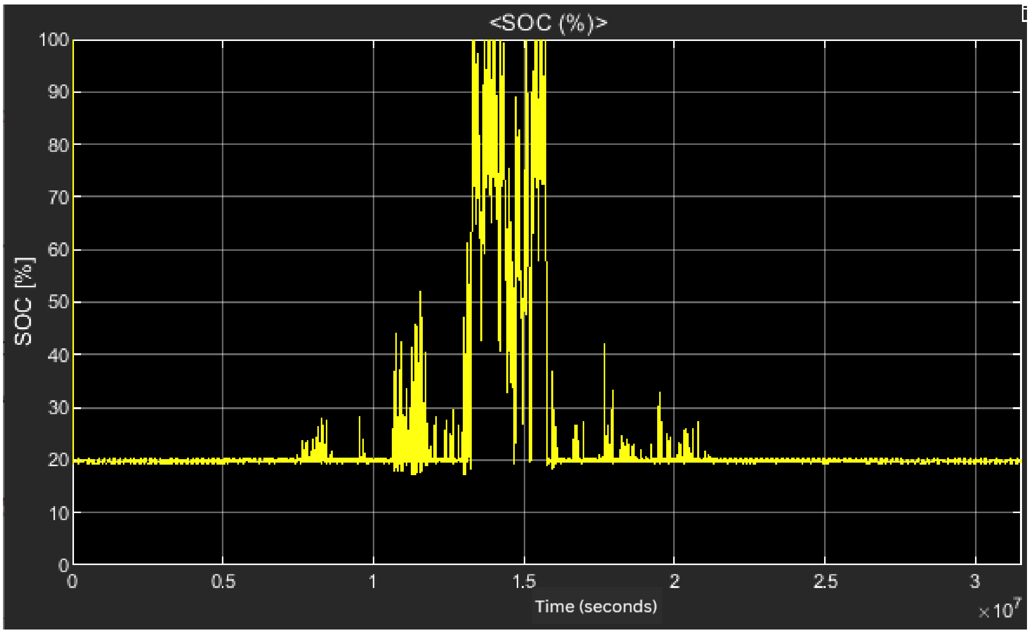

Figure 14: The SOC of the battery per second for a whole year for the hospital case.

The third case focuses on a medium-sized house in the Netherlands. The total annual electricity consumption for the house was 2,997 kWh. This aligns with the maximum usage threshold for the price ceiling of electricity in 2023 (Vattenfall, n.d.). For this case, the hourly electricity consumption exhibits significant variability (appendix A.2). This is due to homeowners consuming more electricity outside of working hours. In this scenario, 5 panels were installed. An 87 Ah battery size was selected. This was based on the largest home battery available from Zonneplan (Zonneplan, n.d.).

The simulation results indicate that the accumulated discharge electricity added up to 97 kWh, while the accumulated charge electricity was 220 kWh (Figure 15 and Figure 16). The SOC of the battery shows a large variance between seasons (Figure 17). Most notable is that there is a period during summer where it barely reaches below 80%.

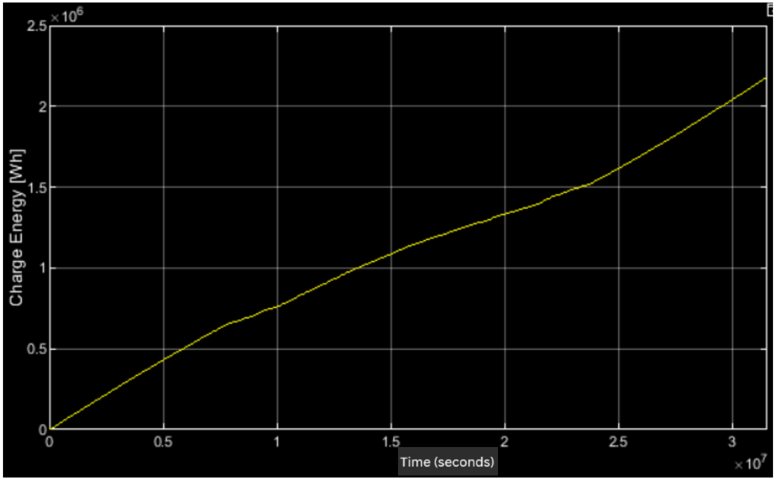

Figure 15: The accumulated charge electricity from the battery in Wh per second over the whole year for the house case.

