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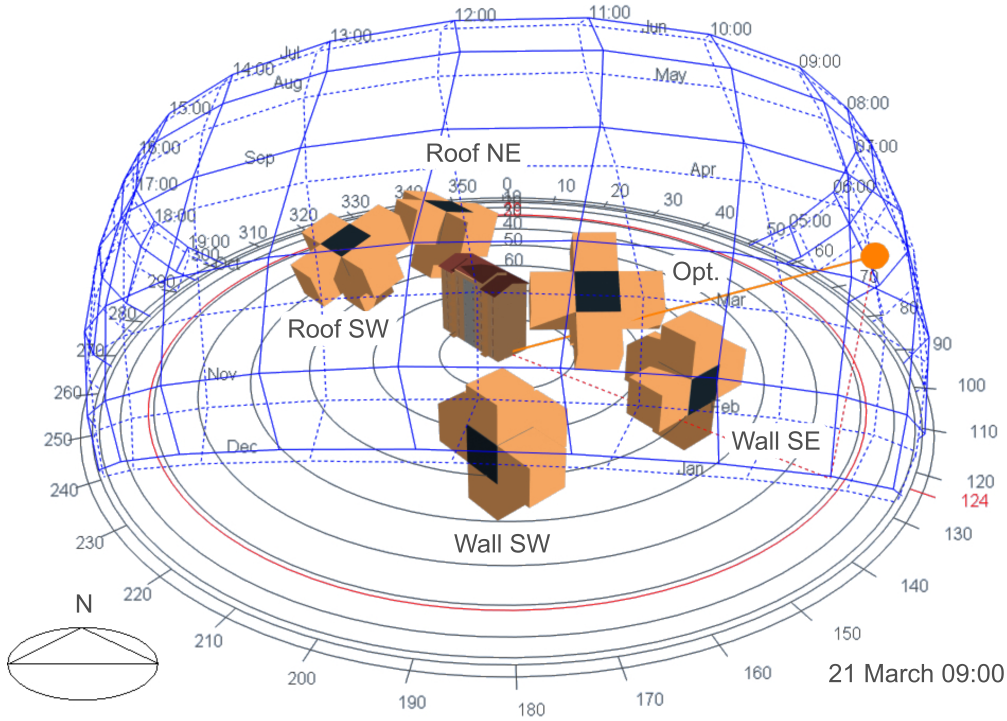

Technoeconomic optimisation of a residential energy system consisting of a PV-attached battery and heat pump

A case study: Treviso, Italy

Master's thesis in Nordic 5 Tech Master in Innovative Sustainable Energy Engineering (Heat & Power track)

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Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Sunpath diagram for the studied building and its corresponding solar PV surfaces.

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Abstract

This thesis assesses the technical and economic feasibility of an energy system renovation strategy for a typical 1970s multi-apartment building in Treviso (Italy) in order to increase its energy efficiency and reduce CO_2 emissions. The strategy is as follows: by adding a heat pump and a battery to a solar PV system (rooftop and facade), the self-consumption of generated electricity is increased, resulting in a lower electricity bill and CO_2 emissions. The goal of this thesis is to (1) to assess the self-consumption increase and (2) to determine the economic feasibility and optimum sizing of its components, particularly the battery. This was done by creating a DesignBuilder 3D building model to simulate the thermal performance of the building and by creating a MATLAB model to simulate the energy system. For PV generation with an PV-to-floor area ratio of 0.33, default self-consumption turned out to be 62%. Adding a heat pump increases the self-consumption significantly, to 87%. Further adding a $0.17kWh/m^2_{floor}$ Li-ion battery increased the self consumption to 92%. All in all, the installation of a PV-attached battery and heat pump system is economically feasible and significantly increases the self-consumption of PV-generated electricity. The heat pump is most economically viable, then solar PV, while the battery barely breaks even. As battery prices dwindle, the business case for batteries is likely to gain traction in the future. By 2025, a PV-attached battery and heat pump systems have the potential to reduce EU carbon emissions significantly.

Keywords: Li-ion, solar PV, heat pump, residential, energy system, feed-in tariff, self-consumption, self-production, optimisation, simulation, building, .

Acknowledgements

This thesis has been performed in close cooperation with the DREEAM project research group at the Division of Building Technology at Chalmers University of Technology. The EU-funded DREEAM project is part of the Horizon 2020 strategy and aims to demonstrate very high levels (75%) of residential energy demand reduction on a multi-building scale. One of its members is ATER Treviso, a public company founded with the goal of increasing the quality of residential accommodation for the less affluent (i.e. social housing) in Treviso, Italy. It is within this context that this thesis has been conducted.

Special thanks therefore go out to my examiner and supervisor at the Division of Building Technology, York Ostermeyer and Claudio Nägeli, for providing me with all the necessary details about the DREEAM project. In doing so, they have made it possible for me to do research that is very closely tied to the real world.

In addition, I would like to express my gratitude to ATER Treviso for providing me with incredibly detailed building data. The credibility of this thesis has been very significantly improved because of it.

Finally, I would like to thank everyone at the Division of Building Technology for making the time working there very enjoyable.

Florijn de Graaf, Gothenburg, 07 2016

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Introduction

According to the European Comission, residential heating and cooling accounts for nearly a quarter of the final energy consumption in the EU. [37] To achieve the decarbonisation objectives set by the EU, buildings have to become more energy efficient, while reducing fossil fuel dependency. This is laid down in the Energy Performance of Buildings Directive: all EU countries must take significant steps to reduce the carbon footprint of their building stock[44]. To do so, each country has to set minimum energy performance requirements for new buildings, as well as for the major renovation and retrofitting of existing buildings.

There are many viable retrofitting solutions to reduce the residential carbon footprint. These solutions range from increasing the energy performance of buildings (e.g. through insulation), to reducing the fossil fuel consumption (e.g. by replacing gas boilers with heat pumps). However, there is currently a lack of attractive financial products for building renovation that incorporate these solutions. [37] The EU has therefore set out to develop a toolbox of measures in order to facilitate renovation in apartment buildings. It is within the context of this toolbox that a renovation strategy for the retrofitting of old energy systems in apartment buildings will be examined.

The specific renovation strategy assessed in this thesis consists of solar panels in combination with a heat pump and battery storage. The big advantage of having solar PV generation with a heat pump and/or battery in combination, is that any excess generated power can be diverted to the battery or heat pump. In doing so, the building owner prevents feeding power to the grid at a lower price than it would cost for him to buy from the grid. On top of that, the addition of a heat pump or battery to a photovoltaic system potentially increases the profitability of said PV system, ultimately allowing for more solar panels to be installed - and thus reducing

CO_2 emissions.

The grid operator also benefits because it prevents large grid power feed-ins during peak generation times (i.e. when the sun is shining), a practice called 'peak-shaving'. Without peak-shaving technologies like storage (batteries) and flexible demand (heat pumps), the widespread implementation of intermittent renewable electricity generation runs into distribution problems when peak generation exceeds demand. In the case of solar PV, generation is heavily concentrated around noon and in summer, when demand is only average. When generation exceeds demand, allocation problems arise. Therefore, the theoretical maximum allowed amount of solar PV in the total energy mix would be roughly equal to its capacity factor, around 15%. $Without peak-shaving technologies, that is.$ As long as intermittent electricity generation remains a small part of the energy mix, allocation problems can be avoided.

However, solar power is well on its way to play a crucial role in tomorrow's carbon-free society. The price of a PV module has dropped more than 80% in the past five years [20]. As a result, solar power has become an obvious choice for building owners looking to reduce the carbon footprint of their buildings. In the EU, installed capacity of PV installations has increased from 100 MW in 2000 to more than 30 GW in 2010, corresponding to a doubling every two years. [25] Germany and Italy are mainly responsible for this growth, with an installed capacity of 32 GW and 16 GW respectively [25]. In Italy, PV installations already meet 7.5% of the national electricity demand. [25] While PV generation currently only accounts for 6% of total EU electricity supply, the growth is likely to continue, with rooftop solar responsible for a large share of this growth [20].

Sustaining this growth rate of solar PV poses serious challenges to both grid operators and energy suppliers. Large-scale intermittent energy generation calls for flexible generation capacity as base-load is put on the margin. This is the reason why peak-shaving and storage solutions have a clear role cut out for them. PV-attached heat pumps and batteries are able to fill this role for the residential energy market segment, a segment that makes up 25% of total energy demand in the EU. This potential is, however, dictated by economics. Heat pumps and solar PV have proven themselves to be economically feasible with an ROI of less than 7 years in most cases, yet the business case for batteries remains harder to make. [24]

Nevertheless,the business case for battery technology is gaining ground. Although batteries have been around for quite some time, it has only been in recent years that we have seen the first battery installation for PV systems come to the market. There are two main reasons identifiable for this development:

Firstly, the rise of Li-ion battery technology due to the electrification efforts of the automotive sector by companies like Tesla Motors. Li-ion batteries' advantage over older, yet well-matured and cheap battery types like Nickel-Cadmium (NiCd) and Nickel metal hydrides (NiMH), is that they have a high round-trip efficiency of over 90%, compared to around 70% for NiMH and NiCd. On top of that, the cost of Li-ion battery technology has dropped from 1000$ per kWh in 2007 to under 400$ per kWh in 2014, and is expected to continue to drop in the near-future. [18]

Secondly, the price of electricity sold back to the grid is expected to be significantly reduced throughout Europe, as photovoltaic technology is regarded to have matured enough to no longer depend on subsidies. [6] [22] This so-called Feed-In-Tariff (FIT) dictates the profitability of battery systems: if a small-scale power producer (e.g. a house owner) receives the same price for feeding into the grid as he pays for drawing out from the grid, then there is no economic benefit to increasing self-consumption via batteries.

The lowering of Feed-In-Tariffs in combination with the declining cost of Li-ion batteries create a clear economic potential for PV-attached battery systems to enter the market. Various studies have assessed this potential under different boundary conditions. Below is an overview of studies that assess the economic potential of PV-attached battery systems (excluding a heat pump):

Naumann et. al. (2015) assessed the cost of PV-attached battery systems in Germany, for an electricity price of 0.30€$/kWh$, and a FIT of 42%. They found that a battery price of 300€$/kWh$ warranted a $4.4kWh$ battery capacity for a $4.4kW_p$ solar PV installation, so $1kWh$ for every kW_p. [35]

Balcombe et. al (2015) ran a simulation over 30 households in the UK with different demand profiles, for a PV-attached battery system in combination with a micro-CHP (combined heat power) unit. They found that, for an average electricity demand of $373W$ and an average PV generation of roughly $3kW_p$, the optimum battery size is $3kWh$. So again, $1kWh$ of battery installed for every $1kW_p$ of solar PV. The battery was, however, not profitable in this scenario, as a $600£/kWh$ battery price was used. [19]

Zucker and Hinchcliffe explored the economic feasibility for a PV-attached battery system in Italy and Germany. They concluded that in Italy, a battery price of $250€/kWh$ is required to reach profitability. This is under the condition of a battery only system, no FIT, a PV production equal to the electricity demand. [25]

Di Pietra et. al. (2015)
With the Li-ion battery market doubling every year and having an associated annual price drop of 6-9% [18], it seems very likely that Li-ion battery technology will become cheap enough in the near future to make PV-attached battery systems a sensible investment. Although variation exists, most studies conclude that domestic Li-ion battery application is on the verge of breaking through [35] [25] [21] [19].

So how does a heat pump affect the battery investment? Unfortunately, adding a heat pump to a PV-attached battery system decreases the economic potential of said battery, as excess power is diverted to the heat pump first. This diminishes the utilisation of the battery and therefore unfortunately reduces its profitability. The question then becomes: how much economic potential is left to add a battery to a heat pump and solar PV installation?

To the author's knowledge, only limited studies have been performed on the combination of a heat pump and battery with a solar PV system, only one of which (partly) considered economics [12]. The economic assessment was limited to a simple doubling of the electricity price for a battery size of 48 kWh in a $5.19kW_p$ PV system in Sweden. This corresponds to a severely sub-optimal battery size of $9.2kWh/kW_p$ (compared to roughly $1kWh/kW_p$ found in other studies), and is thus not a very useful conclusion from an economical stance. Other papers focused on technical aspects instead, like peak-shaving potential [26] or self-consumption potential [24], with positive results. While the peak-shaving and self-consumption potential are essential characteristics from a technical stance, the success of PV-attached Li-ion battery systems in combination with heat pumps is also dependent on economics.

The goal of this thesis is therefore to assess not only the technical performance, but also the economic potential of a PV-attached battery system with a heat pump and battery. The main technical parameter of interest is the self-consumption increase as a result of installing a heat pump and battery. This self-consumption increase measures to what extent PV power is used locally, and is therefore also directly related to money savings. The money savings are essentially the sum of energy savings due to self-consumption increase minus the cost of the storage device that enables said self-consumption increase. The main economical parameter of interest is therefore the expected money savings of the system.

The outcome of this research is dependent on many boundary conditions and is inherently case-specific. The choice of residence type and location play an important role on the outcome, as it influences essential factors like building energy performance, climate and prices. In order to arrive at a useful conclusion, it is important to select these boundary conditions in such a way that they are representative for the general building stock in Europe. For this reason, a typical soon-to-be-renovated 1970s apartment building in Treviso, Italy, was chosen as a case study. As identified earlier, buildings built in the 1970s or earlier make up half of Europe's building stock and have the highest energy savings potential. The choice for an apartment building is based on the fact that they tend to be homogeneous and modular, making a specific renovation strategy more easily adaptable to other cases.

Several boundary conditions for the research question will be unknown initially. They will result from an extensive analysis of the building. Examples include building energy performance and PV system size. Building energy performance dictates the heat pump size, while building geometry dictates the PV system size. Once these parameters are known, the focus will be on optimising the size of the Li-ion battery and the heat pump tank.

Minor variations in factors like battery price, electricity price or building energy performance can have a large impact on the overall business case. In order to strengthen the results obtained from this particular case and make them more applicable to similar cases, an extensive sensitivity analysis will be performed for both technical and economical parameters. In doing so, the effect of various parameters will become more clear. By analysing their sensitivity, more understanding can be gained as to how the business case will turn out in other regions or countries.

All in all, the research performed in this thesis should give a clear answer to the question: "What is the optimal energy system configuration for a typical 1970s multi-apartment building renovation consisting of a heat pump, solar PV and a Li-ion battery?" In addition, sub-questions like "How will this change in the future?" or "How does the optimum configuration change when (for instance) the amount of solar PV, the battery price, or the heat demand changes?" will also be adressed.

2

Methodology

The research setup for this thesis consists of two modelled components: the Building Model (BM) and the Energy System Model (ESM).

The BM combines the climate data with the building data in order to create a realistic model of the building in the DesignBuilder software. DesignBuilder can simulate building energy performance up to a quarter-hourly resolution. The simulated building energy performance is then exported as load profiles for the heat and cooling demand and solar irradiation. An hourly resolution was found to be sufficient for this [7].

The load profiles are then used as input for the ESM, together with the component data (i.e. efficiencies and characteristics of the heat pump, solar PV and battery), as well as the economic data (e.g. component and electricity price). Although the building energy performance and corresponding load profiles count as results generated by the research, they still belong to the methodology section. The reason being, that the building energy performance serves as input data to the ESM, which is the main process of interest in this research. See Figure 2.1 for clarification.

The ESM then simulates the performance of the energy system, resulting in the desired output for the research question. This simulation can be performed for a whole series of input data, resulting in 2D or 3D graph outputs. By varying the size of different components of the system, the optimum size can be determined for various components (such as the battery).

Certain other components, such as the heat pump or the solar PV system, have their size dictated as a direct consequence of some predetermined factor, such as heat demand or the amount of sun-facing surface area. These factors will therefore act as a boundary condition for the main research question pertaining to this particular building. However, in order to gain insight into the effect of these parameters (so that the conclusion can be applied to other buildings too), they will be hypothetically varied in the sensitivity analysis in Section 4.2.

For instance: what if it were possible to install twice the amount of solar PV, how would this affect the optimum battery size? There might, after all, be a nearby parking spot that can have a PV-roof installed over it. Or what if the heat demand is twice as low because the building owner decided to insulate before installing a heat pump, what would be the optimum system size then? These questions will all be dealt with in the technical and economical sensitivity analysis performed at the end.

In the following chapter the research method will be explained. Generally speaking, the method can be divided into three consecutive parts:

1. The building model made in DesignBuilder.

2. The hourly load profiles.

3. The energy system MATLAB model.

These three parts combine to make up the whole energy system simulation, as will be explained in the following sections.

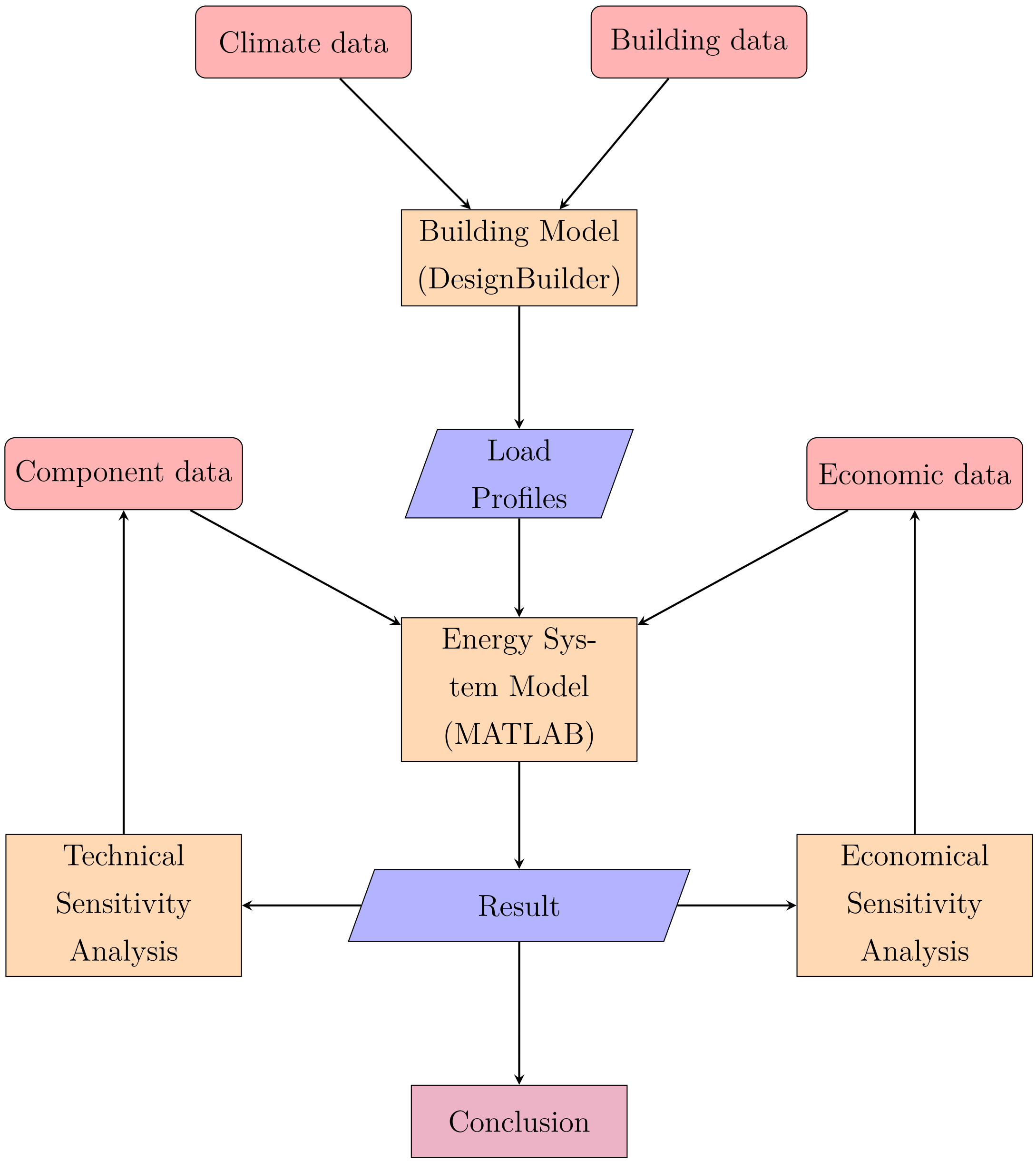


Figure 2.1: Schematic overview of the methodology. Red boxes indicate input data, orange boxes indicate a process, and the blue boxes indicate the simulated results.

2.1 Building model: Treviso, Italy

For this thesis a case study will be conducted on a multi-building apartment block in Treviso Italy. There are three main reasons for this. First of all, the building is very typical in its construction and therefore resembles a significant portion of the European building stock. Secondly, it has been built in the 1970s and is thus severely lacking in terms of energy efficiency. Last but not least, due to the building site being part of the DREEAM project, detailed building data (both measured and simulated) is available from ATER, the Italian housing association responsible for the building.

2.1.1 Climate data

Treviso is a medium-sized city in the northeast of Italy. It is the capital of the province Treviso, housing roughly 80,000 inhabitants. Like most other coastal regions in Europe, Treviso has a temperate oceanic climate (Köppen classification Cfb), characterised by mild winters with a mean temperature above 0°C and warm summers with a mean temperature over 10°C. The average annual temperature is 13.0°C with a fair amount of precipitation, 928mm per year [42]. Since temperatures in Treviso can well exceed 30°C in summer, cooling is required during the summer months.

Table 2.1: Site data for Treviso. Source: Weatherbase [42].

Municipality	Treviso (TV)
Latitude	45°41'02" N
Longitude	12°12'38" E
Height	15 m.a.s.l.
Heating degree days	2378
Köppen climate classification	Cfb (Marine)

Hourly resolution climate data was obtained through the DesignBuilder database. The average annual temperature for the DesignBuilder data is 1.2 degrees lower than the ATER data. The distribution for both data sets is very similar (see Figure 2.2), with the spring and autumn periods having the biggest deviation.

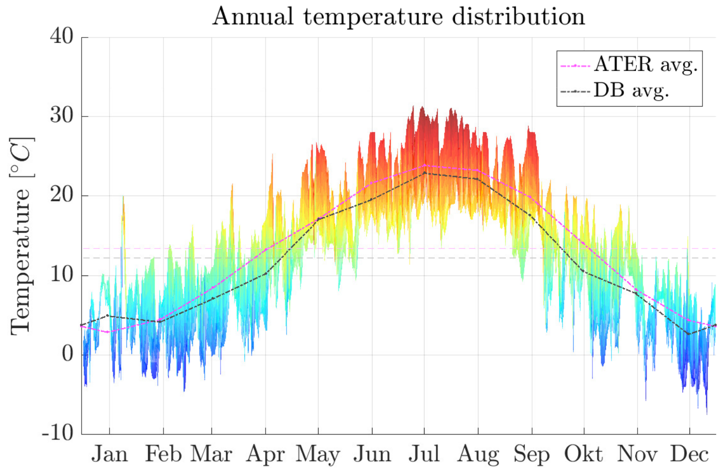


Figure 2.2: Temperature throughout the year. Source: [47] and [40].

The average solar irradiance is $158kW/m^2$, with peaks of up to $1kW/m^2$. This means that a horizontally oriented solar PV panel with an efficiency of 15% will produce $23.7W/m^2$ on average and $150W/m^2$ at most.

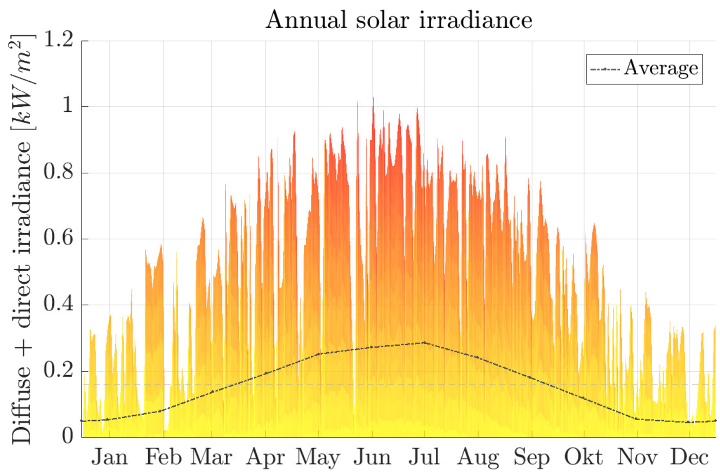


Figure 2.3: Solar radiation throughout the year. Source: [47].

2.1.2 Building data

In the outskirts of Treviso, in the district of S. Paolo, lies Biscione, the building complex that is the focus of this thesis. The district was built in the 70s and is characterised by long streets with parallel green areas and building blocks. Biscione is a 7 stories high apartment building complex consisting of 8 connected blocks. Seven of these blocks are used as social housing, and one of the blocks is owned privately. On either side of the building complex is a neighbourhood park that is further surrounded by small, 3-stories high apartment buildings.