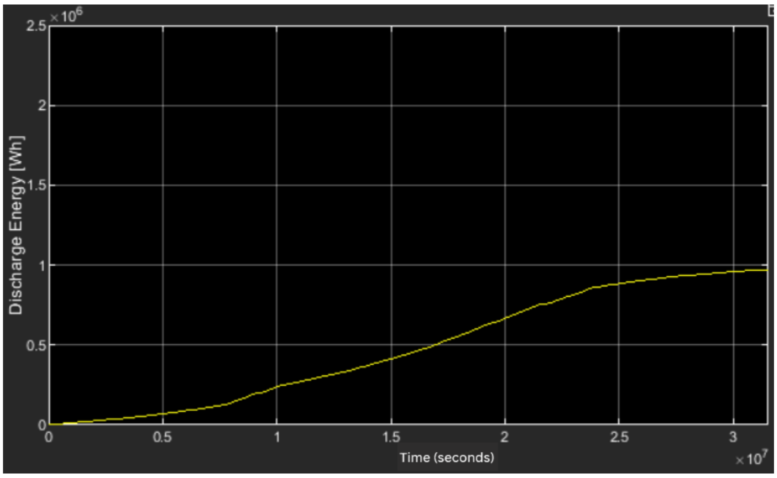

Figure 16: The accumulated discharge electricity from the battery in Wh per second over the whole year for the house case.

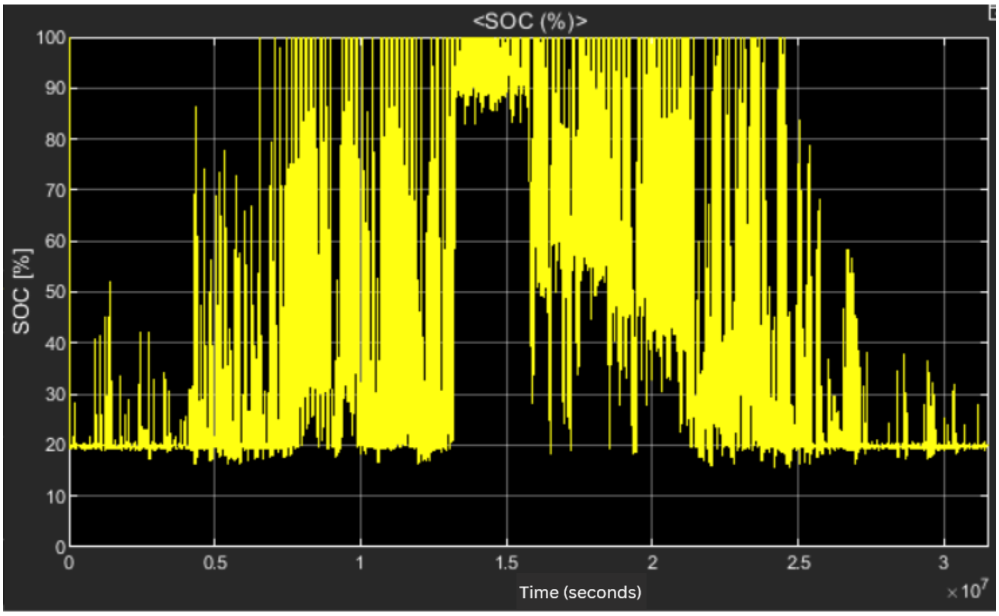

Figure 17: The SOC of the battery per second for a whole year for the house case.