Figure 2.4: Blueprint of the whole appartment block.

Figure 2.5: Birdseye view of the Apartment block.

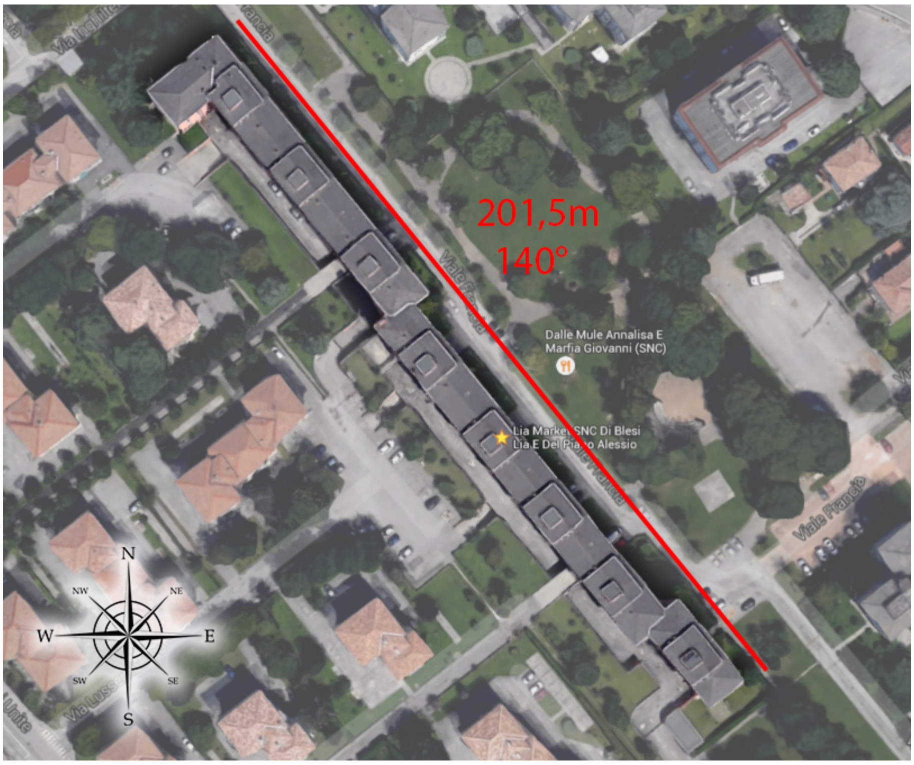


Figure 2.6: Biscione.

The building complex is constructed in a manner that is typical to the 70s and 80s, inspired by the 'Ville Contemporaine' and 'Ville Radieuse' ('ideal city') model of the famous architect Le Corbusier. These types of building are very popular in the suburban areas of Italy and Europe, and therefore represent a significant portion of the European building stock. Their building style focuses on efficiency and comfort through a linear, well-ordered design. As a result, every aspect of the building is extremely uniform, from the windows to the finishing and even the energy performance. The framework of the building is made from concrete, with perforated brick blocks in between and masonry slabs on the exterior. With single glazed windows, poor insulation of the facade and absence of cooling systems, the thermal performance of the building leaves much to be desired.[1]

[1] Although significant gains in terms of energy reduction can be achieved through proper insulation, this thesis will mainly focus on the active measures, i.e. increasing energy generation efficiency instead of reducing energy usage. The reason being, that the cost of retrofitting a building with insulation is too case-specific and would therefore muddle the business case of the energy system alone. If it is decided to apply insulation, this will simply result in lower heating generation requirement, a factor that *will* be considered in this thesis.

2.1.2.1 Heating system

The heating system of the building currently consists of four gas boilers with a heating capacity of 1350 kW, two large ones (420 and 630 kW) for heating and two smaller ones (150 kW each) for domestic hot water (DHW). Their design value is $123kWh/m^2/a$, or $14W/m^2$. For heating purposes, hot water is transported through the radiator network in a closed loop. This distribution network will also be used for the heat pumps. For DHW purposes, there are currently two storage tanks (500 and 800 l) and a direct plate heat exchanger for instant production.

The efficiency of the heaters is rather low since they date back to the seventies; 81.8% for the large boilers and 77.9% for the small DHW boilers. Newer boiling systems tend to have efficiencies of 90% or higher. Hence the potential energy savings for using a heat pump is high. The proposed idea by ATER is to replace the four generators with four vertical ground-source heat pumps. This thesis will combine them into a single heat pump for ease of calculation.

2.1.3 DesignBuilder Building Model

The building model was created in order to obtain realistic hourly values for heat and cooling demand, as well as solar PV production. For the modelling of the building, DesignBuilder v4.05 was used. DesignBuilder is a 3D modelling software designed for building energy calculations. It is based on EnergyPlus, an open-source software package from the US Department of Energy that can model heating, cooling, water use, lighting, ventilation and other energy flows in buildings. The building heating set point was set to $20°C$ and the cooling set point was set to $25°C$, on the basis of data provided by ATER [43].

Figure 2.7: Frontview of block T2. Source: ATER [43].

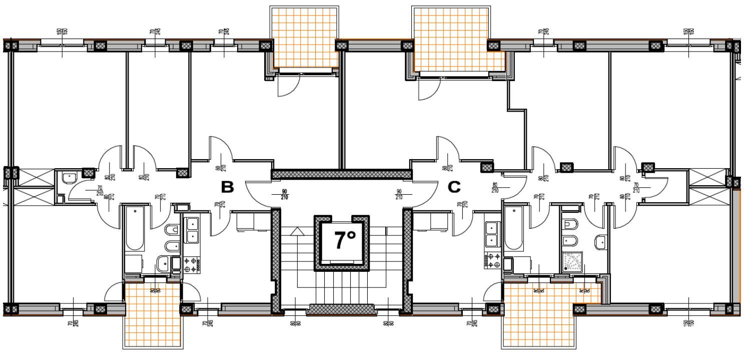
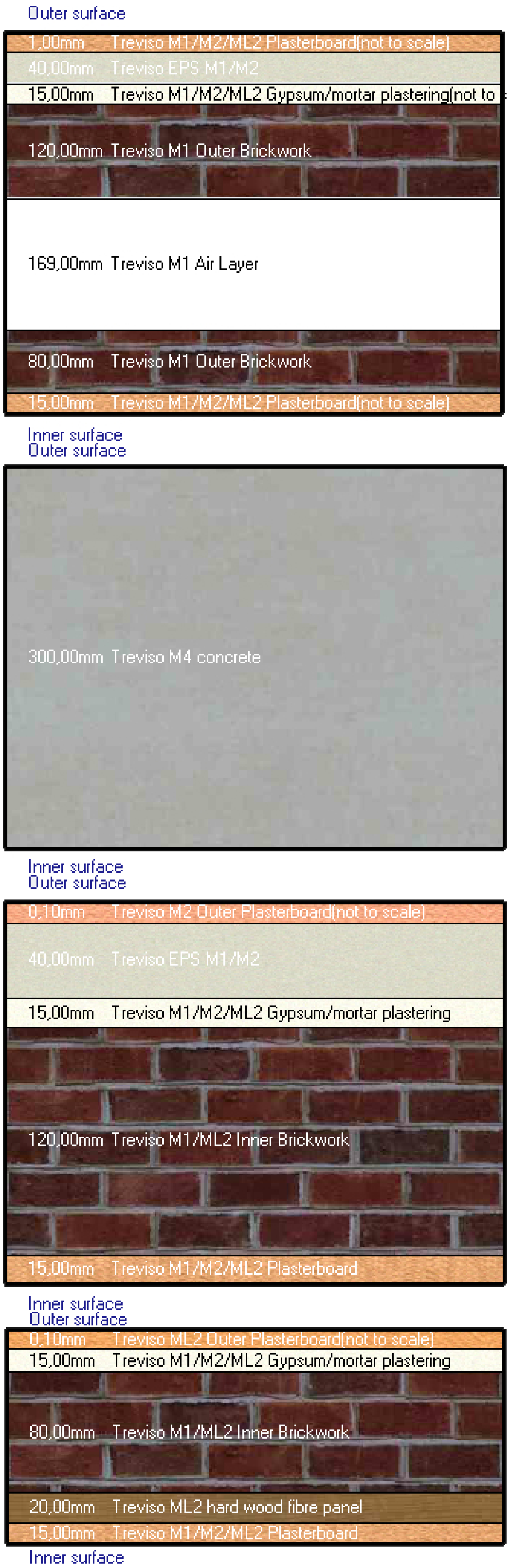


Figure 2.8: Blueprint of a single floor in block T2. Source: ATER [43].

Using the blueprints, construction data and material composition provided by ATER (and show in Figure 2.7 and Figure 2.8), it was possible to completely model the apartment building in high detail. Due to the modular construction of the building, only several wall, roof and floor compositions had to be defined in order to start the modelling process.

Figure 2.9: Wall compositions.



Width [mm]	k $\frac{W}{m \cdot K}$	R $\frac{m^2 \cdot K}{W}$	U $\frac{m^2 \cdot K}{W}$
M1 outer wall			
40	0.041	0.98	1.02
15	0.17	0.086	11.60
120	-	0.31	3.23
169	0.33	0.51	1.96
80	-	0.20	5.00
15	0.70	0.021	46.67
M4 outer wall			
300	2.10	7.00	0.143
M2 outer wall			
40	0.041	0.983	1.018
15	0.174	0.086	11.60
120	-	0.310	3.23
15	0.70	0.021	46.67
ML2 outer balcony wall			
15	0.174	0.086	11.60
80	-	0.20	5.00
20	0.14	0.14	7.20
15	0.70	0.021	46.67

Table 2.2: Heat transfer properties obtained through DesignBuilder and ATER. [43]

	Width [mm]	Area -	R-value $\frac{m^2 \cdot K}{W}$ ATER	DB	U-value $\frac{W}{m^2 \cdot K}$ ATER	DB	Deviation -
M1 outer wall	440	50%	2.280	2.165	0.439	0.462	5.1%
M4 outer wall	300	16%	0.403	0.403	2.484	2.482	0.1%
M2 outer wall	190	22%	1.570	1.533	0.637	0.644	2.6%
ML2 outer balcony wall	130	11%	0.616	0.617	1.622	1.622	0%

Table 2.2 shows the DesignBuilder U-values for the different wall sections validate the ATER values, differing only 5% at most. Any difference can be attributed to a slightly different calculation of the internal and external convective heat transfer coefficients.

Multiplying the relative wall areas by their respective U-values gives us an indication of their contribution to the total heat loss. As can be seen from Figure 2.10, the pure concrete outer wall that surrounds the staircase (M4) is particularly inefficient, as it makes up only 16% of the total area while losing an estimated 41% of the heat. Keep in mind though, that the staircase is its own zone in the actual building model. The heat loss is therefore not entirely linearly proportional to area due to zone geometry.

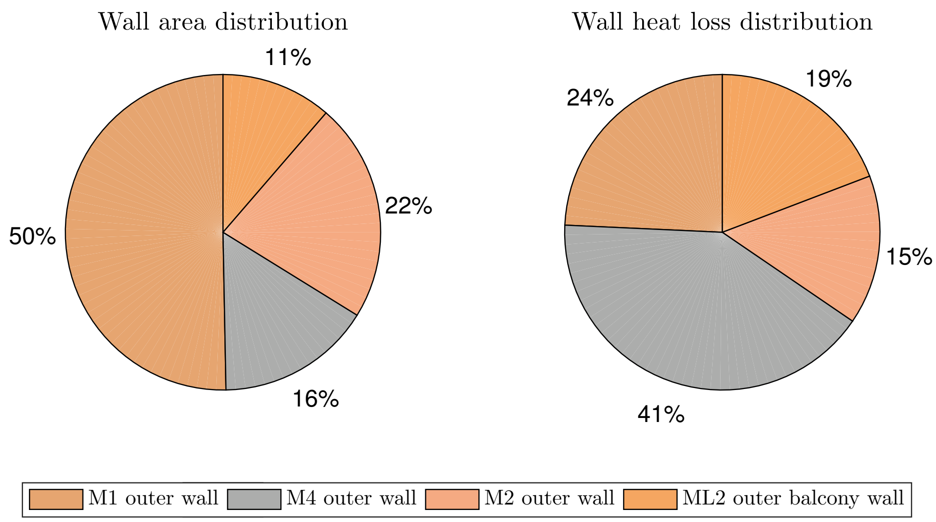


Figure 2.10: Estimated wall area and heat loss distribution.

Zone analysis of the actual simulation shows that the actual heat loss through the staircase wall is more on the order of 30% than 41%. Still, this wall would be the best place to start in order to improve the thermal efficiency of this building. An overall heat loss reduction of 20% is realistically possible by adding insulation on the outside of the concrete (e.g. 10cm of polystyrene).

Another good candidate for extra insulation is the ML2 outer balcony wall. It loses roughly four times more heat per area than the main outer wall that makes up half of the envelope. Insulating this wall up to similar standards as the M4 outer wall will therefore reduce overall heat loss by nearly 15%.

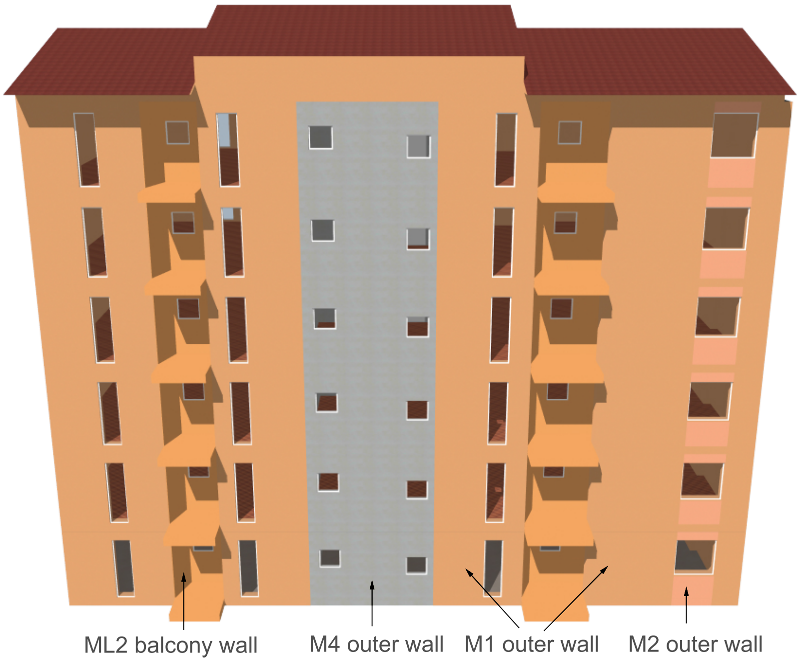


Figure 2.11: 3D model of block T2. Source [43]

The building model was created separately for the four blocks T1, T2, T3 and T4. It was found that modelling the internal wall partitions had little to no effect on the overall simulation. It was therefore decided to lump all the internal zones together to reduce simulation time significantly. An exception was made for the concrete wall surrounding the staircase (M4), due to the high U-value of this particular wall section (see Table 2.2).

The actual 3D model disregards the deviating geometry of the ground floor, which is dedicated to retail shops and has an overhanging ceiling over the pavement. It was assumed to be a similar floor to the apartment floors above (see the ground floor being equal to the apartment floors in Figure 2.11). Since this ground floor only makes up 1/7th of the total number of floors and has similar wall structures, the overall effect of this decision is negligible, especially when normalising the results to floor area.

Balconies can be seen protruding from the building in Figure 2.11. These balconies do not take part in any energy calculations; they are modelled as inert component blocks that only affect shadow simulation. The reason is, that it was impossible to model the thermal bridging aspect properly in DesignBuilder. In reality, these balconies act as a thermal bridge since they are concrete slabs directly connected to the floor foundation. The thermal bridging effect is equal to $0.16W/m/K$ according to ATER. Multiplying this value by the sum of the length of the balconies and dividing it by the floor area gives us an average heat loss of $7.4 \cdot 10^{-3}W/m^2_{floor}/K$. With an average temperature difference between indoor and outdoor of 7.8 degrees, this results in an average heat loss of $0.06W/m^2_{floor}$. In Section 2.2.3 we will come to see that this heat loss is insignificant.

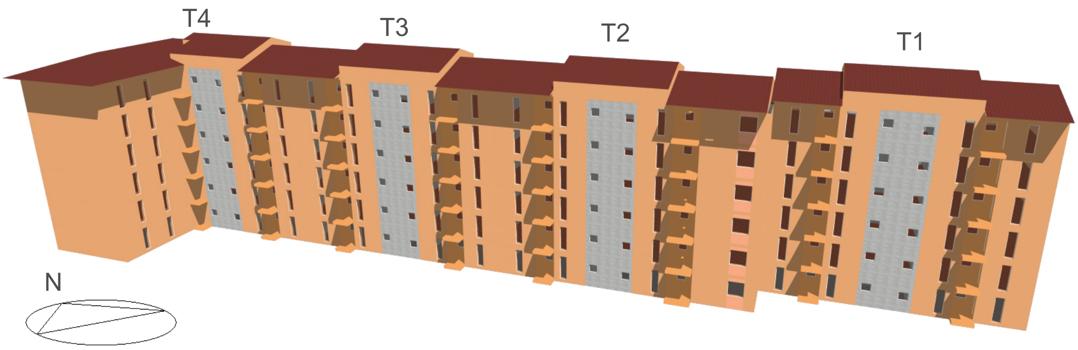


Figure 2.12: 3D models of the individual building blocks attached.

The four different building blocks that constitute the whole apartment block were all modelled and simulated independently. It was not possible to simulate the whole building because the model was too big to handle for the software. Therefore a boundary condition of zero heat transfer was set on those sides of the building blocks that are connected to another block. The overall building performance was then aggregated from the individual blocks.

In Appendix A extensive simulation data can be found, such as the heat gains and losses over time for individual segments of the building, as well as detailed blueprints and cross-sections of the building.

2.2 Load profiles

In the following section the procedure for obtaining hourly data for electricity demand, electricity production and heating demand will be explained. These hourly load profiles are a key input component of the Energy System Model. Great care has been taken in processing the data to ensure realistic values. The energy consumption and production values are all normalised to the building floor area so that it is easier to compare them to buildings of different sizes. In addition, the energy is expressed in average power (W_{avg}/m^2_{floor}) instead of energy per annum ($kWh/m^2_{floor}/a$), the reason being that it makes it easier to compare monthly versus daily and hourly values. The load profiles are thus all expressed in average power per floor area (W/m^2_{floor}). The conversion factor from $kWh/m^2_{floor}/a$ to (W_{avg}/m^2_{floor}) is 8.76.

2.2.1 Electricity demand

There is no hourly measured data available from ATER for the power consumption of the apartment building. The only available data is the yearly cooling electricity demand and total electricity demand for the whole building. Therefore, a residential load profile from the American OpenEI database was used in order to obtain a realistic hourly power consumption. This load profile was carefully selected to match the climate for Treviso. It was selected from a region that has the same Köppen climate classification as Treviso (Cfb), namely Pulaski, Virginia, US.

The data provided was separated per energy use, such as appliance electricity, heater electricity, lighting electricity and heating gas. The relevant categories for Treviso (appliances, lighting and miscellaneous) were imported to the model and normalised to match the average electricity demand minus the average cooling electricity demand ($3.91 W/m^2_{floor}$). This normalisation makes the absolute values from the source data irrelevant, only the relative fluctuations will influence the building model. The electricity demand was assumed to be distributed equally over the total floor area of the building.

Measured data obtained from ATER from the Treviso building site showed that cooling accounts for $0.5 W_{avg}/m^2_{floor}$. The cooling demand hourly load profile data was simulated using the Treviso building model created in DesignBuilder and normalised to the measured data $0.5 W_{avg}/m^2_{floor}$. Using the same weather data for the simulation of the electricity production, cooling demand and heating demand, made sure that the individual profiles were realistically related. So during a summer day, when the sun shines and the outside temperature is high, the increased electricity production due to high insolation partially matches the increased cooling demand due to high temperatures.

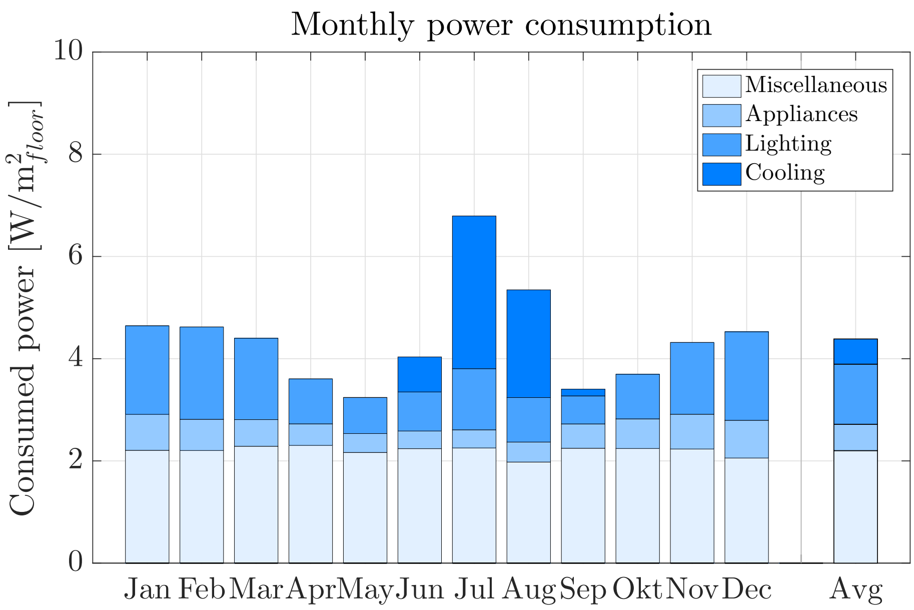


Figure 2.13: Average monthly power consumption normalised to floor area.

As can be seen from Figure 2.13, cooling is only required during the hottest two to three summer months, when the electricity production can also be expected to be the highest. This is beneficial for self-consumption when having a PV installation, because it means that less electricity will have to be sold back to the grid. However, the electricity demand also goes up slightly during winter, when PV electricity production is at its lowest.

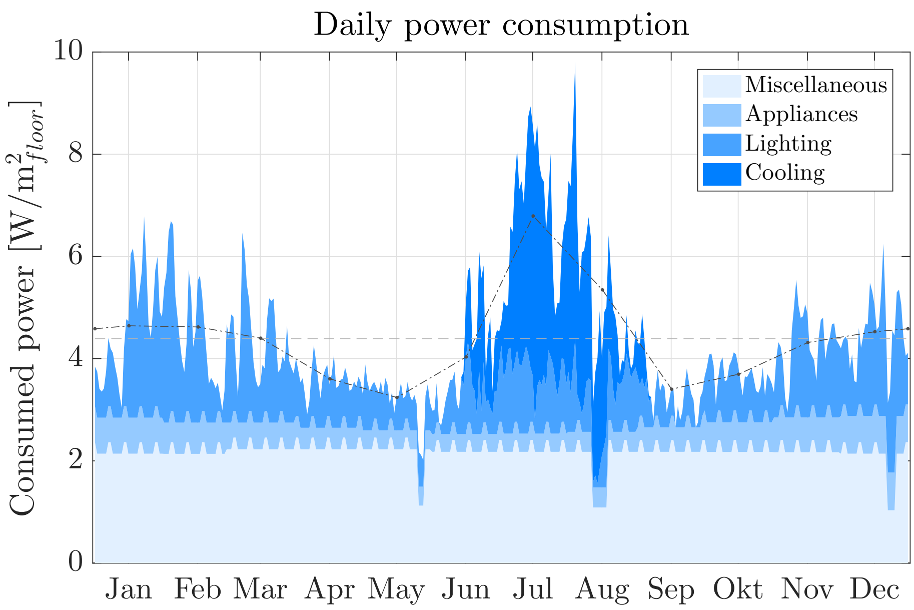


Figure 2.14: Average daily power consumption normalised to floor area. The dotted lines represent the monthly and yearly consumption.

The daily variations in electricity demand are highest during the winter and summer. Figure 2.14 shows several periods with decreased electricity demand. These periods correspond to vacation time incorporated in the OpenEI data. It was decided not to remove these anomalies as it is not unlikely that similar behaviour might occur for the Treviso site. If anything, the anomalies will have a conservative effect on the performance of the model (i.e. less self-consumption increase).

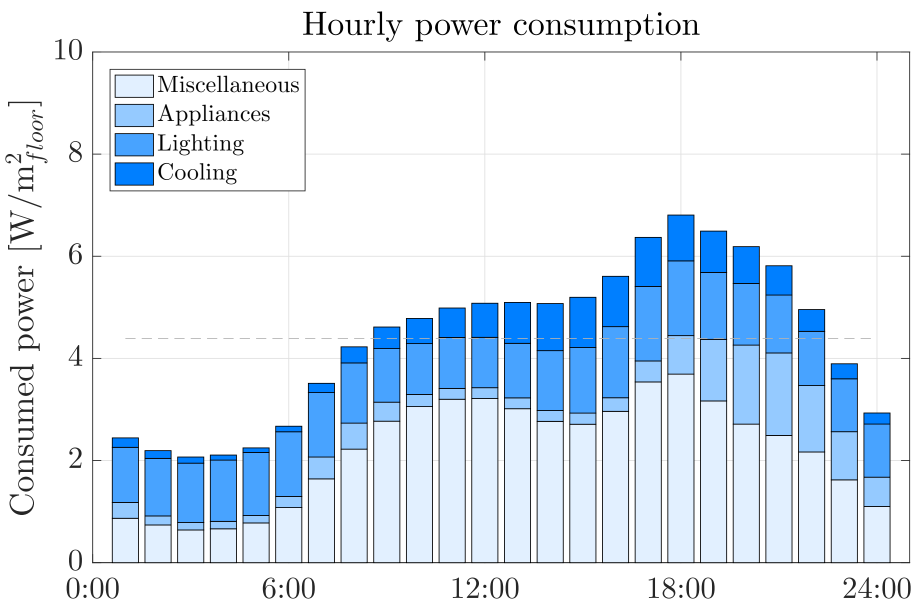


Figure 2.15: Average yearly power consumption per hour normalised to floor area. The dotted line represents the yearly average.

When looking at the average hourly power consumption profile one can see how the bulk of the electricity demand occurs between 07:00 in the morning to 22:00 in the evening, as is to be expected from a residential building. There is a clear peak around 18:00 in the evening, which is later than the expected peak of solar power production around noon. This means that there is a clear potential for battery storage to store excess production at noon for use in the evening.

The power consumption during the evening is only slightly higher than during the day. Depending on the amount of people that are working during the day, the power consumption during working hours (09:00 to 17:00) could in reality be lower than is depicted in Figure 2.15. This is important to note, because most of the electricity production will happen during working hours. If therefore there are more people away at work, it will lead to more of a mismatch between production and consumption, thereby increasing the advantage of having a storage option in the form of a heat pump or battery.

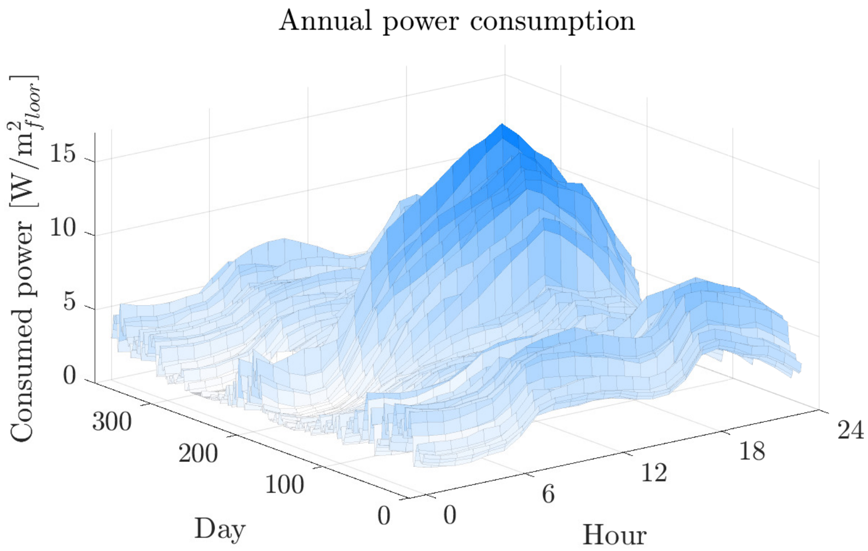


Figure 2.16: Power consumption normalised to floor area.

The yearly power demand is stored in the form of a 365x24 matrix corresponding to the hourly electricity demand profile shown in Figure 2.16. There is a clear peak visible in the midst of summer, corresponding to $17W/m^2$.

2.2.2 Electricity production

Solar PV panels will be mounted on the roof and southern-facing facades (southwest and southeast), to maximise the amount of energy produced by the building in order to assess its full potential. As mentioned in section 2.1.2, all building surfaces neither have the optimum slope nor azimuth for PV panels to produce their maximum power. The southwestern facade, by far the largest south-facing surface, deviates 53 degrees from the optimum slope of 37 degrees [40], and 50 degrees from true south. The V-shaped roof has a gentle slope of 18 degrees. However, as we will come to see, the benefit of having a positively sloped roof on the southwestern side is roughly cancelled by the negative slope on the northeastern side.

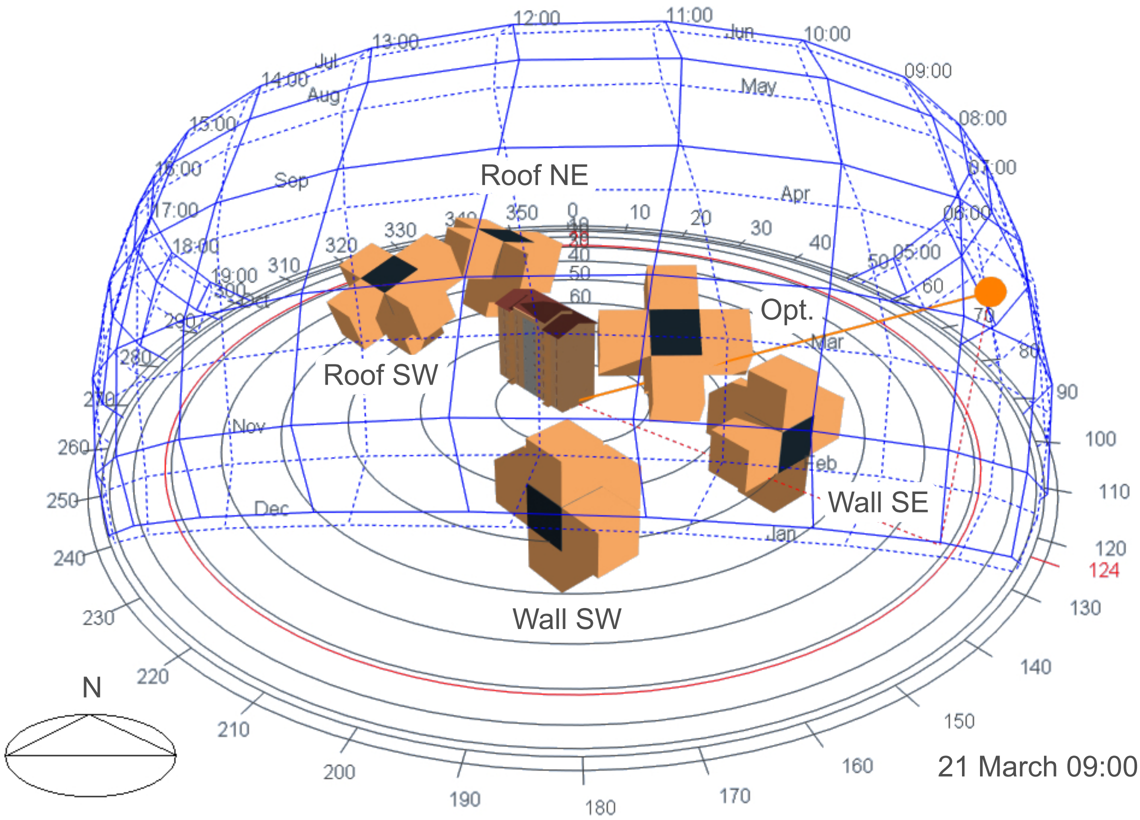


Figure 2.17: Sunpath diagram for the four different building surfaces plus the optimum slope angle surface. The dark blue surfaces are the simulated solar PV surfaces.

The solar PV production was simulated using DesignBuilder for the various building surfaces show in Figure 2.17. There were two main reasons for using DesignBuilder to simulate the annual solar PV output, instead of doing calculations using complex weather models or simply making assumptions. Firstly, just as with the cooling demand, it is important that there is a correlation between the individual load profiles for heat demand, electricity demand, and electricity production. Secondly, models for simulating solar power that account for cloud cover, diffuse irradiance and other atmospheric effects tend to be rather complex. It would either be unnecessarily tedious or overly simplified to achieve this using for instance MATLAB.

MATLAB was used, however, to process the data. First, the DesignBuilder output was normalised to solar panel area W/m^2_{PV} for each surface (Wall SW, Wall SE, Roof NE, Roof SW, optimum). The output per solar panel surface area was then aggregated over the whole building (by multiplying it with the corresponding surface area size) in order to arrive at the total PV output. A coverage factor of 70% was used for the solar PV wall and roof. Remember that apartment block T1 makes a small 90 degree turn, and thus also features a SE and NW roof. It was decided to lump these parts with the SW and NE roof. The difference in output is negligible since the roof's orientation for both cases is nearly 45 degrees from true south (40 vs. 50 degrees), and T1 makes up only one out of eight building blocks.

The model assumes all the PV panels to lie flat on the surface they are attached to. In reality, a PV panel installer may choose to adjust the slope and azimuth of the panels using stands. While this may lead to more efficient usage of the PV panel area, the projected surface area normal to the sun (and thus the power output) will remain unaffected. It is thus only an economical factor, not a physical one. Using stands will only decrease costs slightly by reducing the required PV area slightly, although the stands are an extra investment in itself. A detailed economical discussion of the PV installation will be handled in Section 3.5.2.1.

Table 2.3: Wall, roof and floor areas.

Surface	Area
Wall SW	3492 m^2
Wall SE	420 m^2
Roof NE	970 m^2
Roof SW	970 m^2
$A_{surface}$	5852 m^2

Block	Floor area
T1	2100 m^2
T2	6000 m^2
T3	2760 m^2
T4	1380 m^2
A_{floor}	12240 m^2

$$\sum A_{PV} = coverage \cdot \sum A_{surface} = 70\% \cdot 5852 = 4096m^2 \tag{2.1}$$

$$\sum A_{PV} / \sum A_{floor} = 4096/12240 = 0.33 \tag{2.2}$$

Table 2.3 lists all the area values used in the model. Note the ratio between PV area and floor area. This ratio is important because it is used to normalise the produced power to floor area, similar to the electricity demand. Moreover, the ratio will vary from building to building. A PV panel area to surface area of 0.33 seems reasonable for most 6-story apartment buildings due to the typical shape of the investigated building. The higher the ratio, the higher the potential for self-production. The upcoming electricity production diagrams include the ratio and thus show the electricity produced per floor area instead of PV area.

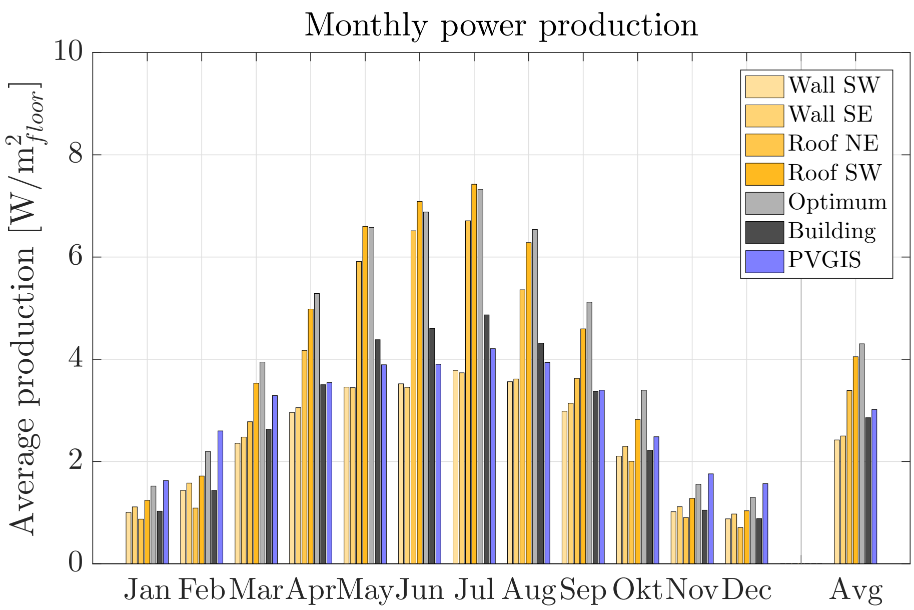


Figure 2.18: Relative average monthly power consumption normalised to floor area for different building surfaces.

Although the electricity produced by the wall-mounted panels is lower, its electricity production is more stable throughout the year. This is likely to increase the self-consumption, as less electricity is fed into the grid during spring and autumn months when cooling is not yet required. In addition, a benefit of having roof-mounted solar panels in the mix, is that their electricity production peaks significantly during summer summer when cooling demand increases electricity demand.

The average solar electricity production is $3.84 W/m^2$, which closely matches the average electricity demand of $4.39 W/m^2$. The average electricity production calculated using the PVGIS tool amounts to $4.04 W/m^2$. This is a deviation of only 5% of the DesignBuilder value, thereby confirming the validity of the achieved results. Interestingly, the calculated PV output using the PVGIS tool shows a more even distribution of electricity production throughout the year. Such a distribution will influence the outcome of the simulation, as it leads to higher self-consumption and self-production. Unfortunately there is no hourly data available from PVGIS to properly assess the extent of this effect. It should thus be noted that the ESM output using DesignBuilder data will be skewed negatively towards self-consumption and self-production compared to the PVGIS data. It is not in the author's abilities to assess which of the two data sets closer represents reality. This model sensitivity should therefore be taken into account when assessing the ESM results.

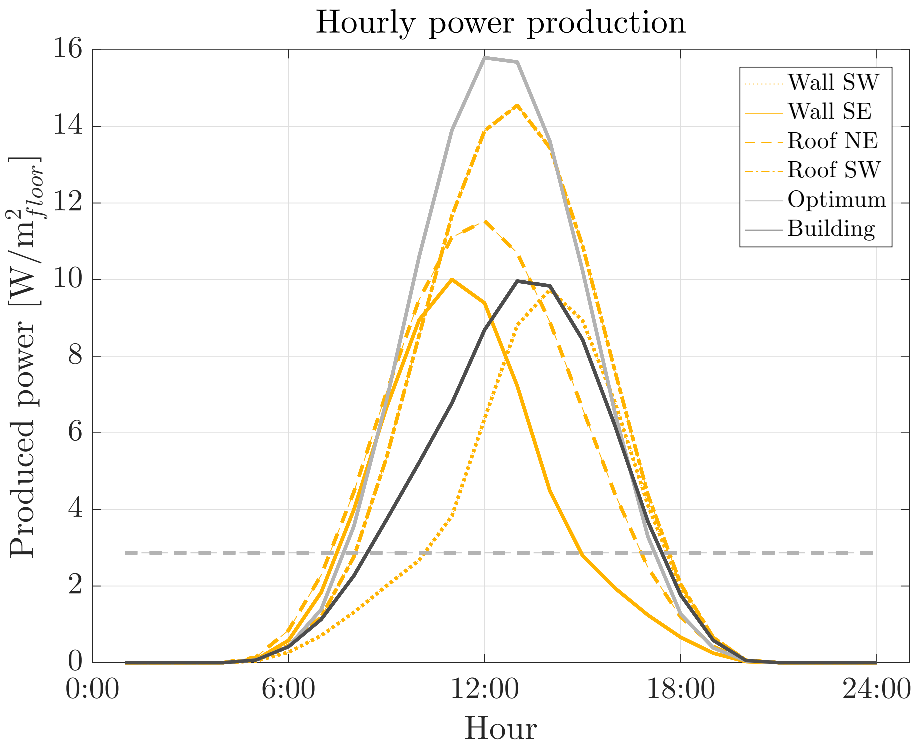


Figure 2.19: Average yearly power consumption per hour normalised to floor area. The dotted line represents the yearly average.

From a daily perspective, there is a clear difference between east and west facing surfaces in terms of temporal distribution. The eastern surfaces produce more power in the morning, with a peak around 11:00, while the western surfaces peak roughly three hours later, around 14:00 as can be seen from Figure 2.19. As we saw in the daily electricity demand profile curve (Figure 2.15), the average electricity demand hardly changes between 10:00 and 16:00, so the benefits of having more western facing PV area are small on average. Nonetheless, western-facing PV panels are preferred over eastern-facing PV panels due to slightly higher electricity production in the evening when demand is highest.

Table 2.4: Production of different building surfaces compared to optimum orientation.

	Opt.	Wall SW	Wall SE	Roof NE	Roof SW	Building
Relative production	100%	56%	58%	78%	94%	66%

The difference between roof and wall solar PV production is clearly visible in Figure 2.18 and Figure 2.19. The actual percentages are represented in Table 2.4. As expected, the electricity produced by roof-mounted panels increases relative to the wall-mounted panels as the sun rises higher in the sky during summer. The wall surfaces are clearly quite inefficient, with over 40% reduced efficiency compared to optimum orientation due to their vertical orientation. Since the SW wall makes up the biggest part of solar PV area, the building average production is heavily skewed towards the SW wall production. The overall efficiency reduction due to orientation amount to 34%, which is significant, yet hard to improve.

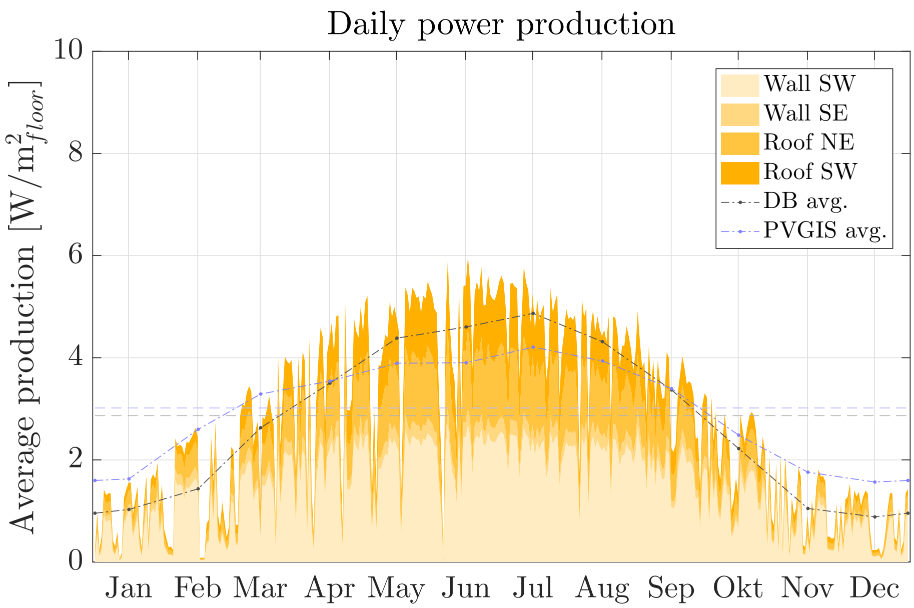


Figure 2.20: Average daily power consumption normalised to floor area.

The individual surface contributions to the average daily electricity production are shown in Figure 2.20. The large influence of the southwestern wall is clearly visible, while the contribution of the southeastern wall is almost negligible. During winter, the southwestern wall is responsible for nearly all the production. There are a few periods where there is hardly any production for several days. These periods are the most difficult to bridge using a battery system, and therefore impose a limit on self-production.

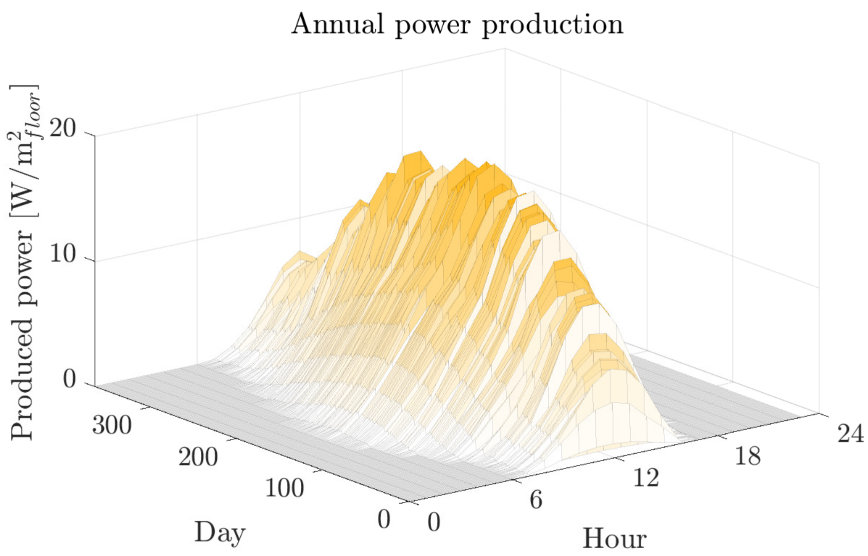


Figure 2.21: Power production normalised to floor area.

The end result of the simulated PV production is shown in figure 2.21. There is a clear peak visible during summer, with the highest value reaching $25W/m^2_{floor}$. This is significantly higher than the maximum electricity demand of $17W/m^2_{floor}$, meaning that overproduction will definitely occur at various times.

2.2.3 Heating demand

A heat demand profile had to be established in order to assess the potential for utilising excess electricity production with a heat pump. Simulated monthly heat demand data has been provided by ATER for the individual building blocks and the building as a whole. This data, however, can only be used as a guide since it lacks hourly resolution and is based on different climate data.

The heat demand was therefore simulated in DesignBuilder using the building model. Although it was possible to simulate the hourly heating demand using DesignBuilder, the hourly DHW usage was assumed to be constant since no hourly DHW usage profiles could be found for Italy. As can be seen from Figure 2.22, any hypothetical variations in DHW usage will be dwarfed by the variations in heating demand, especially during peak load in winter time. Moreover, it is unlikely that DHW usage will vary significantly from winter to summer. The constant DHW usage assumption is therefore unlikely to have a significant impact on the results.

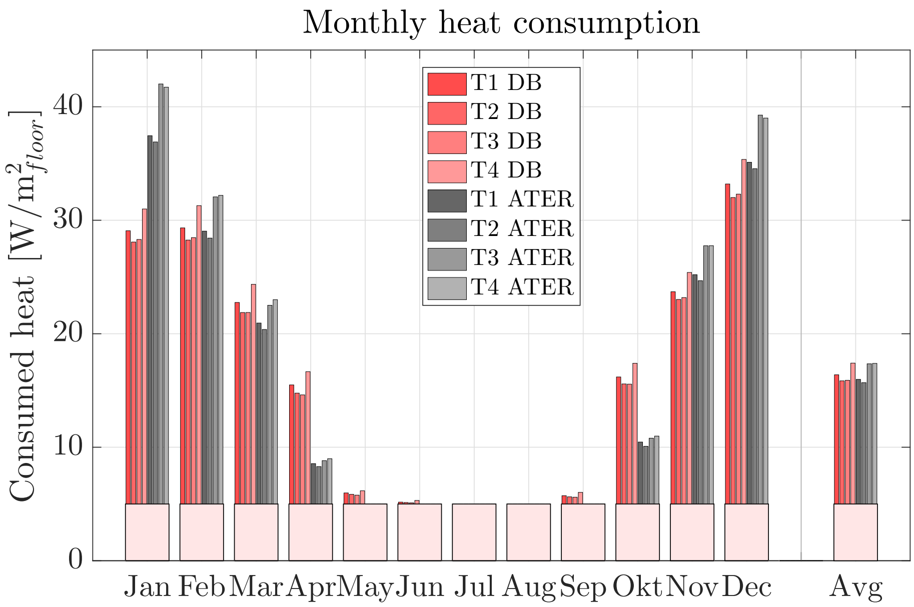


Figure 2.22: Annual heat consumption normalised to floor area.

The average difference between the simulated heat demand provided by ATER and the simulated heat demand obtained through DesignBuilder is very small. The results for the individual building blocks seem to correspond with the results from ATER, with T4 having the highest heat load, and T2 the lowest. There is a slight discrepancy for the results of T1 and T3, although this is hardly significant as it is on the order of around 5%.

Looking at the relative heights of the bar graphs in Figure 2.22, the DesignBuilder values look more realistic than the ATER values, due to the individual block characteristics: T1 and T4 perform worse than T2 and T3, which is to be expected since they're only connected to the whole building on one side, while the other side is exposed to the outdoors.

It is interesting to see that the DesignBuilder simulation results are distributed differently from the ATER simulation results, even though the yearly average is the same - similar to the PVGIS simulation. The difference is most likely caused by having different climate data, which is more temperate for the case of the DesignBuilder simulation (milder winters and summers).

The DesignBuilder simulation yields more desirable results since the heat demand is lower in winter and higher in summer, thereby more closely matching the PV electricity production. Moreover, peak heat demand in winter is lower. Peak demand is the main metric used for sizing the heat pump, and it is roughly 30% higher for the ATER simulation. In this case - contrary to the electricity production model - the DesignBuilder results will tend to favour self-consumption, self-production and heat pump size. Again, this model sensitivity should be taken into account when assessing the results.