The fourth case examines a small-sized supermarket built approximately fifteen years ago with an annual electricity consumption of 10,400 kWh (CBS, n.d.). Similar to the first two cases, the monthly electricity consumption is divided with the same percentages. As supermarkets are often open seven days per week, the daily electricity consumption does not differ for weekdays and weekends. The hourly electricity consumption is similar to the office case, but now with extended hours (appendix A.1). It was assumed the supermarket was open from 07:00 to 20:00. 10 solar panels were used in this model. An 87 Ah battery was used in this simulation, the same as the house case.

As depicted in Figure 18 and Figure 19, the accumulated discharge was around 62 kWh, while the accumulated charge was approximately 250 kWh. Just as the previous case, there is a large seasonal variable in the SOC of the battery (Figure 20).

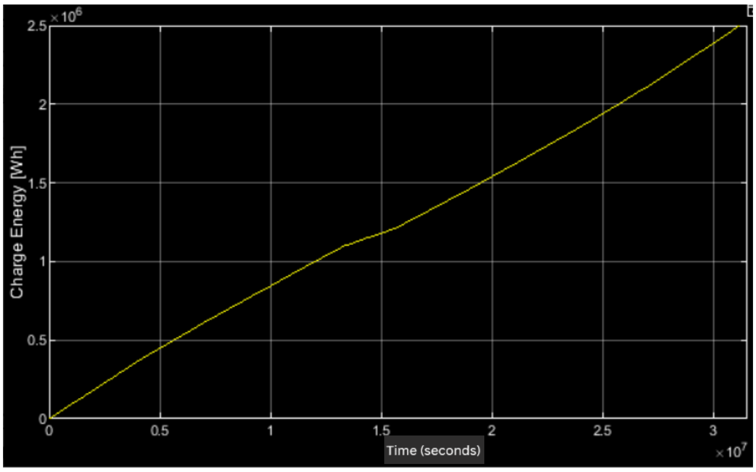

Figure 19: The accumulated charge electricity from the battery in Wh per second over the whole year for the supermarket case.

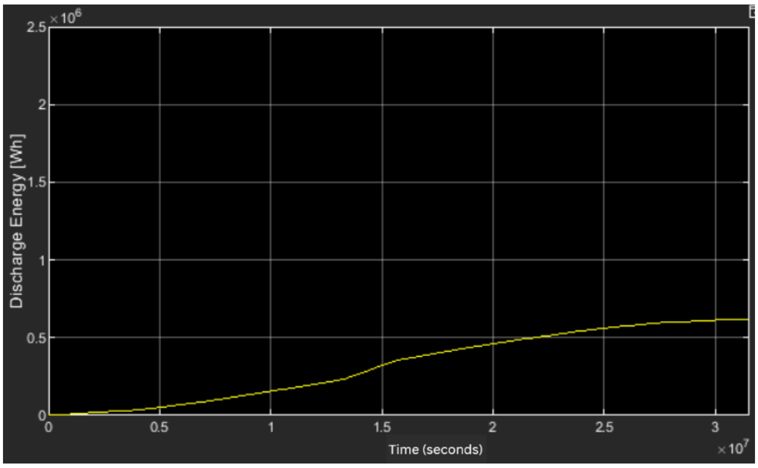

Figure 18: The accumulated discharge electricity from the battery in Wh per second over the whole year for the supermarket case.