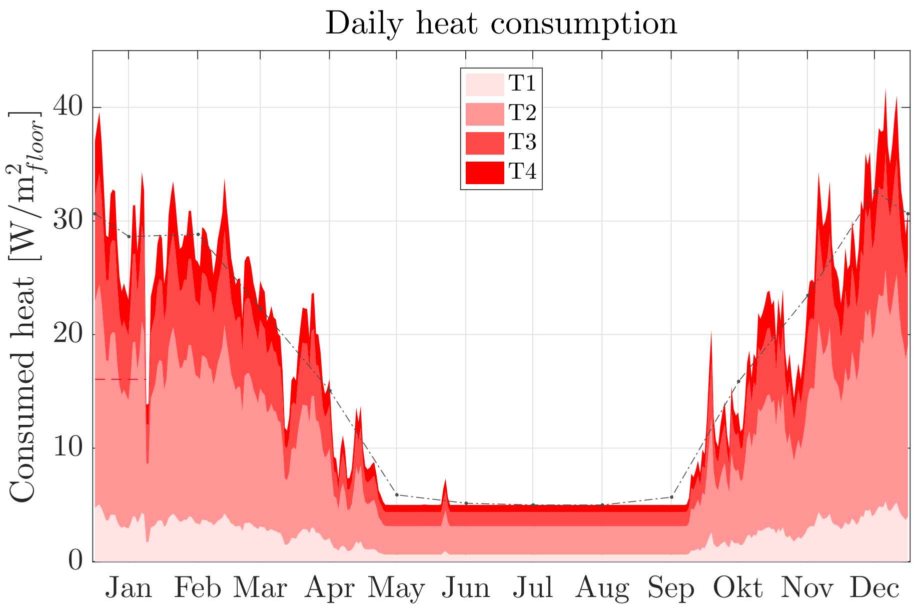


Figure 2.23: Average daily heat consumption.

The data from the individual building blocks was aggregated to arrive at the average building heat load. Since T2 makes up four out of eight building blocks, it dominates the average building heat load as can be seen in Figure 2.23. The heat load for T2 was the similar for both the DesignBuilder and ATER simulation, resulting in an almost identical average building heat load ($16.06 W/m^2_{floor}$ and $16.35 W/m^2_{floor}$ respectively, a difference of less than 2%).

As is to be expected, daily variations are most extreme during winter. By adding a hot water tank, these variations can be buffered resulting in a lower peak demand and thus smaller design requirements for the heat pump. The amount of reduction in peak demand is dependent on the hot water storage tank size. The maximum average daily heat demand is approximately $40 W/m^2_{floor}$. So, suppose the HW tank can buffer a full day's worth of heat, then the heat pump should have a peak capacity of $40W/m^2_{floor}$. In Section 2.3.3.2 the exact size will be discussed in more detail.

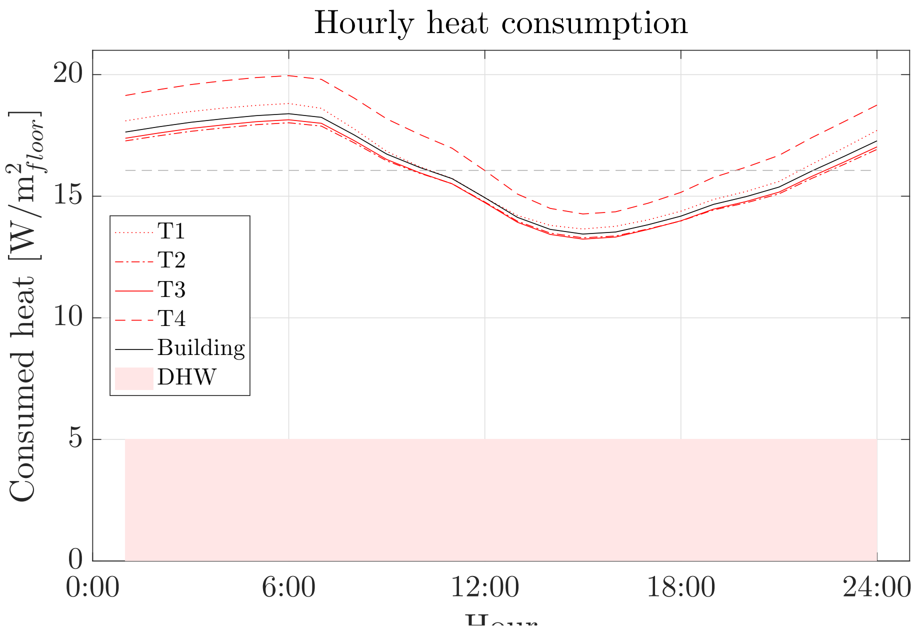


Figure 2.24: Yearly average hourly heat consumption per hour.

The average daily heat demand profile is fairly constant, fluctuating slightly between 13 and 18 W/m^2_{floor}. Heat demand is highest during the night, precisely when excess electricity is not available. Note that a constant setpoint temperature of 20 degrees C was used for the simulation. In reality, a comfortable indoor temperature may be slightly lower while people are sleeping, e.g. 18 degrees. This will decrease the fluctuation in the daily heat demand profile, making it nearly constant. As a result, peak load is smaller in reality (thus increasing the capacity factor), which in turn allows for a smaller heat pump size.

The outcome of the simulation was the 365x24 matrix depicted in Figure 2.25. The shape of the surface plot confirms the conclusions drawn earlier; seasonal variations are significant, while daily variations in heat demand are small. Since daily variations during winter are insignificant, a peak heat demand of $40W/m^2$ is a justifiable value for the dimensioning of the heat pump.

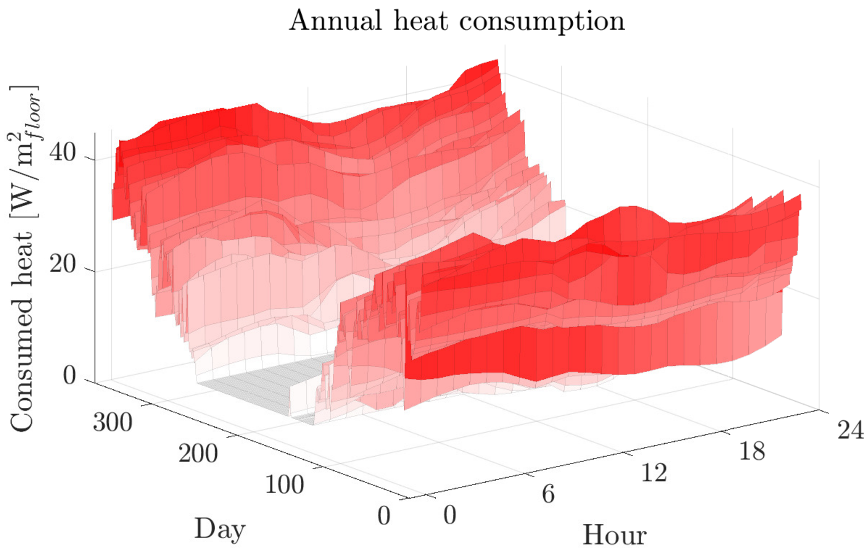


Figure 2.25: Heat consumption.

2.3 Energy System Model

The Energy System Model (ESM) uses three types of input data:

1. **Load profiles:** have been discussed in Section 2.2. They are dependent on the building and weather models used by DesignBuilder. Although differing up to 30% locally, the yearly averages were similar (<5%) for the DesignBuilder model and the PVGIS and ATER models. The load profiles can therefore be assumed to be fairly accurate.
2. **Component data:** includes the properties of the various components used in the ESM, such as the heat pump, battery and solar panels. This data consists of parameters like efficiency or operational range. They will be discussed in Section 2.3.1.
3. **Economic data:** includes the prices for various components, as well as interest rates and expected lifetimes. They will be discussed in Section 2.3.2.

Using these three sources of input data, the model could be created in MATLAB. The ESM simulates the usage of the energy system over the course of a hypothetical year (dependent on the climate data), and outputs the relevant technical and economical parameters such as self-sufficiency and energy costs. It will be discussed in detail in Section 2.3.3.

2.3.1 Component data

The most important component input parameters are efficiencies for the various components, and the minimum and maximum storage capacity of the battery and heat pump. The chosen efficiencies and operational ranges for the solar panels, heat pump and battery are justified Section 2.3.1.1, 2.3.1.2 and 2.3.1.3 respectively. The storage capacities of both the battery and the hot water tank will be discussed in the results later on in Section 3.3.3.

The choices for the component input parameters are shown in Table 2.5.

Table 2.5: Technical input parameters

Parameter	Value	Unit	Source
Heating			
Distribution losses	10	%	[43]
Boiler efficiency	81.8	%	[43]
Heat pump efficiency	90	%	assumption
Heat pump COP	400	%	[9]
Max. tank temperature	60	$^{\circ}C$	[4]
Min. tank temperature	40	$^{\circ}C$	[4]
Solar PV			
PV panel efficiency	15	%	
Inverter losses	15	%	[40] [25]
Angular reflectance losses	2.8	%	[40]
Temp. and low irradiance losses	9.8	%	[40]
Battery			
Efficiency	90	%	[35],[27]
Self-discharge	6	%/month	[35]
Max. SOC	80	%	[24]
Min. SOC	20	%	[24]

2.3.1.1 Solar panels

According to a calculation tool provided by the PhotoVoltaic Geographical Information System (PVGIS) [40], the PV panels were assumed to have an efficiency of 15%. Losses due to angular reflectance, cables and inverters, and temperature and low irradiance were also taken into account. These losses amount to 25.4% (2.8%, 15.0% and 9.8% respectively) for polycrystalline silicon cells. For the optimum orientation, this results in a peak power output of $130W/m^2$. Polycrystalline cells tend to be cheap, but unfortunately they do not perform efficiently in high temperatures [1]. If power output is valued more than cost per Watt, it could be decided to opt for more expensive and efficient solar panels. This will be discussed more in-depth in Section 3.5.2.1.

2.3.1.2 Heat pump

The current heating system consists of a gas boiler with an 81.8% efficiency [43]. ATER has decided that this system will be completely replaced by four heat pumps. According to ATER, there are 10% distribution losses in the distribution system, which will be used to distribute the heat in the new setup as well. Furthermore, a pumping efficiency of 90% was assumed, as well as a COP value of 4.0 [9]. So the overall efficiency, defined as

$$overall\ efficiency = COP \cdot transmission\ losses \cdot pumping\ efficiency \tag{2.3}$$

becomes: $4.0 \cdot 90\% \cdot 90\% = 324\%$.

The operational temperature range for the heat pump will be between $40°C$ and $60°C$, for reasons that will be explained in Section 2.3.3.2.

2.3.1.3 Battery

The two relevant technical parameters for battery packs are their lifetime and round-trip efficiency.

The round-trip efficiency of Li-ion batteries is generally considered to be between 90-95%. [35]. [26] uses a round-trip efficiency of 90% for Li-ion battery technology.

It was therefore decided to opt for the more conservative round-trip efficiency of 90%.

The lifetime of Li-ion batteries is dependent on two types of ageing: calendric ageing and cyclic ageing. Calendric aging is responsible for the gradual degradation of the battery over time. This degradation leads to both efficiency and capacity decrease. The capacity decrease is non-linear in nature, and accelerates over time. Cyclic ageing corresponds to the degradation of the battery with each cycle. It is dependent on the depth of a cycle, and is expressed in Equivalent Full-load Cycles (EFC). A tyical Li-ion battery has a cycle lifetime between 3000-6000 EFC [35]. As we will come to see in section 3.3.3, the amount of EFC in a year does not exceed 150, or 3000 EFC in a 20-year timespan. Since a Li-ion battery has a calendric lifetime of 15 years, the calendric lifetime trumps the cycle lifetime of 20 years. The battery is thus assumed to have a lifetime of 15 years.

An important factor affecting the lifetime is the depth of discharge (DOD). It is considered good practice to reduce the depth of discharge (DOD), since Li-ion batteries degrade faster when the depth of the charge and discharge is deeper. [33] propose a minimum and maximum SOC between 15% and 85%, while [24] propose a more conservative SOC between 20% and 80%. It was decided to go with the more conservative SOC values, thereby effectively reducing the battery capacity by 40%.

2.3.2 Economical data

The economical input data consists of the investment cost and operational cost of the various components of the energy system, as well as the utility price of gas and electricity. Inflation was used to compensate for future electricity prices. Lastly, the Feed-In-Tariff is of crucial importance to the economic viability of the battery.

The choice of parameters is shown in Table 2.6

Table 2.6: Economic input parameters

Parameter	Value	Unit	Source
General			
Gas price	0.08	€/kWh	[43]
Electricity price	0.15	€/kWh	[43]
FIT	0	% of el. price	Assumption
Inflation	2.5	%	[38]
Heating			
HP lifetime	20	years	[9]
HP investment costs	1.28	€/W_p	[9]
HP operational costs	0.02	€/W_p/a	[9]
HW tank investment costs	2200	€/m^3	[4]
Solar PV			
PV lifetime	20	years	
PV investment cost	0.60	€/W_p	[39]
PV installation cost	15	% of inv. cost	[41]
PV operational cost	10	% of inv. cost	[41]
Inverter cost	0.10	€/W_p	
Battery			
Battery lifetime	10	years	
Battery cost	300	€/kWh	262-734€/kWh [25] [18]

2.3.2.1 General

The electricity price is taken to be 0.15€/kWh based on data provided by ATER [43]. According to Eurostat, however, the electricity price in Italy averaged 0.23€/kWh in 2015 [46]. The difference may be due to region, or ATER may have made a deal with the utility companies that includes some discount. In any case, it was decided to go with the ATER value as it is a direct source. Of the two, it will lead to the most conservative economical result. The effect of electricity price variation is further discussed in Section 3.5.2.3.

Similarly for the gas price; ATER lists 0.08€$/kWh$ [43], while Eurostat notes 0.091€$/kWh$ for households in 2015. Again, for the same reasons, it was decided to opt for the ATER value.

The inflation rate results from the increase in price of services and goods over time. For the simulation, the inflation rate affects the future cost of replacing parts, such as the battery. The electricity price is assumed to increase proportionally to this inflation as well. In the past ten years, inflation in Italy has averaged around 2.5% [38]. The inflation rate used in the model is extrapolated from this data and is thus assumed to be 2.5% as well.

Feed-In Tariff A crucial parameter in the ESM is the Feed-In Tariff (FIT). If the Feed-In-Tariff is equal to the electricity price, all economic potential for storage is gone. A proper assessment of the FIT, now and in the future, is therefore critical to the economical validity of the results. Italy's FIT has been changed five times between 2005 and 2012 [6]. At one point, the FIT has even been changed retroactively, much to the frustration of solar PV installation owners [6]. The solar PV incentive climate is thus very turbulent, making the proper FIT very hard to determine. If anything, FITs are being significantly reduced throughout Europe due to increasing economic competitiveness of solar PV installations [22]. It is not unthinkable that, in the future, FITs will be completely removed. **Therefore, the FIT is assumed to be zero** in the basic model.

Assuming no FIT will result in a minimum economic viability of the system, revealing the most conservative payback period and cash flows. It is the 'worst-case' economic model for the system. On the other hand, it is the 'best-case' scenario for any storage systems, since any energy that is stored is not lost to the grid.

In addition, the no-FIT-assumption also makes the results more easily comparable to other cases. It provides a clear baseline - independent of region - for minimum economic viability for the system as a whole, and maximum economic viability for any storage systems. This baseline will be used as a starting point for an FIT price sensitivity analysis in Section 3.5.2.2.

2.3.2.2 Heating

The price of a heat pump varies depending on size. According to Boissavy et al. the unsubsidised price of an $8kW$ vertical loop ground-source heat pump is 14700€, whereas the price for a $1200kW$ unit is equal to $1.54M€$ [9], or $1837€/kW$ and $1283€/kW$ respectively. Since the required heat pumps will be in the hundreds of kW, the latter value of $1283€/kW$ was chosen.

The same paper suggested an operational cost for the heat pump of $0.02€/W/a$ and a lifetime of 20 years [9]. This means that roughly 1/3 of the lifetime cost will be spent on operation.

There are various types of hot water storage tanks on the market, at different price levels. The cost per volume is practically constant for various tank sizes, i.e. scaling up does not bring much economical benefit. An important factor influencing the cost of a storage tank is whether there is a heat exchanger required. A heat exchanger roughly doubles the cost per volume for a storage tank. The tank will be supplied by a heat pump that circulates its own working fluid, so a heat exchanger is required. Prices for storage tanks with a heat exchanger coil range from $2200€/m^3$ for epoxy and vitrified steel tanks to $5000€/m^3$ for stainless steel tanks [4].

Since there is no particularly need for a stainless steel tank, a price of $2200€/m^3$ was assumed for the storage tank.

2.3.2.3 Battery price

The Li-ion battery price is crucial for the business case of the battery. Fortunately, the Li-ion battery market has seen an incredible price drop in recent years, one that is likely to continue due to the electrification of the road transport sector.
A noteworthy paper by Nykvist et al. performed a literature review that analysed over 80 different reports of Li-ion battery packs for the automotive industry. Between 2007 and 2014, the cost of Li-ion battery packs has decreased by 14% annually, from over 1000$ in 2007 to 400$ in 2014. This is the average cost for the industry as a whole. For market leading electric vehicle manufacturers, the cost is estimated

to be even lower, by roughly 30%, although exact numbers are a closely guarded company secret. [18]

The learning rate (i.e. the cost reduction associated with a doubling in production) for battery packs is on the order of 6-9%. Li-ion battery technology is still in its infancy, so this learning rate is expected to be sustained. Moreover, economies of scale will further drive cost reductions. Since 2011, the production rate is growing by an incredible 100% every year. Hence a cost reduction of 8% per year is expected in the near future. By 2020, Li-ion battery production costs are estimated to be less than 250\$$/kWh$. [18]

Another study examined the cost of Li-ion batteries for residential applications came to the more conservative conclusion that the market price of Li-ion battery systems is expected to drop to $263 - 375/kWh$ in 2020 due to the fast-growing electric car industry . Since this study assessed the market price for household applications, instead of the production price for the automotive industry, it is a more realistic indicator for the battery price that a house owner has to pay. [25]

Therefore, in order to stay in line with the realistic, 'minimum economic feasibility' boundary condition of this thesis, a more conservative battery price of 300€$/kWh$ was selected. Due to the modular nature of a battery system, there is no significant financial benefit in scaling up the system.

2.3.3 MATLAB model

2.3.3.1 Power model

The core of the MATLAB model is a simple rule-based controller that determines the allocation of power flows. It uses the load profiles obtained in Section 2.2 to control its behaviour. For each timestep (one hour), the controller compares the electricity demand to the electricity production (ΔP). If the demand is higher than the production, electricity is drawn from the grid. Vice versa, if the production is higher than the demand, electricity is diverted to the heat pump, battery, or grid. The output data is then stored in a 365x24 matrix (for each power flow). A simplified version of the code is shown in Figure 2.26.

```
%% Controller

for d = 1:365       % Number of days in  a year.
    for h = 1:24    % Number of hours per day.

        % Under- or overproduction?
        dP = P_prod(d,h) - P_demand(d,h);

        % Underproduction:
        if dP < 0
            % Draw from grid.
            P_grid(d,h) = dP;

        % Overproduction:
        elseif dP > 0

            % Tank storage available?
            if T_tank < T_tank_max
                % Feed to heat pump.
                P_HP(d,h) = dP;

            % Battery storage available?
            elseif SOC < 80
                % Feed to battery
                P_bat(d,h) = dP;

            % No storage available.
            else
                % Feed to grid.
                P_grid = dP;
            end
        end
    end
end
```

Figure 2.26: Simplified MATLAB code for the controller.

The actual controller is more complicated as it also takes into account storage and its respective losses. It also divides ΔP into a hundred pieces in order to ensure the proper amount of energy is stored, since the energy stored is not allowed exceed the storage capacity of the hot water tank or battery.

2.3.3.2 Heating model

There are various tank configurations possible for heating with a heat pump. The simplest model is a lumped capacity model, which assumes a constant temperature distribution throughout a single tank. A more advanced tank model is one that takes into account stratification, that is, an uneven temperature distribution with the hot water floating on top of the cold water. The cold water is heated in the bottom and rises to the top, where it is tapped for DHW and heating purposes.

$$V_{tank,lumped} = \frac{Q_{tank,lumped}}{c_{p,water}\rho_{water}T_{tank}} \tag{2.4}$$

$$V_{tank,strat} = \frac{Q_{tank,strat}}{c_{p,water}\rho_{water}\int_0^h T_{tank}(h)} \tag{2.5}$$

Both tank models have to be able to deliver the same amount of heat, but a stratified tank can be dimensioned smaller due to it requiring a smaller heat exchanger area, as well as achieving maximum temperature for a lower bulk temperature. For the same reason, however, a stratified tank will have lower heat buffering capacity than an equal-sized lumped capacity tan In addition, a stratified tank is, more expensive than a normal tank [4].

An important design condition for a PV-attached heat pump system, is the fact that the tank has to be able to efficiently absorb the intermittent production of electricity by the solar panels. Suppose the tank operates in a closed loop heating system (i.e. exclude the DHW consumption for a moment). This means the tank will always be filled (since it's closed loop). Any loss of heat has to be continuously compensated for by the heat pump in order to satisfy the design temperature condition, thereby effectively rendering the storage ability of the tank obsolete. One can circumvent this effect somewhat by setting boundary conditions for the minimum and maximum tank temperature.

For instance, by allowing the tank bulk temperature (or top layer temperature in case of a stratified tank) to drop to $40°C$, so the bulk or top layer temperature can be increased up to $60°C$ once PV electricity is available during the day. The PV generation buffering capacity is then linearly proportional to the minimum and maximum temperature difference. A stratified tank may be able to increase its temperature gradient somewhat during overproduction of electricity, although its unfavourable buffering capabilities will leave it struggling with absorbing excess heat compared to a lumped tank of the same size. In both cases, allowing the maximum temperature to drop is a serious compromise, as it significantly decreases the heating capabilities and thus requires extra heating area (radiators). When considering DHW as well, this unfavourable buffering behaviour is unaffected. Moreover, law regulations do not allow DHW to go below 60 due to risk of legionella.

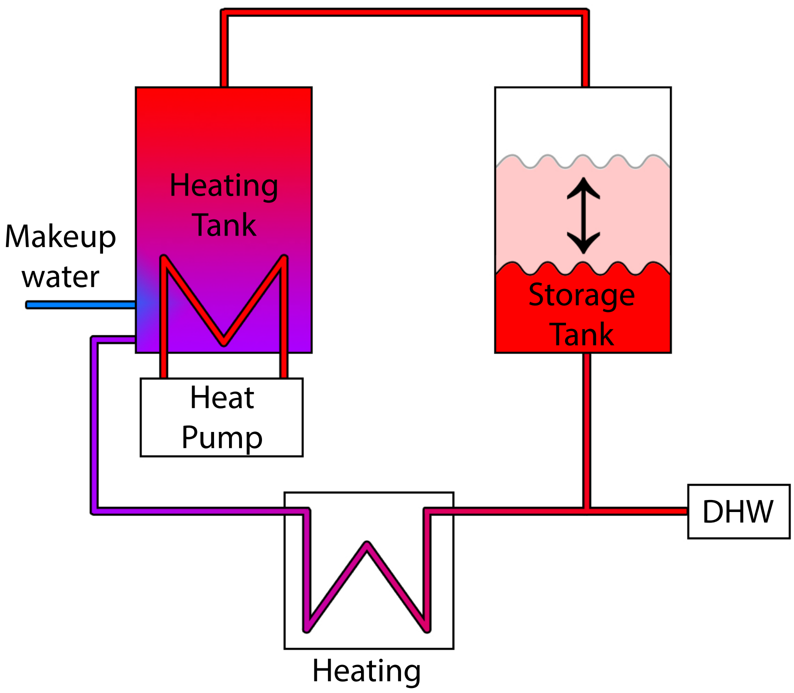


Figure 2.27: Tank model with two tanks.

The solution is to use two tanks (see Figure 2.27, where one tank has a variable water level. The first tank is the minimum tank installation required for any system configuration. It simply contains the heat pump heat exchanger and can be either lumped capacitance or stratified. It has to be no larger than the heat pump heat exchanger area required to meet the peak heat demand. That is, the first tank has to be able to supply the continuous heat demand at the design temperature condition of 60°C and does not act as storage.

The second tank is the storage tank, where excess electricity production is stored as heat. The temperature in this tank is constant at 60°C, while the water level will vary between 0-100%. As a bonus, this storage tank is much more efficient in storing heat than in the case of a single tank, since any water added to the tank comes from outside at a temperature of 10°C, instead of being the return water from the heating system at 40°C. Heat storage capacity is thus increased by a factor of 2.5.