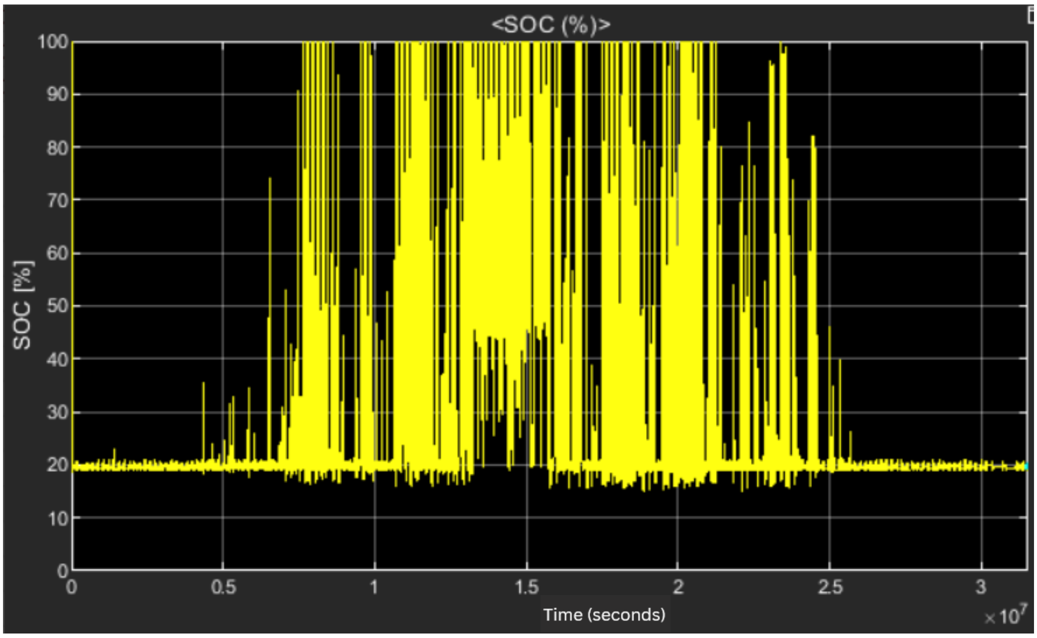

Figure 20: The SOC of the battery per second for a whole year for the supermarket case.

Technologies

To accompany the PVT systems, the following technologies were researched, besides the technologies already present in the model: thermochemical storages (TCS), electrical vehicle (EV) charging and heat pumps with thermal energy storage (TES) systems. These technologies ensure that the excess electricity produced can be used in by the building itself without sending it to the grid.

TCS systems represent an advanced method for storing excess electrical and thermal energy, particularly in applications where long-term storage is required. TCS operates by using the excess energy to drive an endothermic reaction. This stored energy is later released through a reverse exothermic reaction (Pardo et al., 2014). The main advantage of such TCS systems is the ability to store energy over extended period, which allows them to balance seasonal changes in energy supply (Parameshwaran et al., 2012). A well-researched TCS system involves the use of calcium oxide (CaO) (Wang, et al., 2022). In this system, the energy stored in CaO undergoes a reaction to form calcium hydroxide ($Ca(OH)_s$). This exothermic reaction releases heat in the process which can be used when necessary. However, there are a few challenges with this TCS system, such the influence of CO_2, the low thermal conductivity and agglomeration (Wang, et al., 2022). These issues can be overcome to a certain extent by adding other materials to the system. The energy needed for initiating the process of the TCS is significant, thus making it suitable for large amounts of excess energy.

Heat pumps are able to use electricity and generated thermal energy, which can then be stored in a TES system. These systems are an effective method for storing excess thermal energy, making them useful for applications where managing fluctuations in energy supply and demand can be vital. TES systems can store thermal energy in multiple forms, such as sensible heat, PCMs and latent heat (Cabeza, et al., 2015). The stored energy can be utilized when necessary to balance out periods of a surplus in demand. The primary advantage of such systems is the high overall efficiency when storing and releasing thermal energy (Din, et al., 2011). For heating and cooling buildings, this system is ideal. It works will with thermal energy generated by PVT panels, as it gives a way to store such energy if necessary. It is not efficient to convert the heat back to electricity however, as it would need to make use of a low efficient conversion technology, such as an Organic Rankine Cycle, Stirling engine or thermoelectric generator (Alva, et al., 2018). The electricity necessary to make use of a heat pump which can fill a TES system is low, thus making it viable for small amounts of excess electricity.

By making use of Smart EV charging, excess electricity during peak sun hours can be used effectively. EV charging stations can be set up to absorb the surplus of electricity to ensure the maximum usage of generated electricity (Engel, et al., 2018). By making use of EV charging stations, people are encouraged to utilize such a sustainable transportation methods. The largest advantage of this system is that it is very flexible. The charging stations can start charging the vehicles as soon as a surplus in electricity is generated. Similar to an electrical battery, it can vary in size. The more cars plugged in, the larger the capacity. New EV charging stations can be integrated into smart grid technologies that can optimize electricity use through real-time grid analysis (Deilami, et al., 2020). There are several challenges with EV charging, such as the availability of electrical vehicles. If there are none at the location of the PVT panels, the excess electricity cannot be utilized for EV charging. Another issue is that on cloudy days, the cars will not be charged with excess electricity as there most likely is none. This can be fixed by integrating the charging stations into a smart grid system, which can ensure these cars being charged, even on days without sun. Newer EV’s provide vehicle to grid (V2G) systems, which provide the option to discharge the EV’s when necessary. This would make it so EV’s effectively become a functional battery.

EV charging can be utilized for both small and large amounts of electricity surplus (Richardson, et al., 2011).

Discussion

This section will provide an analysis of the results presented in the previous section. First, the results from the model will be examined. These results will first be discussed case by case by analyzing the graphs created by the model. The relationship to these results and the technologies will be discussed. After that, relevant findings when comparing the cases will be mentioned and discussed. This analysis will address the first sub-question by evaluating the performance of the PVT systems in different cases. The second sub-question is explored by looking at which complementary technologies are most effective per scenario.

In the simulation results for the PZH office case, it is indicated that having a battery enhances the office building's energy management significantly. The battery is frequently charged a to its full capacity throughout the year, thus reliably providing electricity for the office when there is a surplus of electricity demand. Given that the SOC of the battery consistently reaches 100%, it is logical to incorporate additional technologies to use the excess electricity production that does not fit in the battery.

Short term energy storage technologies are preferable to optimize the energy use for the PZH office building. This is due to there not being a necessity for long term storage, as there is only a brief period throughout the year where the panels are not able to keep up with the solar production. Technologies such as heat pumps or EV charging stations could make use of the electricity surplus. Depending on the building's specific needs, a choice between these two technologies can be made. If the demand for either heating or cooling exceeds the thermal energy production of the PVT panels, a heat pump system integrated with TES can use the electricity surplus. If there is no demand for additional heating or cooling, the electricity is best used for EV charging. This can be done by installing smart EV charging stations.

Depending on the need for heating or cooling, the heat pump should be used. In case the PVT panels do not generate enough heat to meet the buildings demand, a heat pump powered by electricity from the panels can be considered for the surplus in electricity. This combination would allow for efficient storage and can be used directly when there is an electricity surplus. If there is no need to generate energy in the form of heating or cooling, installing smart EV charging poles can be considered. These charging stations can directly make use of excess electricity and can adapt to the amount of electricity provided. Office buildings are a logical area to make use of smart EV charging stations, as the excess electricity is often generated throughout the day when the cars are plugged into the charging stations.

When looking at the second case, which involves a hospital, it is observed from the results that the battery rarely charges above 20%. This indicates that the electricity generated from the panel is insufficient to meet the hospital's continuous high electricity demand. Only on a few summer days, when the solar production peaks, does the battery fully charge. Integrating a battery in this system is not necessary, given these conditions, as there is rarely any stored electricity which provides a benefit for later. Additionally, incorporating other energy technologies is not logical in this case as there is minimal excess electricity available. Before incorporating other technologies, increasing the number of PVT panels can be considered, besides reducing the energy demand of the building.

The results of the third case, involving a medium-sized house, indicate a significant amount of excess electricity. This is mostly during the summer months, where the SOC rarely drops below 80%. This provides an ideal opportunity for additional technologies to be utilized. As there is a large seasonal variance in electricity generated, long term energy storage can be considered. This could be either in the form of a TES system with heat pumps or thermochemical storage. Either system can store energy for a long period of time. Thermochemical storage systems require a large amount of electricity to function, which suits this scenario, as there is most likely a great deal of electricity available during summer months. This energy can then be used during the winter period, either by regenerating electricity or by converting it into thermal energy.