2.3.3.3 Simulation examples

Now that the programming of the underlying power- and heating model has been explained, it is time to show the functioning of the model. By running the model for different system configurations, a better understanding of the influence of battery and tank storage on the self-consumption can be gained. Therefore, the following section will provide insight into the behaviour of the following four systems by providing several examples of their daily behaviour[2]:

1. PV only
2. PV + heat pump with tank
3. PV + battery
4. PV + battery + heat pump with tank

[2]The precise dimensioning of the battery and hot water storage tank is a key outcome of the research question and will not be explained for now. Justification for this selection of tank and battery size will be given in Section 3.3.3.

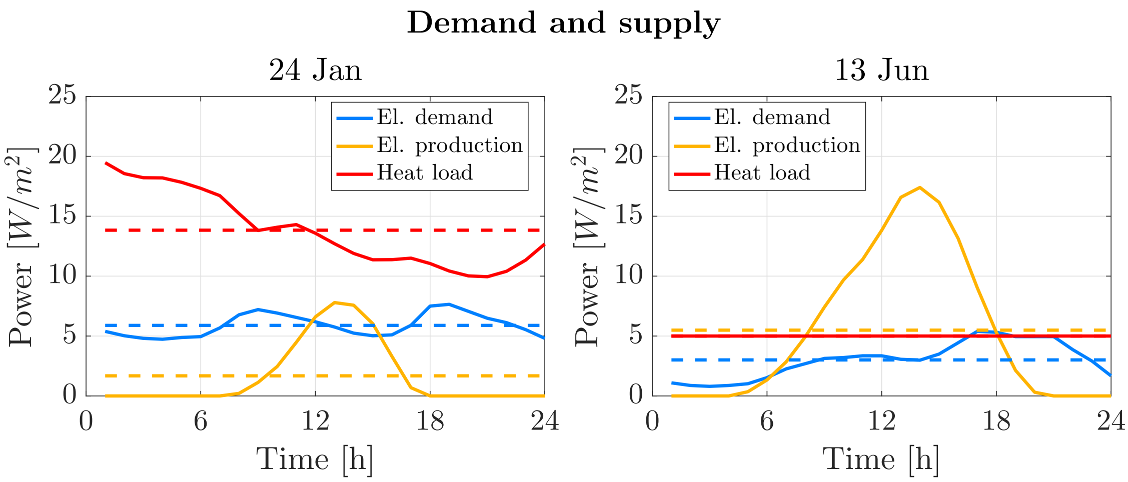


Figure 2.28: Daily demand and supply profiles for a winter and summer day.

In Figure 2.28 the difference between a winter and summer day for electricity production/demand and heating demand is clearly visible. The dotted lines represent the daily average. The heat load is the primary heating energy required, not the electricity to drive the heat pump. In addition, the electricity demand represents the household electricity demand, not the grid demand.

Electricity production is lowest outside of midday, while both electricity demand and heating demand are highest. This seasonal mismatch between production and demand poses serious limits on both self-consumption and self-production, as we will come to see in more detail in Section **??**.

The presence of significant overproduction during summer means that there is a potential for both a heat pump and a battery to absorb the excess electricity production. During winter, the electricity production hardly exceeds the demand, indicating a low storage potential. More on this in Figure 2.31 later.

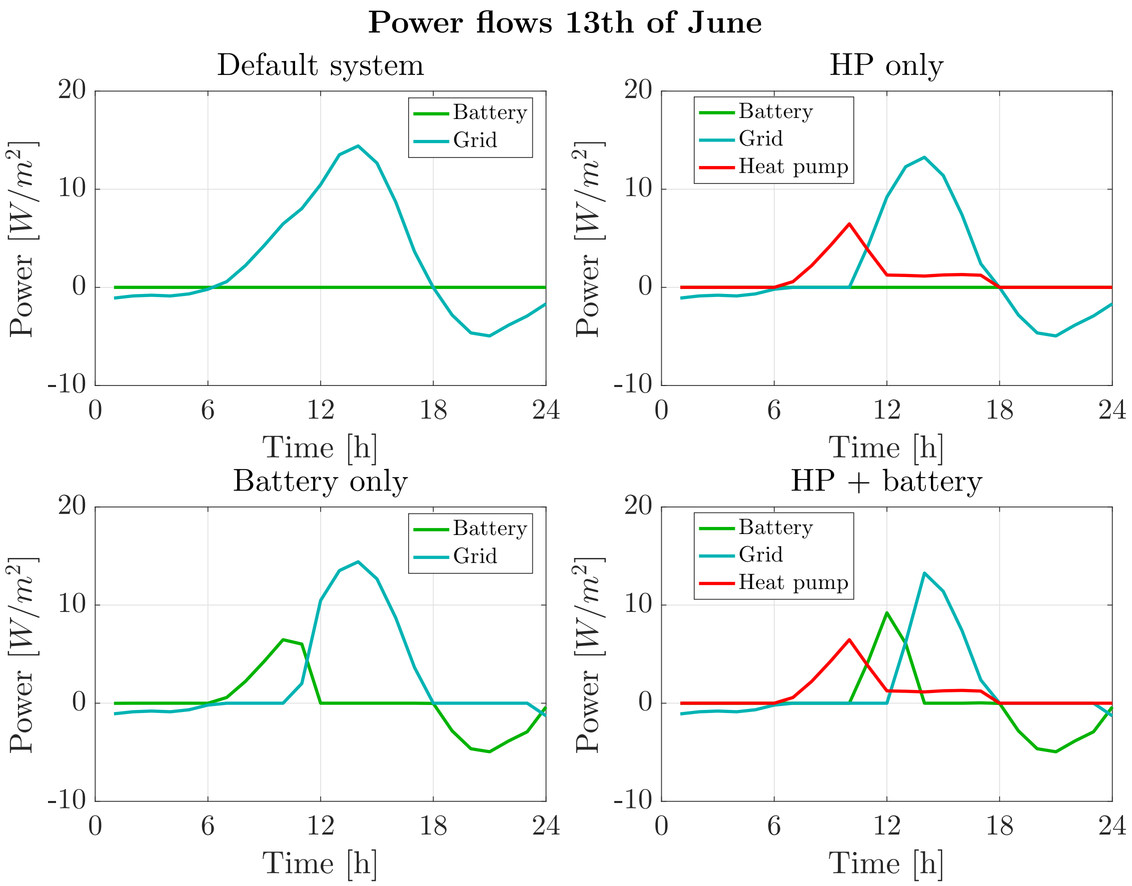


Figure 2.29: Power flow visualisation for various system configurations on a summer day.

Figure 2.29 shows the effectiveness of the four system configurations in dealing with the excess electricity production during a summer day. If no heat pump or battery is present, the majority of generated electricity is fed back to the grid.

By having a heat pump or battery installed, the overall amount and peak load of electricity being fed back into the grid is significantly reduced.

Moreover, a battery reduces the amount of electricity being drawn from the grid in the evening hours, when demand is highest.

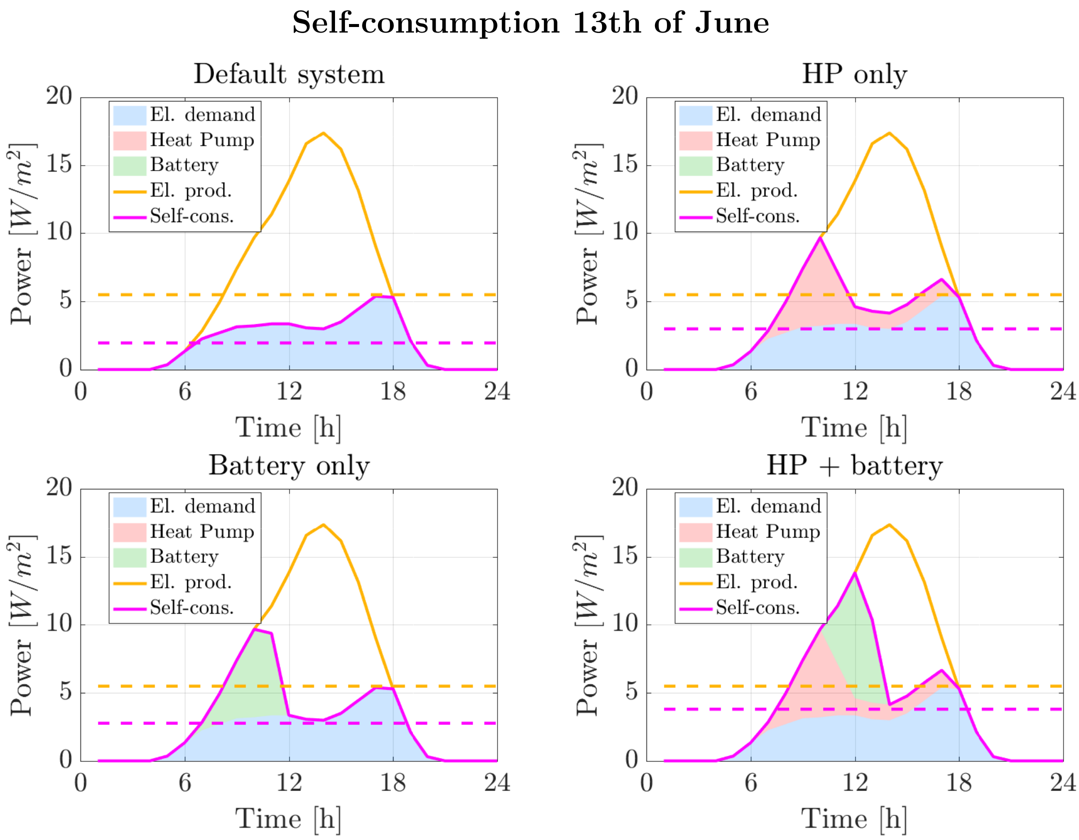


Figure 2.30: Electricity self-consumption on a typical summer day. The coloured area is the portion of generated electricity that is self-consumed.

In Figure 2.30a, the blue-shaded area represents the default electricity demand, and the yellow line the electricity production. The production is clearly higher than the demand, resulting in a self-consumption for this particular day of only 31%.

The self-consumption increase resulting from installing a heat pump, battery, or both, is clearly witnessed from Figure 2.30a, b and c. For this particular day, having a heat pump increases self-consumption to 52%, while having a battery results in a self-consumption of 50%. The addition of a heat pump and battery roughly doubles the self-consumption of electricity from 31% to 65%.

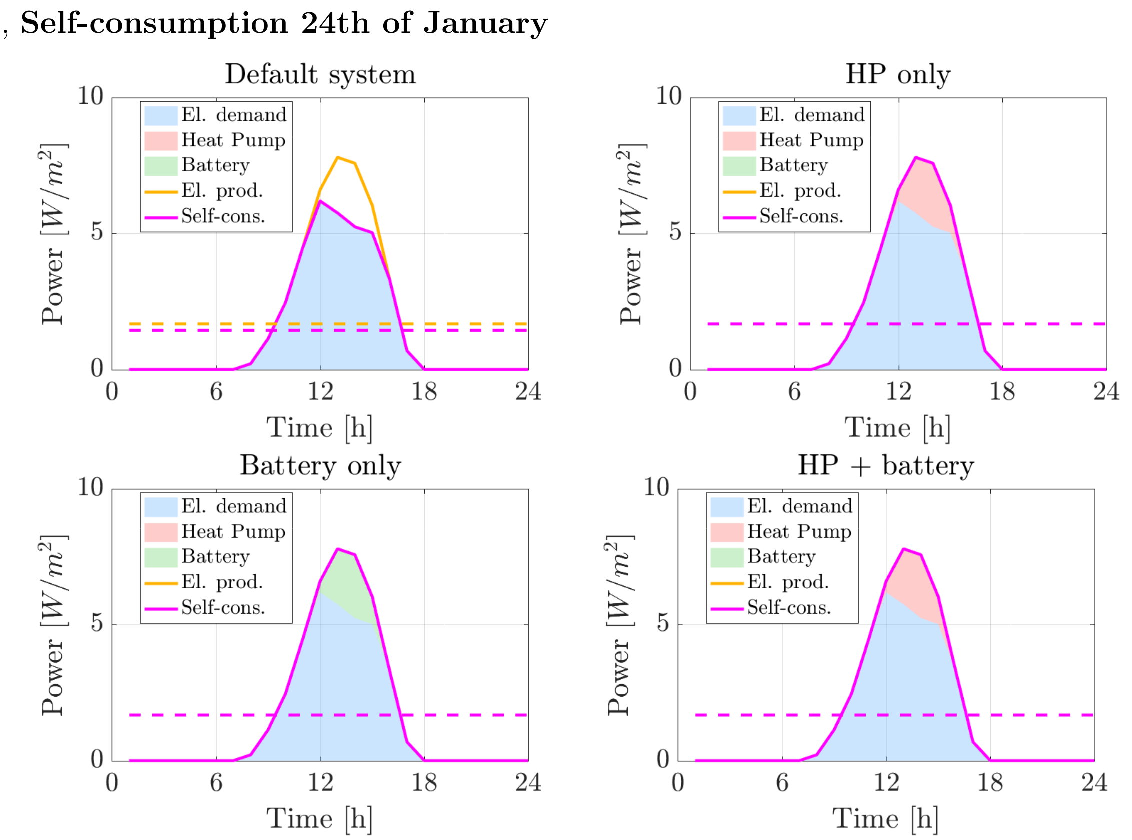


Figure 2.31: Self-consumption on a typical winter day.

In Figure 2.31 the self-consumption during a typical winter day is visible. Because there is so little electricity generation, hardly any electricity is left to power the heat pump, let alone to store it in a tank or battery.

During the winter, the battery is almost never put to use, as all the excess production is easily absorbed by the heating demand - as can be seen from Figure 2.31. As a result, both the battery and the hot water storage tank will remain empty (Figure 2.32a).

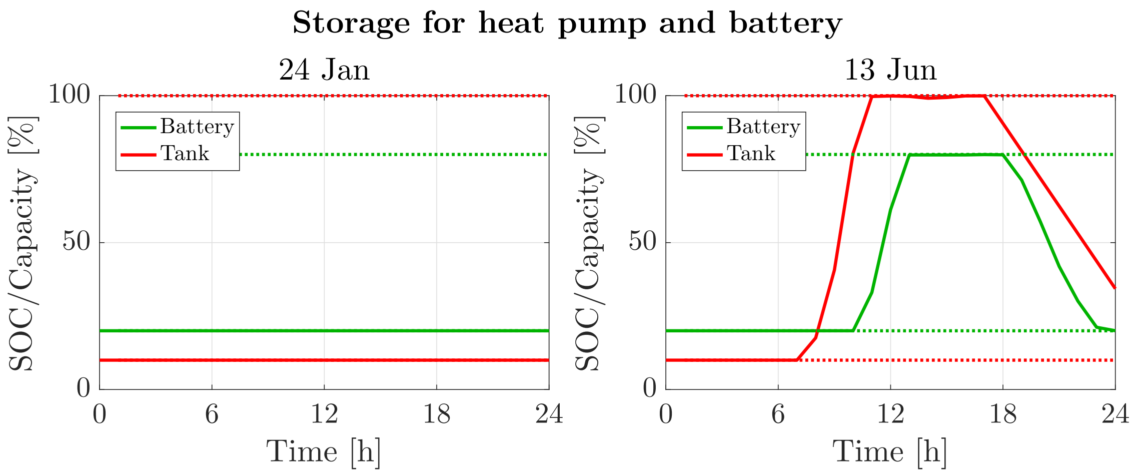


Figure 2.32: Heat and power storage for a winter and summer day. The dotted line represents the operational range.

Figure 2.32 shows how, for a heat pump and battery system, the battery only starts charging once the storage tank is filled. During a sunny summer day, both the battery and storage tank are filled in a matter of hours. On June 13th, it takes only four hours to completely fill the storage tank, and only two hours for the battery to reach the maximum SOC of 80%. On a full charge, it takes roughly three times as long to discharge.

3

Results

Before reviewing the results, let us have a quick reminder of the research question:

"What is the optimal energy system configuration for a typical 1970s multi-apartment building renovation consisting of a heat pump, solar PV and a Li-ion battery?"

To answer this research question, the size of the three constituent components has to be determined:

1. **Solar PV**
2. **Heat pump** (including hot water storage tank)
3. **Li-ion battery**

3.1 Solar PV size

The size of the solar PV system follows directly from building geometry and does therefore not require optimisation. By modelling the building, a PV area to floor area ratio of 0.33 was found. This value was then used in the ESM in order to simulate yearly electricity production. The peak electricity production capacity is roughly $400kW_p$. Average PV production is $2.87W/m^2_{floor}$, or $35kW$ on a building level, which is able to provide 24.86% of total energy demand (including heat pump heating electricity).

3.2 Heat pump size

The size of the heat pump follows directly from building energy performance and does therefore also not require further optimisation. Using the Building Model, a peak heat demand of $40W_{th}/m^2_{floor}$ was found. On a building scale, this is equal to roughly $500kW_{p,th}$.

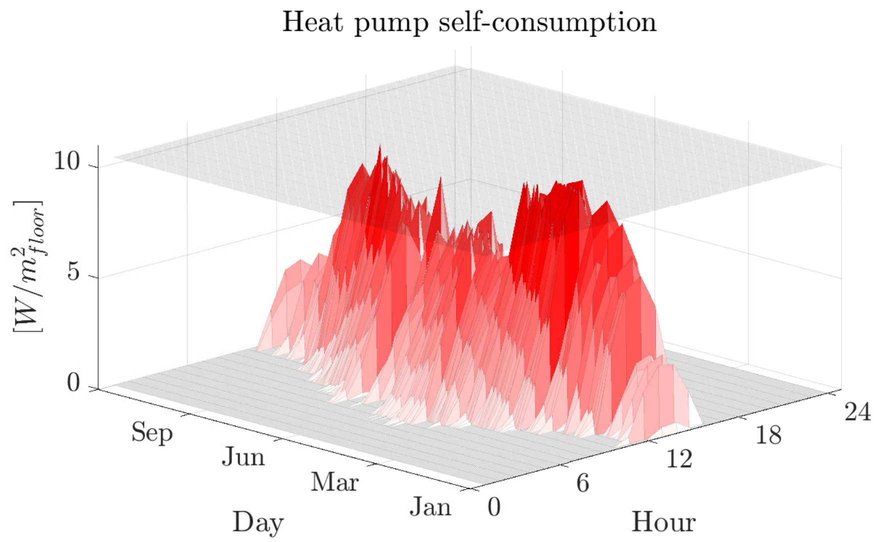


Figure 3.1: PV power self-consumed by heat pump. The grey plane indicates the heat pump peak capacity.

The peak heating capacity of $500kW_{p,th}$, corresponds to a maximum electrical peak load of $10.3W_e/m^2_{floor}$. This is therefore the maximum amount of power that can be diverted from the solar panels to the heat pump. This limit is reached only several days a year during spring and autumn (see Figure 3.1, where the graph touches the grey plane indicates the maximum power). In no case does this affect the total amount of PV electricity being diverted the heat pump.

Average heat demand is equal to $16.06W_{th}/m^2_{floor}$ (see Table 3.1), or $3.96W_e/m^2_{floor}$ (roughly $200kW_{th}$, or $50kW_e$ on a building scale). Electricity required to operate the heat pump makes up roughly half of total electricity demand (47.43%).

Table 3.1: Building energy demand and production.

	Building	Per area	Normalised
	MWh/a	$kWh/m^2/a$	W/m^2
Heating demand	172.22	140.70	16.06
PV production	30.73	25.10	2.87
El. demand	47.07	38.46	4.39

3.3 Storage size

Two component sizes are left to determine: the Li-ion battery size and the hot water storage tank size. These components *do* require optimisation, and in order to properly determine their optimum size, two key parameters were identified:

1. Self-consumption increase
2. Expected money savings

To properly assess the increase in self-consumption, the default self-consumption of the PV system without storage capability had to be established first.
The ESM was used to determine this default self-consumption based on the following formulae:

$$\text{Total production} = \sum_{d=1}^{365}\sum_{h=1}^{24} P_{prod}(d,h)\cdot dt = 25.10kWh/m^2/a \tag{3.1}$$

$$\text{Overproduction} = \sum_{d=1}^{365}\sum_{h=1}^{24} \left[\Big(P_{prod}(d,h) - P_{cons}(d,h)\Big) > 0\right]\cdot dt = 9.55kWh/m^2/a \tag{3.2}$$

$$\text{Default self-consumption} = \text{Total production} - \text{Overproduction} = 15.55kWh/m^2/a \tag{3.3}$$

So, of the $25.10kWh/m^2/a$ of produced solar PV power, 62% is directly self-consumed through the electricity demand. This means that 38% of the produced electricity that is produced can not be consumed directly and thus has to be fed back to the grid in case of no storage (tank or battery).

Since a FIT of zero is assumed, the maximum potential money savings due to storage amounts to:

$$\text{Money savings potential} = \text{Overproduction} \cdot \text{El. price} = 9.55 \cdot 0.15 = 1.44\text{€}/m^2/a \tag{3.4}$$

The default self-consumption and the money savings potential defined in Equations 3.3 and 3.4 demarcate the solution space for the research question. That is, no system configuration can have a self-consumption increase greater than 38% or save more money than 1.44€$/m^2/a$ in electricity.

The optimal system configuration is now solely dependent on the optimisation of self-consumption increase versus investment cost as a function of the size of the battery and tank: the bigger the battery or tank size, the higher the money savings but also the investment cost. Since self-consumption as a function of storage capacity is subject to diminishing returns, there is an optimum size to be determined.

3.3.1 Hot water storage tank performance

The tank storage tank was modelled using the ESM and simulated at various sizes. The effect on the heat pump self-consumption can be observed in Figure 3.2, which shows the average PV power diverted to the heat pump for different hot water storage tank sizes.

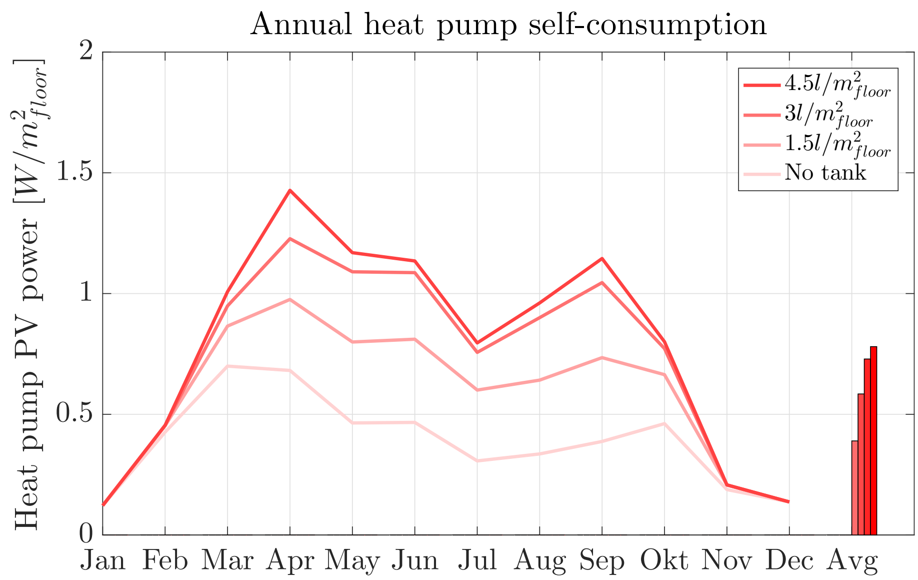


Figure 3.2: Average monthly and yearly PV power used for heating.

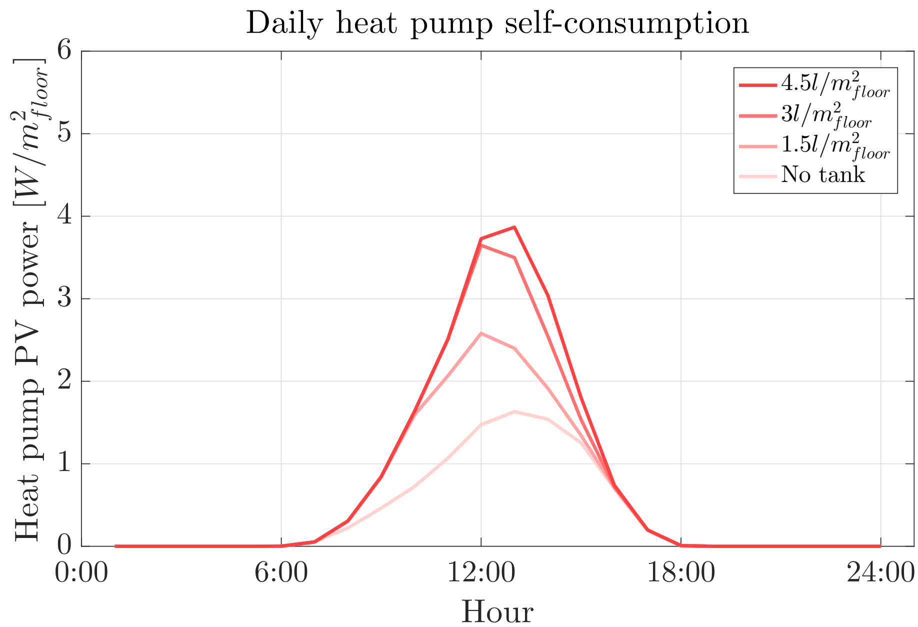


Figure 3.3: Average PV power used for heating.