The fourth case focuses on a small-sized supermarket. This case shares multiple similarities with the previous case, but with larger seasonal variabilities. A difference is that the SOC varies more during summer. An increase in battery size could be considered, as this would allow for less large fluctuations in the battery's capacity. Besides integrating a large battery, long term energy storage systems could be considered in this scenario. As there is no excess electricity during the winter, the need for long term energy storage becomes necessary. Either a TES system with heat pumps or a thermochemical storage system is recommended.

For all cases, it is evident from the observations that the accumulated charge electricity exceeds the accumulated discharge electricity significantly. This discrepancy can be explained due to several factors. Firstly, the battery does not have a charge/discharge efficiency is not 100%. This necessitates more electricity to be used than is discharged. This loss of energy is primarily caused due to electrical resistances in the cables and battery's inverter, where energy is lost due to heat. Another possible issue is that the electricity that is generated when the battery's capacity is full has nowhere to go, it goes into the battery and is counted as charged electricity, while in reality it does not charge. This possible system error could be resolved by including another switch that allows the excess electricity to go to a ground source when the SOC is 100%. It was chosen not to implement this however, as the first switch in the system already slows the model down significantly. By adding a second switch, the model would have been more inert, which would have held back the simulations done for this research.

Furthermore, when analyzing the SOC graphs, it is revealed that the battery occasionally discharges to below 20%. This behavior cannot be attributed to the response time of the battery, as this is set at 0.1 seconds, but rather due to the delay timer. This timer, which is set to 100 seconds, is incorporated to allow the battery to charge back up to above 20%. This also forces the battery to be delayed by 100 seconds when shutting off. Thus allowing for a slight period of discharging time when the battery is charged below 20%.

It is noteworthy to examine the difference in accumulated charge between the first two cases and the final two. The first two cases exhibit a tenfold increase in accumulate charge and discharge electricity compared to the other two cases. This is surprising because the first two cases have approximately a hundred times more PVT panels. This suggests the difference in energy to be hundredfold as well, which is not the case. This can be explained by the significant higher load demand from the first two cases. This results in a larger proportion of generated electricity from the panels to be utilized directly by the load. Merely the leftover electricity is stored in the battery, which does not reflect the total amount of electricity generated by the PVT panels. .

All in all, it is observed that for cases with large amounts of excess electricity and high seasonal variability in SOC of the battery, such as the supermarket and house, the TES system powered by heat pumps and a thermochemical storage system are recommended for long term storage. In the case of the office building, both EV charging as heat pumps with a TES system are recommended, depending on the building's needs. For the hospital, no additional technologies are suggested. It can also be considered to utilize PVT panels without a battery.

Limitations

During this research, multiple limitations were encountered. Most importantly the fact that the thermal system was difficult to do simulations with. It was hoped to compare the thermal system with the electrical system and through that make well considered advice for which technologies to use for different cases. It is possible to make simulations with the thermal system, but all constants need to be accurate for the simulation to run, which requires a great deal of work when simulating multiple cases without accurate data. Regarding the data, a limitation found is that accurate hourly data on energy consumption per case would have been preferable. This would allow for less assumptions made while dividing the electricity consumption and thus more reliable results. This data would most likely allow for a difference in energy consumption per weekday, as some weekdays are busier than other in offices. Vacation days, such as Christmas, were not taken into consideration.

A few limitations were found in the model. First being the battery used. This battery could consider the influence of outside temperature on its performance and could simulate aging effects. When trying this out, it was found that either these additional effects slowed the model down significantly, which is why it was chosen not to make use of this, even though it would have yielded more accurate results.

Future research

Further research is crucial to enhancing our understanding of which technologies should be combined with PVT installations for different cases. By eliminating all limitations encountered in this study, future results will be more precise. One key area of focus should be obtaining accurate data from the buildings, which can be incorporated in both the thermal system as the electrical system. This detailed data would enable researchers to make better conclusions about PVT systems.