As can be seen from Figure 3.2, the heat pump self-consumes $0.39W/m^2_{floor}$ on average with no storage tank present. Increasing the tank size results in an increased self-consumption. A storage tank of $3l/m^2_{floor}$ already allows the heat pump to self-consume $0.73W/m^2_{floor}$. The diminishing returns in self-consumption as a result from increasing tank storage size are clearly visible. Increasing the tank size by 50% from $3l/m^2_{floor}$ to $4.5l/m^2_{floor}$ only results in 5% more self consumption.

The heat pump self-consumption is highest during spring and autumn, when both heat demand and power production are average. Self-consumption increases from increased storage tank size is unevenly distributed over the year, as spring and autumn see the highest increase. This can be attributed to a higher heating demand than summer, and a lower residential electricity demand due to the lack of air conditioning. The winter months remain unaffected, as PV production hardly exceeds electricity demand during this time.

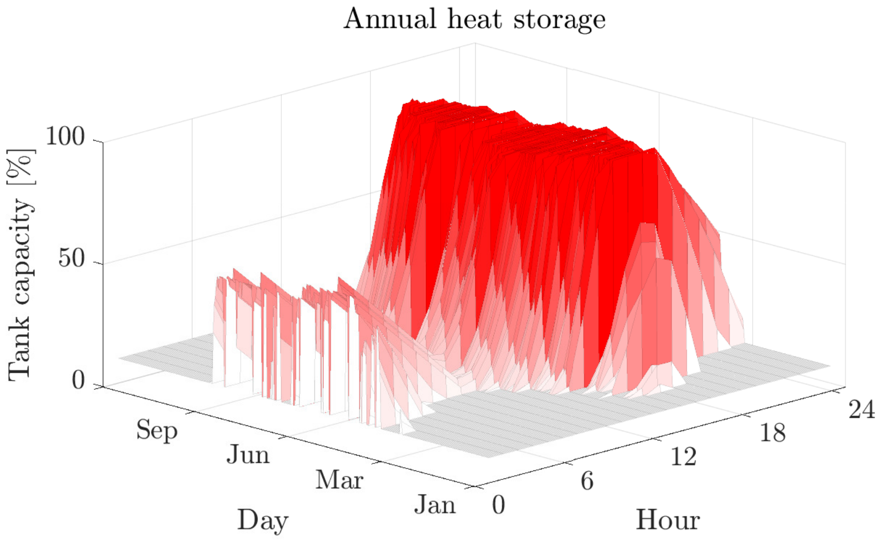


Figure 3.4: Hot water storage for a $3l/m^2$ tank throughout the year.

A $3l/m^2_{floor}$ storage tank is filled nearly every day when the sun shines from March to September (Figure 3.4). During summer, the storage tank provides enough heat to last one day on a full charge. This explains why increasing the storage tank to over $3l/m^2_{floor}$ has so little effect: if the storage tank is not emptied on a particular day, it reduces the storage potential for the next day.

3.3.2 Li-ion battery performance

The battery works similar to the tank due to the fact that they are both electricity sinks during overproduction. There are two big differences though: (1) the battery can also act as an electricity provider and (2) the battery is activated *after* the storage tank is full, thereby decreasing its potential. Both effects are visible for various battery sizes in Figures 3.5 and 3.6.

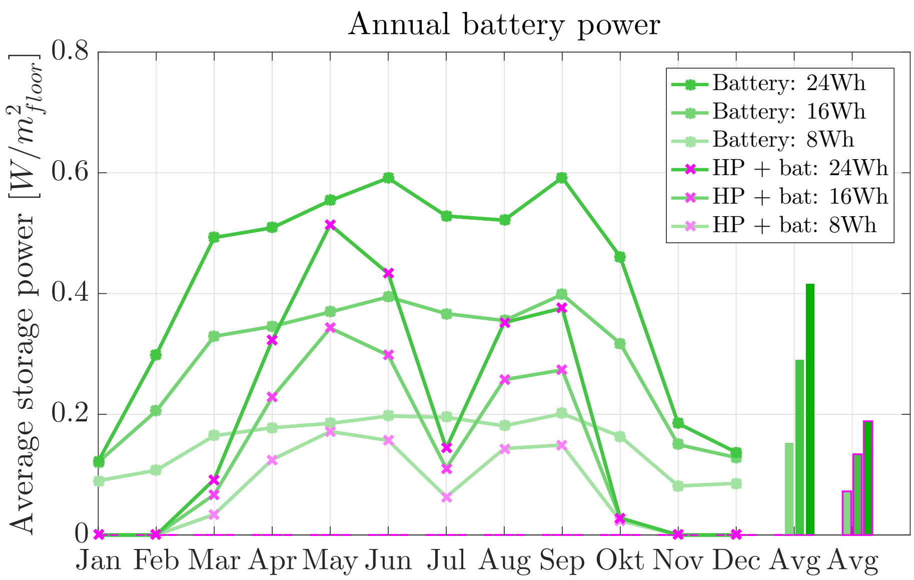


Figure 3.5: Annual monthly average storage power profile.

The difference in battery power for a system with and without heat pump can be observed in Figure 3.5. There is a clear valley during summer for the battery system in combination with a heat pump due to the cooling electricity demand eating away at the solar PV electricity. The battery is used roughly half as much for a system with heat pump. The diminishing returns for increased battery capacity are less obvious than for the heat pump tank size, yet still present.

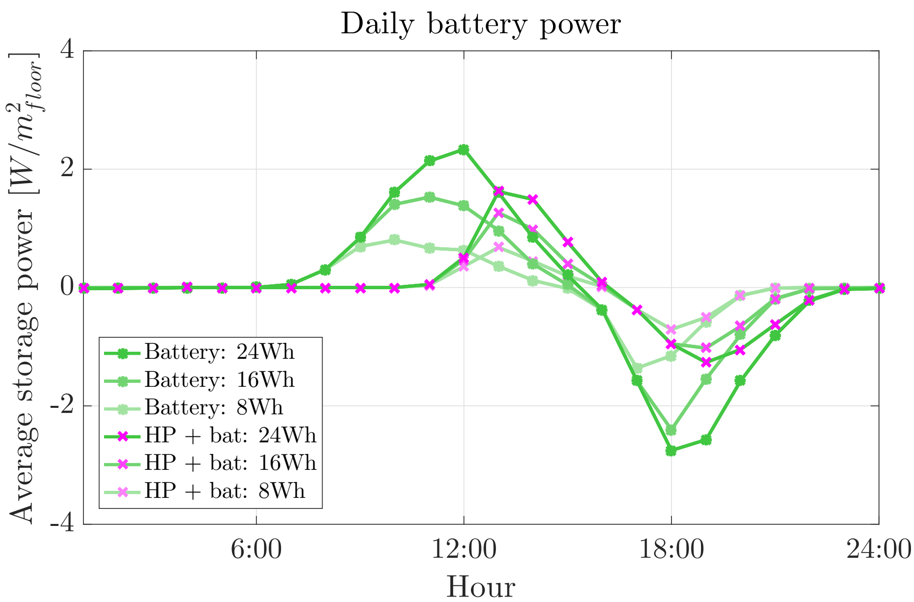


Figure 3.6: Yearly average storage power per hour profile.

From a daily perspective, the delay in charging time for the battery with and without heat pump is clearly visible in Figure 3.6. When there is a heat pump present, the battery is charged a couple of hours later (than when there is no heat pump present) and to a lesser degree. This effect is also visible in Figures 3.7 and 3.8

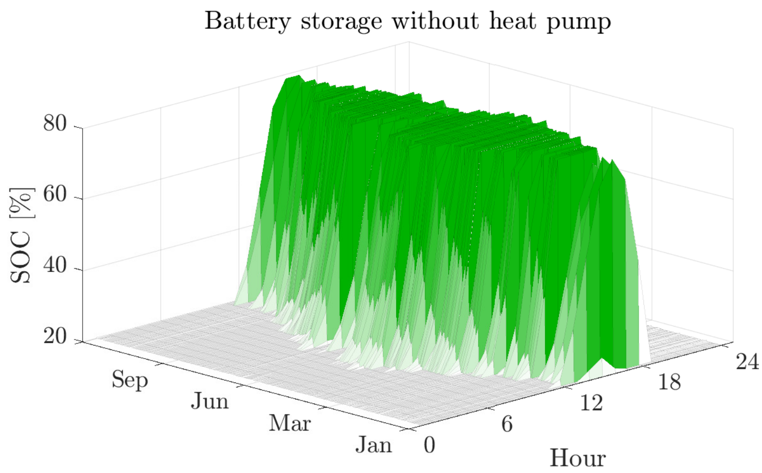


Figure 3.7: Battery State Of Charge throughout the year for the system without a heat pump.

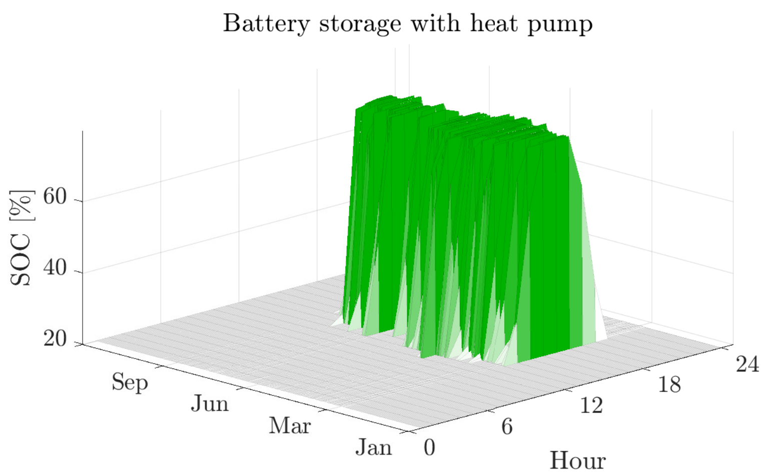


Figure 3.8: Battery SOC throughout the year for the system with a heat pump.

Without a heat pump, the battery is used throughout the year, with full charges occurring even during winter (Figure 3.8). The amount of Equivalent Full-load Cycles (EFC) in a year is 150, giving it a cycle lifetime of 20 years. With a heat pump, the battery is only used during summer, reaching full charge on most days from April to September. The amount of EFC in a year is only 68, giving it a cycle lifetime of

44 years.

Table 3.2: Cyclic ageing versus calendric ageing with and without heat pump

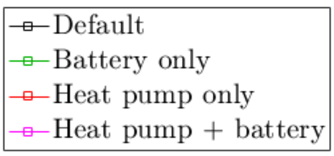
	without heat pump	with heat pump
Equivalent Full-load Cycles	150 EFC/year	68 EFC/year
Cycle lifetime (3000 cycles)	20 years	44 years
Calendric lifetime	15 years	15 years

Although the battery may have a cycle lifetime of 44 years for the system with heat pump, which is more than double the amount for a system without heat pump, the lifetime of the battery is dictated by the calendric lifetime for both cases. However, it can reasonably be assumed that the battery will last longer for both cases - especially for the system with heat pump - due to the low amount of cycles. How much longer precisely is hard to say, and therefore not considered for the economical optimisation in upcoming Sections 3.3.3 and **??**.

3.3.3 Storage optimisation

Now that the performance of the hot water storage tank and the Li-ion battery has been determined, it is time to optimise their performance with respect to costs. This optimisation is done for both the technical and economical aspects of the system simultaneously, meaning that the cheapest solution is not the best solution per se. If a large amount of self-consumption increase can be gained at a fraction (<5%) of the overall cost, the extra cost is assumed to be justifiable for peak-shaving and self-sufficiency reasons.

Disclaimer: In the upcoming sections, four different system configurations will be compared simultaneously. Please keep the following colour coding in mind when assessing the upcoming diagrams:



3.3.3.1 Self-consumption

Before jumping into the cost optimisation, let us consider the technical relation between tank- and battery capacity on the self-consumption depicted in Figure 3.9.

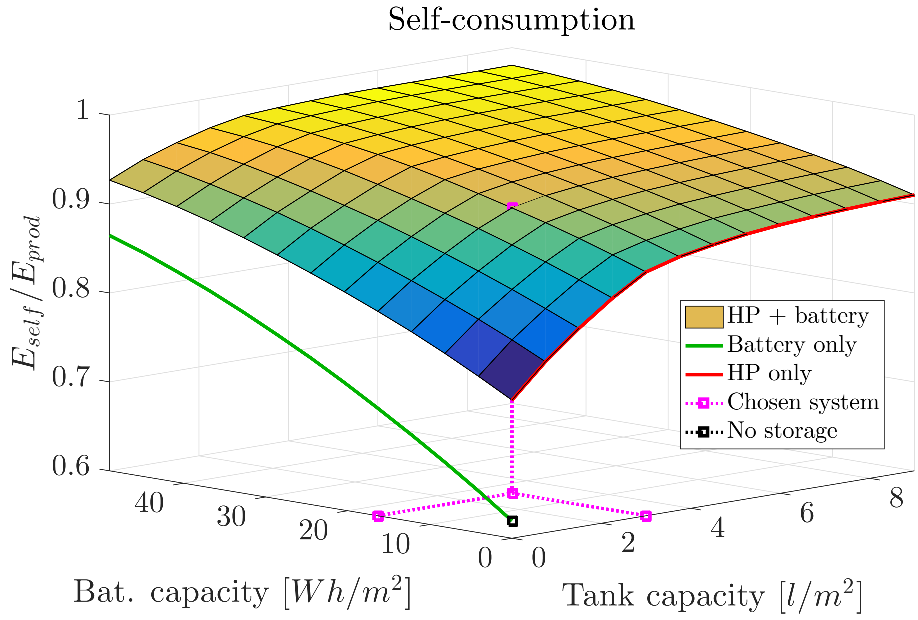


Figure 3.9: Self-consumption as a function of battery and tank storage size.

All four system configurations are visible in Figure 3.9. The green line represents the battery only system, while the red line represents the self-consumption for a heat pump only system. With no battery storage and no heat pump, the default self-consumption is 0.62 (represented by the black dot). The surface plot represents the self-consumption for a heat pump and battery system at different battery and tank sizes. The purple dot indicates the optimal system configuration, which will be justified in Section 3.3.3.2.

There is a clear gap visible between the battery only system and the battery plus heat pump with no storage tank system. This gap corresponds to the immediate self-consumption gains resulting from installing a heat pump, even if there is no storage tank available. The sole addition of a heat pump results in self-consumption increase from 0.62 to 0.76, or 22%.

The diminishing returns from adding extra storage capability are clearly visible for all systems. Especially in the case of tank storage capacity, there is a clear cutoff point visible around $3l/m^2$, with self-consumption increasing only marginally beyond that point. This cutoff point is a result of the heating demand being nearly satiated (as discussed in Section 3.3.1). The self-consumption at this point is equal to 0.87, and is a function of heat load instead of PV production and will therefore remain similar for increased PV-production.

For battery storage capacity, no clear cut-off point is visible on this axis scale, although the curve is clearly nonlinear in nature. The chosen optimal heat pump plus battery system configuration is already shown in Figure 3.9 and will be justified in Section 3.3.3.2, corresponds to a self-consumption of 0.92, or an increase of 49% compared to the default system. The choice of optimal heat pump plus battery system is not just the result of maximising the self-consumption, as it is also dependent on the amount of electricity saved from the grid compared to the investment costs of storage.

3.3.3.2 Money savings

In Section 3.3.3.1 the chosen Li-ion battery and storage tank size was already depicted. The economic validation for that system configuration is dependent on the relationship between (1) grid savings and (2) investment costs of storage (battery and tank): the larger the tank or battery, the higher the savings, but also the investment costs. The outcome of that relationship is the resulting net savings (over a 20 year time frame) depicted in Figure 3.10.

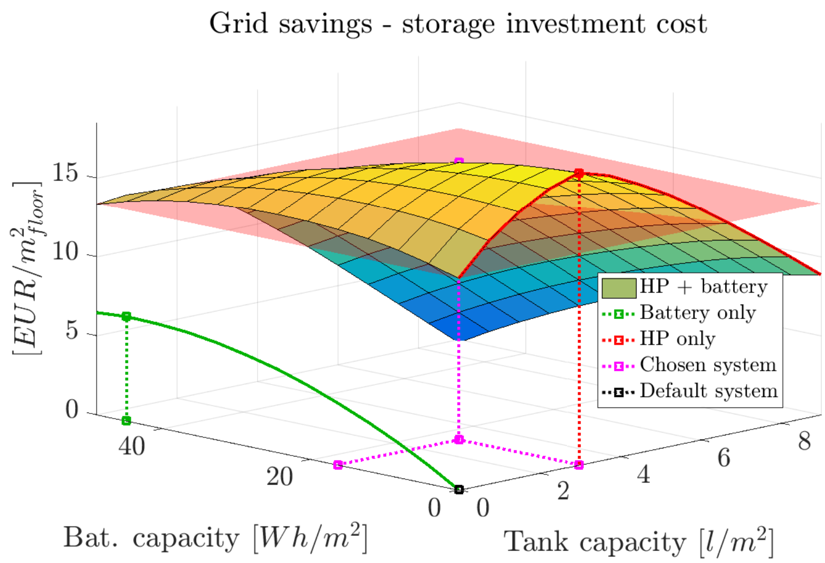


Figure 3.10: Grid savings minus storage investment costs as a function of battery and tank storage size. The coloured dots indicate the optimal configuration for different systems. The red plane indicates the default grid savings as a result of having a heat pump.

Any point below the red plane in Figure 3.10 on the surface plot represents an economic loss due to tank or battery, since the red plane indicates the grid savings as a consequence of having a heat pump. So having a battery capacity over $50Wh/m^2$, or a tank capacity over $6.75l/m^2$ will result in a net loss. It is important to note that the storage investment costs do not include the heat pump investment costs, just the tank itself. The reason being, that the heat pump investment costs are counted on the heating side of the balance sheet, instead of the electricity side. More on this in Section 3.4.

Again, the four different system configurations are discernible. For both the battery and the tank, there are clear optimums visible (indicated with the green and red dotted lines in Figure 3.10):

- For the default system (black), there are no grid savings nor investment costs due to storage. Therefore there is no economic optimum.
- For the battery only system (green), the economic optimal battery size is $45Wh/m^2_{floor}$, corresponding to a self-consumption of 0.85 (37% increase from default state).
- For a heat pump only system (red), a $3l/m^2_{floor}$ hot water storage tank is the

economically optimum size, corresponding to a self-consumption of 0.87 (41% increase from default state).

- **For the battery and tank system (purple), there is no economically optimum size.** That is, for a $3l/m^2_{floor}$ hot water storage tank, any size of battery will cost more than it saves.

3.3.3.3 Technoeconomic optimisation of storage capacity

Selecting an optimum tank plus battery system is somewhat arbitrary, as it depends on how much weight is assigned to economic values versus technical values. There is enough room to play around with battery and tank size while maintaining economic viability. Since there is no economic optimum battery size, the optimal size becomes dependent on technical factors as well. The self-consumption increase has to be weighed against the cost increase. A building owner can therefore look at Figure 3.11 and determine what type of system would work best for him.

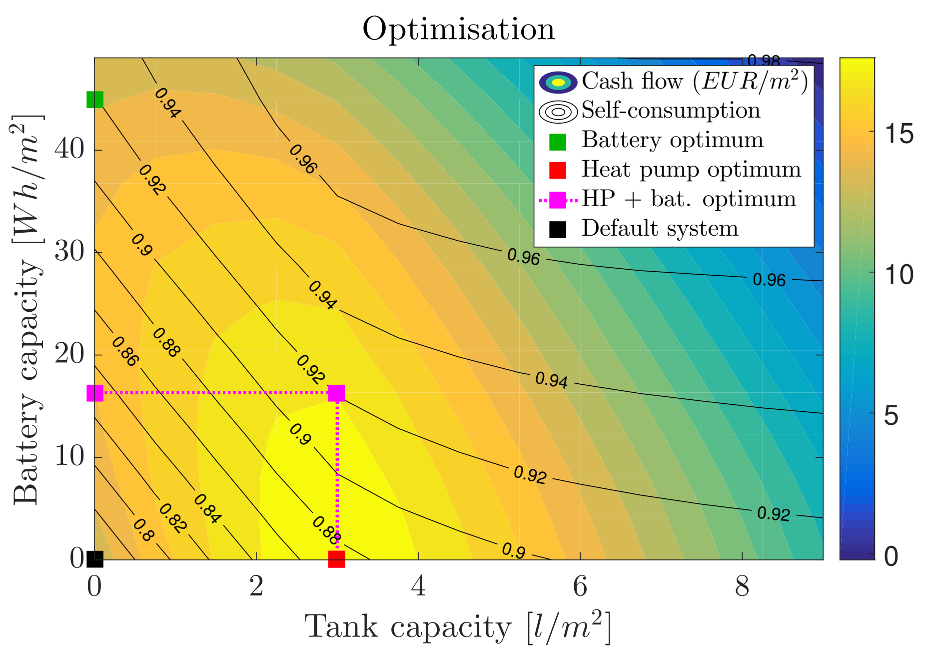


Figure 3.11: Two-dimensional view of storage savings minus investment costs (coloured surface) and self-consumption (black contour) as a function of battery and tank storage size.

For illustrative purposes, a battery size within 5 % of economic optimum storage configuration was selected. This is shown in Figure 3.11, which is a top-down view of Figure 3.10 that includes self-consumption as well. The brightest yellow area indicates the most economically optimum storage configuration (i.e. the height of the surface plot of Figure 3.10), and the black contour lines indicate the self-consumption (i.e. the height of the surface plot in Figure 3.9) as a function of battery and tank storage. The most economically optimal system is that which has no battery storage and a $3l/m^2_{floor}$ storage tank. Adding a battery of $17Wh/m^2_{floor}$ results in nearly (less than 5% deviation) the same net savings, but with a 5% higher self consumption. For illustrative purposes, it is decided to opt for a system with both high economic viability and self-consumption. **The size of the Li-ion battery is therefore taken to be $\mathbf{17Wh/m^2_{floor}}$.**

The size of each part of the energy system has now been determined: the average solar PV production is $2.87W/m^2_{floor}$, the heat pump requires $3.96W/m^2_{floor}$ on average, the hot water storage tank is $3l/m^2_{floor}$, and the Li-ion battery $17Wh/m^2_{floor}$. On a building scale, this corresponds to a $393kW_p$ PV system, a $490kW_p$ heat pump, $36.7m^3$ of hot water storage tanks and a $208kWh$ Li-ion battery.

3.4 Business case

The business case of the system can now be constructed by balancing the investment costs (Capital Expenditure - CAPEX) and operational costs (Operational Expenditure - OPEX) with the expected utility savings (gas and electricity). This was done for the different components individually over a 20 year time period with an inflation rate of 2.5% as established in Section 2.3.2.[1] Capital investment was assumed to be made instantly, without the consideration of taking out any loans and corresponding interest rates. The resulting cash flow can be observed in Figure 3.12

[1]The inflation rate affects future utility price and operational expenditure.

Table 3.3: Costs and savings over a 20 year time period for the various components of the energy system.

		Costs €$/m^2_{floor}$	**Savings** €$/m^2_{floor}$	**ROI** [%]
Heat pump	CAPEX	-53,81		
$490kW_p$	OPEX	-20,84		
$3.96W/m^2_{floor}$	Gas savings		303,20	
	Grid savings		13,38	
	Subtotal	**74,65**	**316,58**	**324,09%**
Tank	CAPEX	-6,60		
$36,7m^3$	Grid savings		10,07	
$3l/m^2_{floor}$	**Subtotal**	**-6,60**	**10,07**	**52,58%**
Solar PV	CAPEX	-27,36		
$393kW_p$	OPEX	-4,21		
$2.87W/m^2_{floor}$	Grid savings		98,59	
	Subtotal	**-31,57**	**98,59**	**212,29%**
Battery	CAPEX	-5,10		
$208kWh$	OPEX	-1,48		
$17Wh/m^2_{floor}$	Grid savings		5,81	
	Subtotal	**-6,58**	**5,81**	**-11,69%**
	Total CAPEX	-92,87		
	Total OPEX	-26,53		
	Total gas savings		303,20	
	Total grid savings		127,85	
	Total:	**-112,80**	**431,05**	**273,21%**
	Net total:		**318,25**	

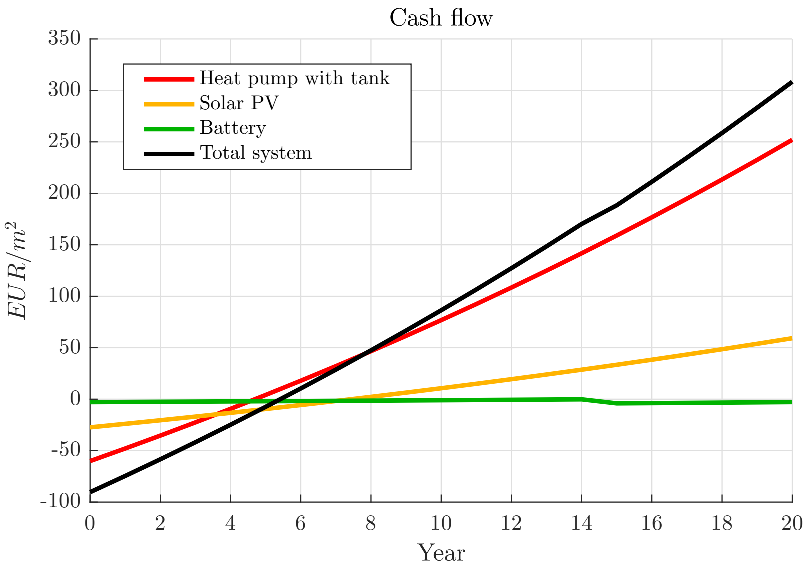


Figure 3.12: Cash flow over a 20-year time-span for a system with heat pump and battery.

As can be seen from Figure 3.12, investing in a heat pump with tank is the smartest thing to do in order to save money. The payback period is only 4.5 years and the Return On Investment (ROI) is over 300% due to the savings in both gas and grid electricity purchases (Table 3.3).

The second most economically desirable component is the PV system, with a payback period of around seven years (Figure 3.12) and a ROI of 212% (Table 3.3). Especially the first few solar panels will significantly reduce the money spent on grid electricity, as all the electricity is self-consumed. The consequences of installing more solar PV panels will be discussed in Section 4.2.

As shown earlier, there is no economic benefit in installing a battery when a heat pump is already present. The ROI of the Li-ion battery is negative: -11,69%. From an economic perspective, the battery is therefore worthless. However, the economic losses are very small; they are hardly noticeable in the bigger picture (see Table 3.3). Over 20 years, the loss of installing a $17Wh/m^2$ battery system is 0.77€$/m^2_{floor}$, which is less than 1% of the total costs of the energy system (112.80€$/m^2_{floor}$), while gaining 5% more self-consumption.

For the system as whole, the economic feasibility is very solid. The net total money saved over a 20 year period is equal to 308.18€$/m^2_{floor}$. For one of the $97m^2$ apartments, this amounts to 30000€, or 1500€$/year$. This is mostly attributable to the money saved from buying gas (303.20€$/m^2_{floor}$) because of the heat pump. The total grid electricity savings of the system amount to 127.85€$/m^2_{floor}$, whereas the total investment costs amount to 112.80€$/m^2_{floor}$. The overall ROI is 273.21%, giving it a payback period of less than six years.

3.5 Sensitivity analyses

The optimal energy system configuration and corresponding business case have been successfully determined for a multi-apartment building in Treviso, Italy. The research question: *"What is the optimal energy system configuration for a typical 1970s multi-apartment building renovation consisting of a heat pump, solar PV and a Li-ion battery?"* has thus been answered in its narrowest sense: the scope is just one building. That building, while typical for a 1970s apartment building, is just one particular case and may therefore not be representative for a large group.

For instance, what happens for a similar multi-apartment building if the orientation is different, allowing for a larger PV area? Or what if a similar building is located in another country, with a different energy price? And what if that building is better insulated? What if the battery price drops in the future? Etc.

All these questions are legitimate followup questions that will be shortly addressed in the upcoming sensitivity analyses. This is done by varying the key parameters that constitute the boundary conditions. They can be separated into two categories: physical and economical. The physical part analysis the sensitivity of the size of the PV production, heat demand, electricity demand, battery size and tank storage. The economical part analyses the effects of PV panel-, electricity-, FIT- and battery price for various system configurations. By mapping the influence of all these parameters, a cohesive overview is formed of a wide range of energy system configurations, for an evenly wide range of cases.

3.5.1 Physical sensitivity

The physical sensitivity of the system essentially boils down to five key parameters:

1. Heat demand
2. Electricity demand
3. Electricity production
4. Battery capacity
5. Storage tank capacity

A sensitivity analysis was carried out to assess the influence of these parameters for various systems on the self-production and self-consumption. Knowing the self-consumption is important, as it is a measure of economic feasibility; low self-consumption means high grid feed in and therefore low money savings. Similarly, self-production is an important measure for the autonomy of the building. The higher the self-production the lesser the dependence on grid electricity. The more autonomous the building, the lower its CO_2 emissions, with a self-production of 1 requiring no carbon emissions at all.

The relation between self-production, self-consumption and grid energy can be expressed by the following equations:

$$\text{Grid feed-in} = (1 - SC) \cdot E_{prod} \tag{3.5}$$

$$\text{Grid intake} = (1 - SP) \cdot E_{demand} \tag{3.6}$$

Both the grid feed-in and intake can be directly translated to economic values by multiplying them with the electricity price. The relationship between self-production and consumption is largely dependent on the PV production.

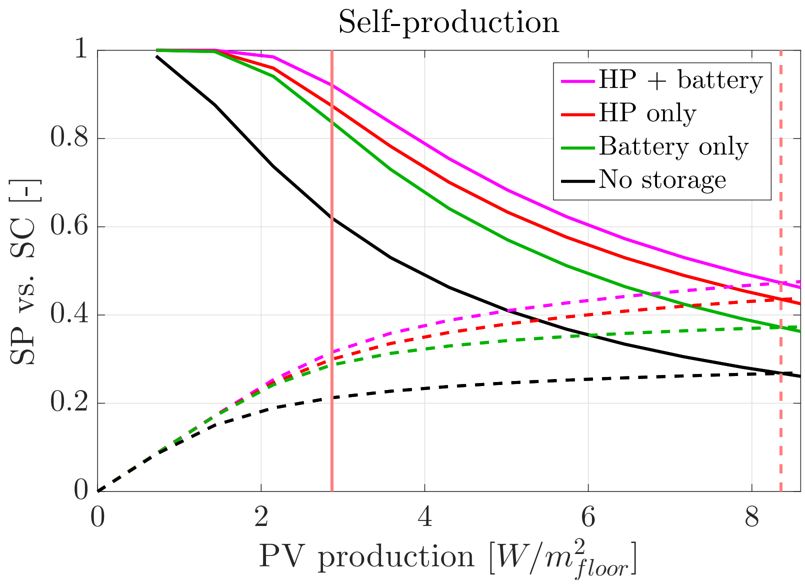


Figure 3.13: Self-consumption versus self-production for the different system configurations.

Figure 3.13 shows how self-consumption and self-production change with increasing PV production capacity. The dotted lines represents the self-production. The self-production shows a steep decline in growth rate with the installation of extra PV power. For the default system without storage, self-production does not exceed 0.3 for a PV production of $8W/m^2_{floor}$, whereas it already exceeds a self-production of 0.2 for a PV production of $3W/m^2_{floor}$. Adding a heat pump or battery can definitely be seen to increase performance, achieving higher self-production values for increased PV production. Still, diminishing returns are clearly visible here as well.

Where the continuous lines and the dotted lines meet indicates the zero-net-energy PV production capacity i.e. when yearly energy production is equal to consumption. The amount of PV power that will have to be installed to achieve zero-net-energy is equal to $8.37W/m^2_{floor}$ (marked by the vertical dotted line), assuming similar orientation to the current PV panels. This is roughly 3 (2.9) times the current amount of PV installed ($2.87W/m^2_{floor}$, indicated by the vertical red line). In reality, there is no room to achieve this, but for illustrative purposes it assumed that there is. At this point, the self-production is nearly twice as high for the system with a heat pump and battery (purple) compared to the system with no storage at all (black). Bear in mind that the storage capacities are optimised for the $2.87W/m^2_{floor}$ system. The optimum storage size will increase with more production capacity.

The relation between self-production and consumption shown in Figure 3.13 is a function of PV production and thus shows the sensitivity of a single parameter. It is therefore quite limited. To gain a deeper comprehension of the interplay between the identified five key parameters for the four different systems, it was decided to display the self-production on the y-axis and the self-consumption on the x-axis. The five parameters were then scaled by a factor of $\frac{1}{2}, \frac{2}{3}, \frac{3}{2}$ and 2, with the resulting diagram visible in Figure 3.14. The reason for not scaling them linear is that both self-consumption and self-production are fractional in nature themselves (i.e. a doubling or halving of a parameter roughly results in an equally spaced difference). By using a fractional scale, the step sizes can be compared to each other, giving an indication of relative in- or decrease.

For instance, if the building owner wants to see what the effect on self-consumption is as a result of installing twice as much solar power, he can easily determine the impact by referencing Figure 3.14. In doing so, he will see that doubling the PV power only increases self-production from 0.22 to 0.26 for a system without any storage capacity, while it increases from from 0.32 to 0.43 for a system with a heat pump and battery. From this, he learns that installing extra PV capacity is more sensible when there is a battery and heat pump available. He can then easily calculate the associated savings in grid energy by using Equation 3.6.

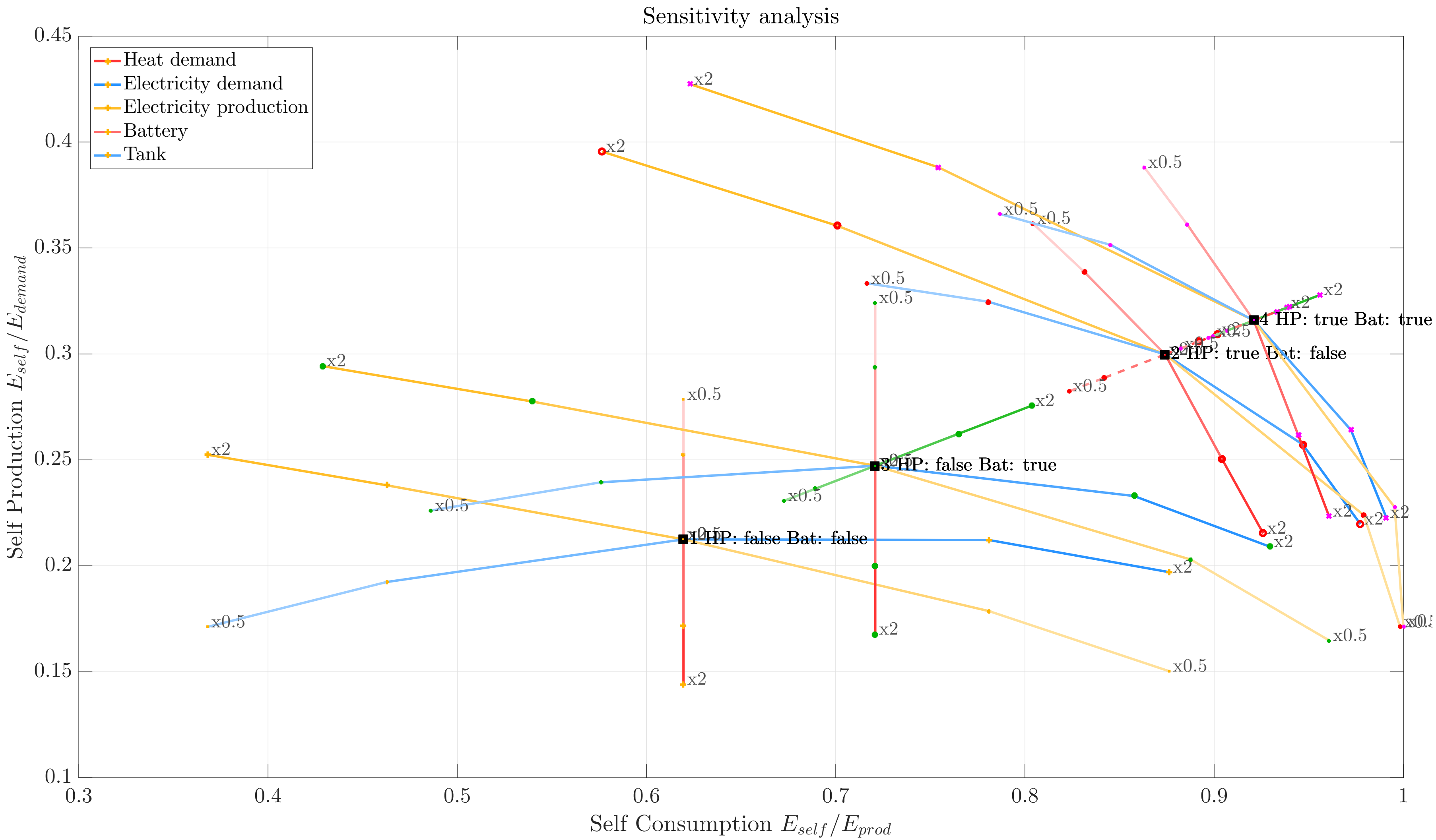


Figure 3.14: Sensitivity analysis for various technical parameters for the four different systems. Each black dot represents the corresponding default system configuration.

All four systems have been mapped in Figure 3.14. As can be observed, the biggest impact on self-production and consumption is the PV production, which has the widest range of values for both self-production and consumption for each system. That is, doubling or halving the PV production has the most effect on self-production and consumption, compared to the other parameters. In addition, the electricity demand mostly affects self-consumption (as observed by the near-horizontal blue lines for the system without a heat pump), whereas the heating demand mostly influences self-production. The reason being, that heating demand dominates electricity demand ($16.06W/m^2_{floor}$ vs. $4.39W/m^2_{floor}$).

For the systems without a heat pump, a vertical line can be seen for the sensitivity of the heat demand: since there is no way to convert electricity to heat, varying the heat demand has no effect on self-consumption. It does, however, affect the self-production: more heat demand means a relatively smaller electricity demand. Electricity is the only energy that is self-produced, therefore self-production decreases as heat demand increases.

The effect of battery storage on self-consumption and production is clearly visible for the battery only system in Figure 3.14. Adding storage increases both self-consumption and production in a linear way: every extra Joule of self-consumption corresponds to a fixed amount of Joule in self-production by definition. That is also why the same linear relationship can be observed for the storage tank. At its extreme (unlimited storage capacity), self-consumption is equal to one, and the corresponding self-production is the ratio between total energy production and demand: E_{prod}/E_{demand}.

3.5.2 Economical sensitivity

In the following section the influence of different parameters on the economical outcome will be discussed. This assessment was done for different levels of PV production, as it was established in Section 4.2 that PV production was the dominant parameter for self-production and consumption. It is therefore the most dominant in terms of grid savings.

The following parameters have been chosen for the economical sensitivity analysis:

- PV panel price
- FIT price
- Electricity price
- Battery size and price for a system with and without heat pump
- Different system configurations

The heat pump and storage price are excluded since their business case is already solid and will not be affected much by adding extra PV production.

Disclaimer: Before diving into the economic sensitivity analysis it is important to understand the following:

1. Firstly, in the following Figures the cash flow and corresponding profits are shown for the electrical part only. That is, any savings in gas resulting from the installation of a heat pump have not been included. The reason being, that including these savings would overshadow the electricity savings and thus make it difficult to compare the scenarios. As shown in Figure 3.12, the heat pump is by far the most financially viable investment and therefore requires no optimisation nor sensitivity analysis.

2. Secondly, the various parameters are each depicted in two separate Figures. The first figure shows both the total savings and the total investment costs of the parameters over a 20 year time period. The second Figure combines the savings and investment cost to arrive at the net cash flow. This makes it easier to see what the optimum system size is, at the cost of losing data.

3. Thirdly, the red lines represent two special PV system sizes. The continuous red line represents the current level of PV, whereas the dotted red line represents the amount of PV in corresponding to a zero-energy building.

4. Finally, the various sensitivities are related and should thus not be observed in isolation. All Figures stem from the same default data and are therefore mutually exchangeable. The separation of parameters was done with the sole purpose of making the Figures more accessible. It would be possible to combine them into a single Figure with many lines, but this would make it unnecessarily complicated.

To help make sense of the upcoming Figures it is useful to keep the following colour coding scheme in mind:

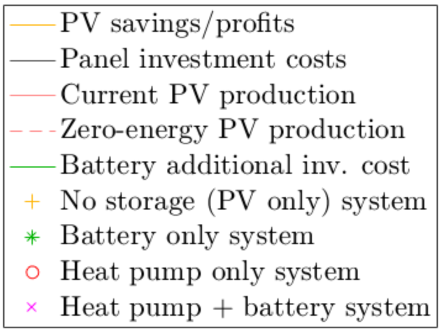


Figure 3.15: Colour coding used in the upcoming Figures for various parameters.

3.5.2.1 PV panel price sensitivity

The PV panel price was taken from [39] for crystalline modules in Italy, and found to be roughly 0.6€/W_p. The business case is very sensitive to the PV panel price, as the investment cost of the PV panel system dwarfs the investment cost of the battery system. Moreover, the price of a solar panel has decreased so much in the past seven years (over 80% [20]) that is not unthinkable that the price of solar PV will drop by another 50% in the coming decade.

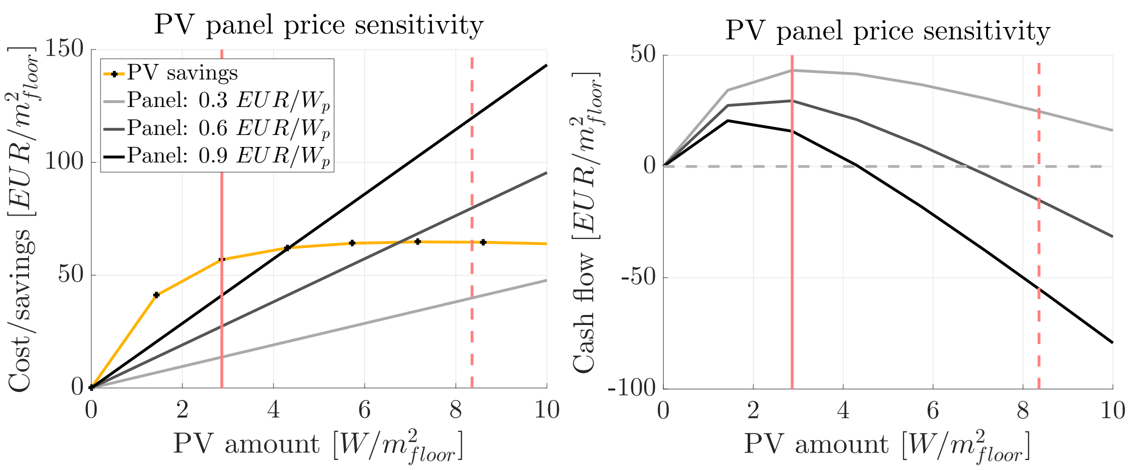


Figure 3.16: Influence of PV panel price on lifetime PV profits.

Figure 3.16 shows the implications of such a price drop for the business case. If the price drops to 0.3€/W_p, the PV installation remains profitable for PV system sizes significantly larger than required for a zero-energy building. Conversely, if the PV panel price turns out to be higher due to unforeseen costs the business case becomes much harder to make. In any case, the current PV system is still economically feasible for a PV panel price of over 0.9€/W_p. Moreover, the current PV system size is optimal for the default PV panel price of 0.6€/W_p as can be seen from the second figure.

3.5.2.2 Feed-In Tariff sensitivity

The Feed-In Tariff remains critical to the economic feasibility of the system. The influence of the FIT on the business case is most pronounced for a system without storage, as it has the lowest self-consumption. That is why in Figure 3.17 a system without storage is considered.

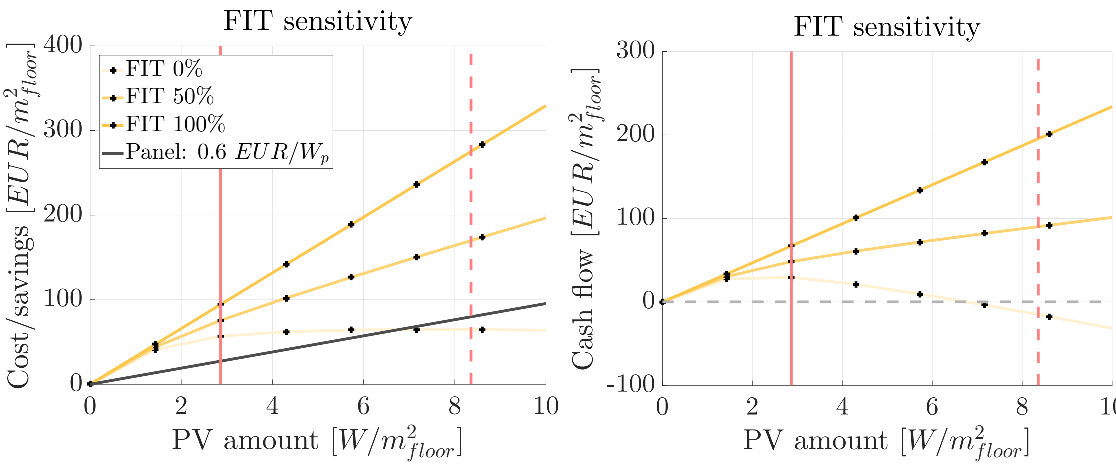


Figure 3.17: Influence of FIT price on lifetime PV profits.

If we look at the projected profits from solar PV electricity in Figure 3.17, it becomes obvious how the FIT is the deciding factor in economic feasibility for increasing PV system size. If the FIT is 100% of the electricity price, there is no drop-off in feasibility for increasing PV production. A smart building owner would then strive to install as many PV panels as physically and financially possible.

However, if the FIT is 0% of electricity price, a fast decrease in profits becomes visible as PV production increases and self-consumption decreases. Furthermore, it can be observed that it is currently not economically feasible to have a zero-energy building without any storage for a FIT of 0%.

3.5.2.3 Electricity price sensitivity

Similarly to the FIT and PV panel price, the electricity price is of great influence on the business case. An electricity price of 0.15€$/kWh$ with an annual increase of 2.5% (due to inflation) was considered. If, for any political, economical or technical reason, the price increase turns out to be much higher in the coming years, the expected savings increase is linearly proportional to the electricity price (see Figure 3.18. A 50% lower electricity price roughly results in 50% lower electricity savings and would already make the PV system unprofitable.

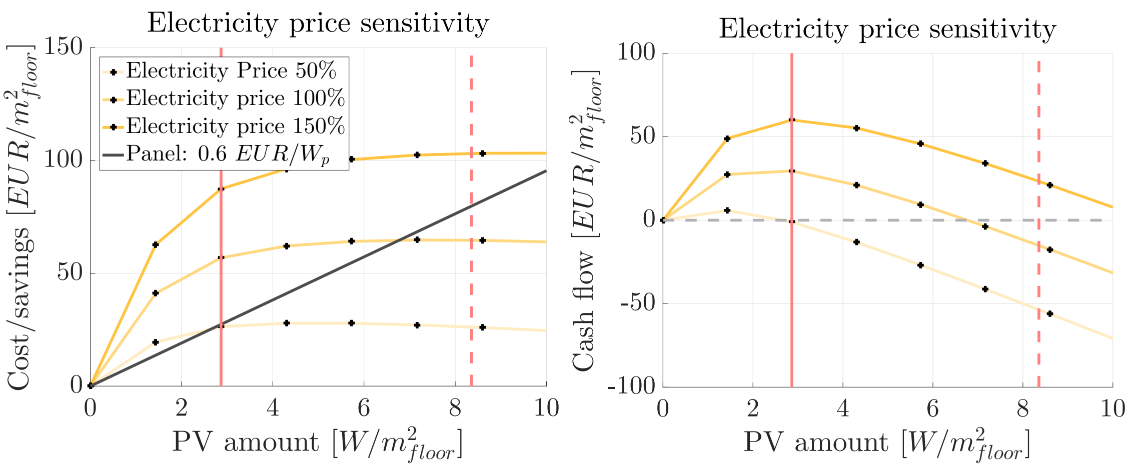


Figure 3.18: Influence of electricity price on lifetime PV profits for a FIT of 0.

3.5.2.4 Battery size and price sensitivity

As mentioned earlier, the battery price makes up only a tiny fraction of the overall system costs. Its influence on the overall business case is therefore tiny. The most important consideration is whether the addition of a battery actually results in a net profit increase. After that, the ROI is another important consideration. Lastly, a battery system decreases the risk of a possible future electricity price increase.

In the following Figures, the green line indicates the additional investment cost for a battery system.