Besides analyzing these systems, further research should prioritize integrating these technologies into MATLAB Simulink. Not many of these technologies exist in the program yet, but by adding them simulations can be run with these technologies to compare them more accurately. This could be achieved by developing systems that simulate these technologies, as was done with the PVT model being used.

Having more accurate and comprehensive results benefits both the academic research landscape and industry stakeholders. For researchers, this would provide them with the ability to simulate more sophisticated models with more accuracy. This would allow them to continue developing PVT systems to achieve higher efficiencies which could lead to it becoming more attractive for the industry to invest in and reducing primary fossil fuel consumption. For industry stakeholders, having access to reliable research findings can make them more willing to invest in PVT systems with additional technologies. These companies can help further research with their own insights to achieve greater results.

An area where further research can be impactful is by exploring the economic implications of integrating PVT systems with various technologies. By conducting a cost-benefit analysis a better understanding can be developed. This would allow for a reduction in technology combination possibilities. This allows researches and companies to asses the financial viability of such systems, which allows for innovation and development to reduce the costs of these systems.

Conclusion

In conclusion, this research analyzed the electricity generated by PVT systems and compared it to the electricity loads of four different building types. This was done through the analysis of a MATLAB Simulink model. This approach facilitated a comparative analysis between different building types and enabled the formulation of recommendations which additional technologies can best be used together with PVT systems.

To effectively implement PVT systems, no additional technologies are recommended for the hospital case due to the high and continuous electricity demand. The office building case showed that long-term storage systems were deemed unnecessary and that the choice for additional technologies, Smart EV charging or heat pumps, is dependent on the buildings thermal energy needs. For the apartment and house cases, the use of long-term energy storage systems, such as thermochemical storage or heat pumps combined with a TES system, is advised. The listed technologies can enhance the effective deployment of PVT systems across various building types, contributing to the reduction of carbon emissions and supporting the vital role buildings have in combating climate change.

Acknowledgements

The aim of this research was to assist Smits van Burgst, a medium-sized engineering firm based in Zoetermeer, in determining when PVT systems should be implemented and what additional technologies are necessary to maximize their effectiveness. I want to thank my company supervisor Bas Rutgers who taught me a great deal about engineering and was always willing to talk, help and teach me something new. Even though it was rather disappointing not being able to generate results for the heat system, it is a satisfying thought to have that the model can be used by the company in the future for calculations of their own.

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Appendix

A.1

Hourly division of electricity used in percentage compared to daily usage

Time	Office building (PZH) [%]	Hospital [%]	House [%]	Supermarket [%]
00:00	0.8	3.0	1.0	1.0
01:00	0.8	3.0	1.0	1.0
02:00	0.8	3.0	1.0	1.0
03:00	0.8	3.0	1.0	2.0
04:00	0.8	3.0	1.0	3.0
05:00	0.8	3.0	2.0	5.0
06:00	0.8	3.0	5.0	5.0
07:00	4.3	4.0	8.0	5.0
08:00	4.3	4.0	10.0	5.0
09:00	4.3	5.0	3.0	5.0
10:00	8.0	5.0	2.0	5.0
11:00	8.0	5.0	2.0	5.0
12:00	8.0	5.0	2.0	5.0
13:00	8.0	5.0	2.0	5.0
14:00	8.0	5.0	2.0	5.0
15:00	6.3	5.0	2.0	5.0
16:00	6.3	5.0	2.0	5.0
17:00	6.3	5.0	8.0	5.0
18:00	3.3	5.0	10.0	5.0
19:00	3.3	5.0	10.0	5.0
20:00	3.3	5.0	8.0	5.0
21:00	1.7	5.0	6.0	5.0
22:00	1.7	4.0	3.0	5.0
23:00	1.7	4.0	2.0	2.0

A.2

Percentage of yearly electricity used.

Month	Percentage of yearly electricity usage
January	10%
February	9%
March	8%
April	8%
May	7%
June	7%
July	8%
August	8%
September	8%
October	8%
November	9%
December	10%