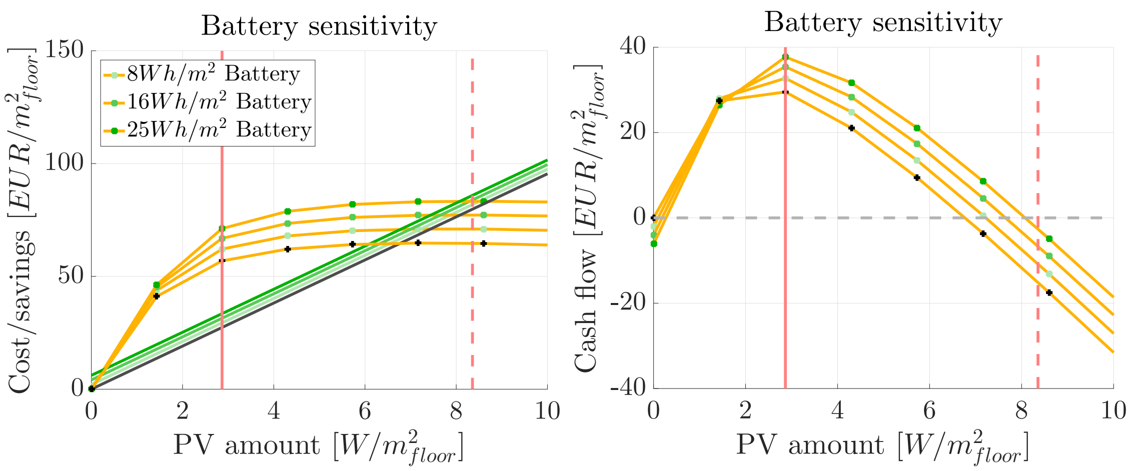


Figure 3.19: Influence of battery size on lifetime PV profits for a FIT of 0.

In Figure 3.19 it can be observed that for a battery only system, the addition of a battery results in an increased profit, as was found earlier in Section 3.3.2. This battery addition results in an increased overall profitability for a PV production of over $2W/m^2_{floor}$.

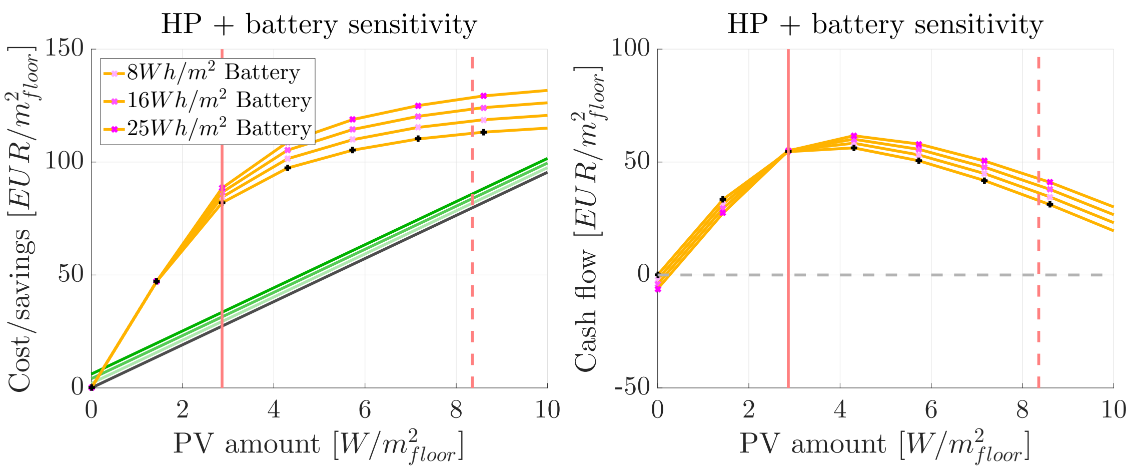


Figure 3.20: Influence of battery size for a system with a heat pump on lifetime PV profits for a FIT of 0.

For a battery plus heat pump system, the overall electricity savings are much higher due to the addition of a heat pump. Again, it can be observed how the addition of a battery is nearly profitable and does not change much for various battery sizes at the current PV production of $2.34W/m^2_{floor}$. For greater PV production the business case becomes more attractive.

Overall, the addition of a battery system does neither poses a great economical benefit nor risk for a battery plus heat pump system.

3.5.2.5 System sensitivity

In Figure 3.21 we can once again see that the most profitable system includes a heat pump, and that the addition of a battery is optimal for the current levels of PV production.

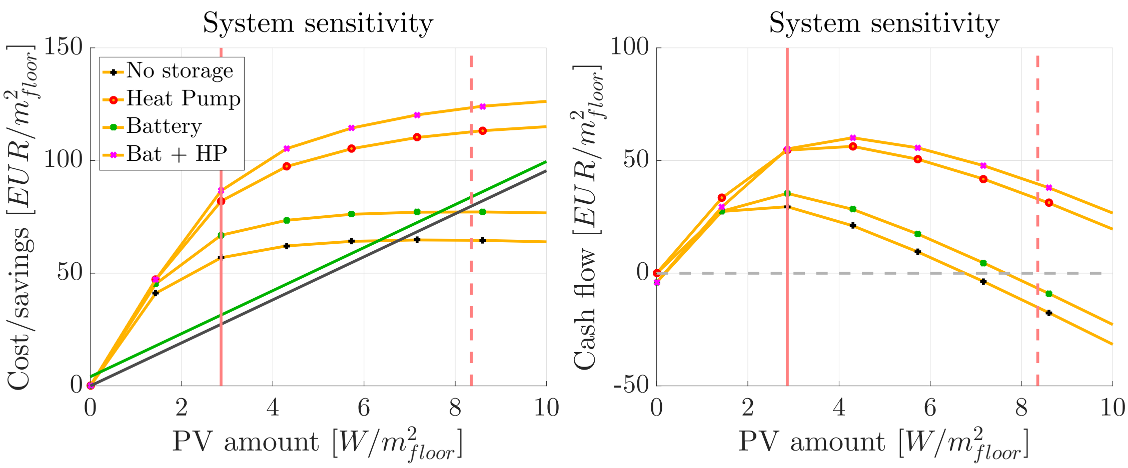


Figure 3.21: Influence of different system configurations on lifetime PV profits for a FIT of 0.

4

Discussion

The technoeconomic optimal energy system configuration consisting of heat pump, solar PV and battery has been successfully determined for a 1970s multi-apartment building in Treviso, Italy. By installing a PV production capacity of $2.87W/m^2_{floor}$, a $3.96W_e/m^2_{floor}$ heat pump with a $3l/m^2_{floor}$ hot water storage tank, and a $17Wh/m^2_{floor}$ Li-ion battery; self-consumption of electricity increases by 48% from 0.62 to 0.92, while 32% of the building's energy is produced autonomically. At a building level, this corresponds to a PV system size of $393kW_p$, a $490kW_p$ heat pump with a $36.7m^3$ hot water storage tank, and a $208kWh$ Li-ion battery.

From a financial perspective, a total amount of $318.25€/m^2_{floor}$ in utility costs can be saved over a 20 year time period, or $3.89M€$ at a building level. The ROI of the system as whole is 273.21%, and therefore makes for a good business case. This is mostly (for 70%) attributable to the gas savings from the heat pump, with an ROI of 324.09%. The electrical side of the energy system is less profitable mostly due to a lower ROI on the tank (52,58%) and a negative ROI (-11,69%) of the Li-ion battery. The solar PV system, however, makes for a good investment with an ROI of 212,29%.

4.1 Model uncertainty

The results listed previously require a bit of context to properly interpret. Important boundary conditions are ingrained in the models themselves, such as building composition, geometry and occupant behaviour are crucial to the validity of the results. Although great care was taken to establish the case study as generic as possible, the business case will vary from case to case. It is therefore important to bear in mind the uncertainties inherent in the Building Model and Energy System Model.

The ratio between roof area and floor area of 0.33 for a multi-story apartment building is equal to the ratio found for the 'generic apartment' building type by the ENTRANZE project, which assessed heating and cooling demand for different building types in the EU [45].

In addition, their simulated heat demand was $11.41W/m^2_{floor}$ (excluding DHW) for an apartment building in Milan, which is nearly equal to the $11.06W/m^2_{floor}$ (excluding DHW) resulting from the BM simulation in this thesis.

However, DHW heat load was $1.89W/m^2_{floor}$ for the ENTRANZE project, while it was $5.0W/m^2_{floor}$ according to ATER. In addition, the cooling demand following from the ENTRANZE project, was $1.81W/m^2_{floor}$, almost four times as much as the $0.5W/m^2_{floor}$ provided by ATER. The data from ATER may have been unreliable, as there was no central cooling system present and DHW was only measured for one apartment block. If cooling demand turns out to be higher, this will have a positive effect on self-consumption, but a negative effect on self-production while the business case for the battery will improve slightly. If DWH heat load turns out to be lower, this will have a negative effect on self-consumption but a positive effect on self-production. For a more accurately quantified statement see Figure 3.14.

Other model uncertainties are present as well. As was seen in Section 2.2, there were some local discrepancies between the DesignBuilder model and the PVGIS and ATER models. The PVGIS model related to the solar PV production, which turned out to have similar output to the DesignBuilder model on average, yet differed 30% locally. During summer, PVGIS predicted lower production, while in winter it predicted higher production. If PVGIS is correct, the less eccentric shape of PV production will have a positive effect on both self-consumption and production, for similar total PV production.

Similarly, for the building heat loss, the ATER model simulated equal yearly average production, while differing up to 30% locally. ATER simulated a higher heat loss during winter and lower heat loss during spring and autumn. The increased imbalance between summer- and winter heat load will have a negative effect on both self-consumption and production for equal total heat demand.

In both cases, it is not possible to determine which model yields more accurate results. This would require extensive investigation into the mechanics of each model, the data of which is not available for both the PVGIS and ATER model.

All in all, the difference in outcome with regards to the self-consumption and corresponding economic feasibility will be significant. Although the averages may be the same, it is precisely the shape of the load profiles that is so important for the calculation of the hourly self-consumption. The maximum local difference of 30% is therefore an indication of the model uncertainty.

On top of that, real-life situations will yield differently shaped load profiles than the ones modelled by ENTRANZE, ATER, PVGIS or this thesis. In order to validate the models used in this thesis, real-life measurements will have to take place. These measurements have to validate the Building Model, the individual load profiles and the Energy System Model. This can be done by providing hourly data for electricity consumption, heat demand and PV production in combination with accurate climate- and component data.

4.2 Parameter sensitivity

Although great care was taken in the modelling of the building and its energy system to ensure realistic energy simulations, the output data can only be as accurate as the input data.Therefore, if there is an error in the data, or if the results are to be applied to a broader range of cases, knowledge on the influence of different parameters is required. To show the effect of input data uncertainty and the influence of parameter variation, a sensitivity analysis has been performed for the technical and economical part.

To illustrate the interpretation of the sensitivity analysis, consider a similar building in a different location in Europe, with a similar climate, that is better insulated and has a more optimal orientation towards the sun. The heat demand will be lower due to better insulation, the electricity demand may vary slightly and the electricity production will be higher. By examining the effect of these sensitivities shown in Figure 3.14, a building owner can make an educated guess on the effect on self-production and consumption. By using the self-production and consumption figures and applying Equations 3.5 and 3.6, an estimate on the total grid savings potential can be made.

The accuracy of the educated guess is then dependent on the actual shape of the corresponding load profiles of the building, which may be slightly different locally from the one modelled in this thesis (instead of just being scaled by a factor). However, the general relationships should remain intact. For instance, extra insulation may reduce the length of the heating season by several weeks (an effect that reduces self-consumption), but the general imbalance between summer- and winter heat load will remain. Similar effects are present in PV production (e.g. more morning production due to orientation) and electricity demand (e.g. reduced electricity demand in summer due to no air conditioning). Effects that are, again, dominated by larger effects (production around noon is much higher than at dusk or dawn, and electricity demand will be higher in the mornings and evenings). Scale will therefore generally be more important than local profile variation. Still, these local effects on load profile shape should be considered.

A more pronounced influence of parameter sensitivity can be found at the economical side of the simulation, as the business case is very sensitive to economical parameters. The most dominant parameter is the electricity price, which has a direct correlation to grid savings: a 50% higher electricity price equals 50% more grid savings. The electricity price used in this thesis was 0.15€$/kWh$, although the EU-28 average is 0.22€$/kWh$ [46]. This means that, in most EU-28 countries, the business case for the PV-attached battery system is looking solid.

The battery price sensitivity has a very small effect on the overall system, but a great effect on the battery profitability. The ROI of the battery itself was negative, at -11.69%. This means that in order for the battery system to become profitable, a decrease in cost or an increase of 11.69% in savings has to be achieved. A decrease in cost can be achieved by (1) an extension of the battery lifetime or (2) a decrease in total battery costs (capital and operational). An increase in savings can be achieved by (3) an increased electricity price or (4) a more intensive use of the battery over its lifetime (i.e. by increasing self-consumption). All four events are very possible to occur in the future. With an annual Li-ion battery price drop of 6-9% [18], Li-ion batteries are set to become profitable for this case within 1-2 years, somewhere between 2017-2018.

As discussed in Section 2.3.2.1, a FIT of zero was assumed. This assumption is crucial to the validity of the results. Applying the results of this thesis' to other cases should therefore not be done without taking the FIT in consideration. A FIT higher than zero will negatively affect the business case for any self-consumption increasing component, be it heat pump, hot water storage tank, or Li-ion battery.

The other economical parameters such as investment costs and operational costs of the heat pump, solar PV and storage tank are important for the total costs and savings, but their economic feasibility is solid with an ROI bigger than 50%. Their feasibility is therefore not very prone to sensitivity.

A useful way to apply the results of the technical and economical sensitivity analyses, is to assess the potential of a building to become more self-sufficient, for instance by installing more solar panels. Self-sufficiency is desired when a building owner wants to reduce carbon emissions as much as economically possible. He will then want to maximise his self-production and self-consumption. Self-production is increased by adding PV generation capacity and increasing self-consumption, while self-consumption is increased through either tank or battery storage, but as we have seen in Section 3.3.3, once the heat demand is satiated there is hardly any increase in self-consumption for increased tank sizes. It thus becomes a matter of optimising PV- and battery capacity versus cost, shown in Figure 4.1.

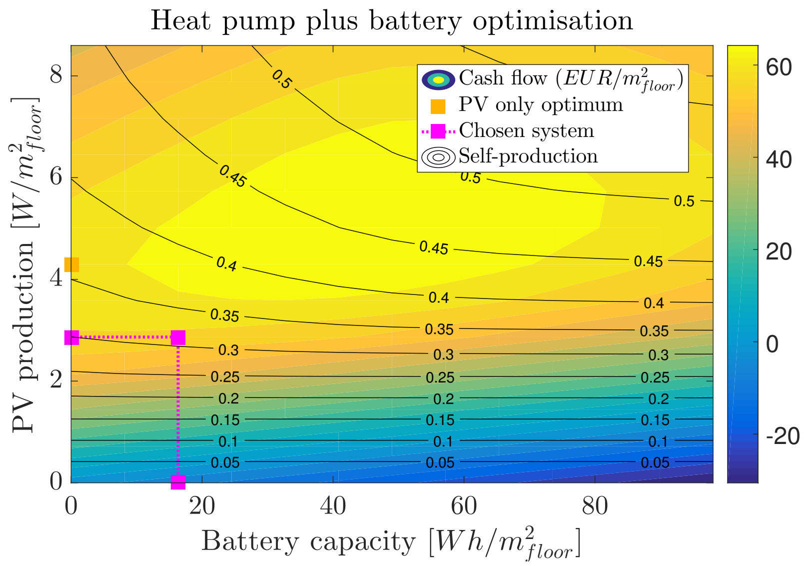


Figure 4.1: Cash flow (coloured area) and self-consumption (black contours) as a a function of PV generation and battery capacity for a heat pump plus battery system.

As can be observed by the brightest yellow area in Figure 4.1, the most profitable system configuration is, one that has roughly twice ($3 - 7W/m^2_{floor}$) the amount of solar PV production and a $20 - 80Wh/m^2_{floor}$ Li-ion battery. This means that it is not just economically feasible, but economically optimal, to have higher levels of both self-consumption and production (in absolute terms that is, not in terms of ROI).

However, a look at Figure 3.14 tells us that, for twice the amount of solar PV and Li-ion battery, self-production will still not exceed 0.50. The technical sensitivity analysis reveals just how difficult it is to have high levels of both self-production and consumption. Generally speaking, they have an inverse relationship: the higher the self-consumption, the lower the self-production, and vice versa. The self-production values in Figure 3.14 do not reach over 0.45 for a system with battery, heat pump, twice the amount of PV production and a corresponding (rather low) self-consumption of 0.63. An ideal house would have both self-production and consumption equal to one. A self-production equal to one means that the building can be completely detached from the grid, as all the energy demand is produced by the building itself. This gives an indication of how hard it is for to become completely grid-independent. The reason being, that there is a seasonal mismatch between energy production and consumption during winter and summer.

The only solution to have both high levels of self-production (>0.5) and consumption, is to have large amounts of both generation and storage. However, the required levels of production and storage in order to become completely autonomous are far beyond practical reality. The case assessed in this thesis has already assumed the best-case-scenario from a technical perspective. There is simply not enough space to have a PV-to-floor area ratio of more then 0.33, nor is it possible to store energy produced in summer to be used in winter. Therefore, unless some form of seasonal storage or non-PV energy production is utilised, it is very unlikely that apartment buildings will become more than 40% self-sufficient.

To sum up: the technical potential to increase self-consumption and PV production, and the economical potential to reduce utility cost savings, is very clear and largely independent of parameter sensitivity. The results of this case study can therefore safely be applied to similar cases, taking into account any difference sensitivities. On the condition that the electricity price is similar or higher and the FIT is indeed zero, the only exception to the generally clear feasibility is the Li-ion battery. The Li-ion battery is not yet economically feasible, but a slight change of boundary conditions such as battery price or PV production will tip it over the edge into feasible territory.

4.3 Result validity

As mentioned in Section 1, several studies have been conducted assessing similar setups as this thesis. A piece-by-piece comparison of their results will be provided below:

Naumann et al. (2015) assessed the cost of PV-attached battery systems in Germany, for an electricity price of 0.30€$/kWh$, and a FIT of 42%. They ran two scenarios; one for a battery cost of 450€$/kWh$ and strong ageing (efficiency reduction over time) of the battery, and a second one for a battery cost of $300EUR/kWh$ with normal ageing. They did not include a heat pump in their simulations, so their results have to be compared to the battery only simulation of this thesis. They found that for an electricity demand of $4.4MWh/m^2/a$ and an installed PV capacity of $4.4kW_p$, the optimum battery size was $4.4kWh$ [35]. In our case, the electricity demand is 106 times higher ($470MWh/a$), and the installed PV capacity is 89 times higher ($393kW_p$), with the optimum battery only size being roughly a hundred times greater as well ($550kWh$). The optimum battery size is equal to $1kWh$ for Naumann et. al and $1.20kWh$ for this thesis for every $1kW_p$ of PV storage. Strangely enough, the battery was found to be less profitable for an electricity price twice as high as used in this thesis, which makes their Li-ion battery profitability results differ from this thesis' by a factor of two. The FIT of 42% could be the reason for the deviating results, although it is hard to say with certainty; as there is no explicit data available on their PV system, self-consumption rate or load profiles. Still, they assessed a similar battery price of 250 €/kWh to become profitable.

Balcombe et. al (2015) ran a simulation over 30 households in the UK with different demand profiles, for a PV-attached battery system in combination with a micro-CHP (combined heat power) unit. They found that, for an average electricity demand of $373W$ and an average PV generation of $310W$ (corresponding to roughly $3kW_p$ for a capacity factor of 12%), the optimum battery size is $3kWh$. So again, $1kWh$ of battery installed for every $1kW_p$ of solar PV. Without a battery installed, self-consumption of solar PV electricity was found to be 51%. The increase in self-consumption by installing a battery was 27% on average. These findings match the technical results of this thesis. The effect of the micro-CHP unit on the results can be considered small since the self-consumption rate of CHP power was over 80%. [19]

Zucker and Hinchcliffe explored the economic feasibility for a PV-attached battery system in Italy and Germany. They concluded that in Italy, a battery price of 250€$/kWh$ is required to reach profitability. This is under the condition of a battery only system, no FIT, a PV production equal to the electricity demand. This is in line with the findings of this thesis, where the battery is nearly profitable at 300€$/kWh$, for a PV production less than electricity demand ($2.9W/m^2_{floor}$ and $4.3W/m^2_{floor}$ respectively). [25]

Williams et. al found that for a four-person household with a heat pump and $5.5kW_p$ of solar PV production, the optimum battery size was $5kWh$. So again, roughly $1kWh$ of storage for every $1kW_p$ of solar PV generation. Their research was very similar to the one of this thesis, as they also focused on self-consumption and self-production for a zero-energy building, in Germany instead of Italy. They found self-consumption levels between 0.55 to 0.65 for a four-person household with low insulation, similar to the 0.62 found for the apartment building in this thesis (also having poor insulation). Moreover, at a generation capacity equal to the energy demand, the self-production (and thus self-consumption as well) was 0.46 with battery, which is exactly the result found in this thesis as well. For other cases (with/without heat pump or battery) the results were very similar as well. This gives a good confirmation of the validity of the technical results found in this thesis. Battery price, however, was not considered. [26]

Thygesen et. al. (2013) found a default self-consumption level of 56% [12], which is close to the 0.62 found in this thesis. In addition, they found self-production levels of 0.28 for a $138m^2$ single house with roof-mounted PV (0.25 for this thesis). The geometry of their setup is vastly different (single house versus a multi-story apartment building), but the fact that the self-production is similar can be attributed to having facade-mounted versus roof-mounted PV panels. A self-production of around 25-28% is therefore appropriate for both facade-mounted multi-apartment buildings as well as roof-mounted single houses, who together represent a large part of the building stock.

All in all, the findings of this thesis are not extremely different from other research, although comparison remains difficult due to the vast set of boundary conditions that varies from research to research. Parameters such as PV production tend to be close (factor 1.5 max deviation) to electricity consumption, with default self-consumption around 0.55 to 0.65, increasing by 21-25% due to battery. Corresponding self-production levels are between 25-28%. As a rule of thumb, optimal battery size seems to be around $1kWh/kW_p$ for systems without a heat pump.

Conclusions on the economical side are more sensitive to boundary conditions, especially FIT and electricity price. Still, it seems that there is general scientific consensus that Li-ion batteries will become profitable once their price drops a little bit more, (below $250 - 200\$/kWh$), even for systems with a heat pump. If the current annual cost decrease trend of 6-9% continues, this will result in a battery price between 130-170$ by 2025. It is safe to say that by this point the investment costs will be low enough for Li-ion battery systems to gain widespread traction, especially when renewable energy incentives have been gradually phased out.

5

Conclusion

The goal of this thesis was to find the optimal system configuration for a typical residential apartment building with a PV-attached Li-ion battery and heat pump, from both a technical (self-consumption) and economical (savings) stance. The decision was made to perform a case study for Treviso, Italy, due to the availability of detailed building data, as well as the typicality of the building to a large portion of the European building stock.

The optimal system configuration is reached by installing as much solar PV as building geometry allows, resulting in a PV-to-floor area ratio of 0.33. The corresponding self-consumption is 0.62, which is increased to 0.87 by installing a $3.96W_e/m^2_{floor}$ heat pump with a $3l/m^2_{floor}$ hot water storage tank, and to 0.92 by installing an additional $17Wh/m^2_{floor}$ Li-ion battery. 25% of all energy demand is then self-produced.

The overall business case of this system is very good, with an ROI of 273.21% over a 20 year time period. On a building level, $3.89M€$ can be saved. This is for 70% attributable due to gas saved by the heat pump with an ROI of 324.09%. The electrical part of the system has a more ambiguous business case, with an overall ROI of 195% (mostly due to solar PV), but a negative ROI of -11.69% for the Li-ion battery.

The Li-ion battery, being the most controversial part of the system, is very close to being economically feasible, however. In this case, economic feasibility for the battery can be quickly reached by installing roughly 10% more PV capacity, having a higher electricity price, or a slight battery price drop to $250€/kWh$. For other cases, sensitivity analyses and various research draw similar conclusions on the near-profitability of domestic Li-ion batteries.

Retrofitting old apartment buildings with a PV-attached battery and heat pump system is therefore a good strategy to reduce both utility costs and carbon emissions. With countries looking to abolish their FIT and Li-ion battery price expected to drop 6-9% annually, this retrofitting strategy will only become more attractive.

By 2025, the widespread implementation of PV-attached battery and heat pump systems can help to reduce carbon emissions significantly in an economically feasible way.

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A

Building data

Figure A.1: Building layout. Top: NE view. Bottom: SW view. Source [43]

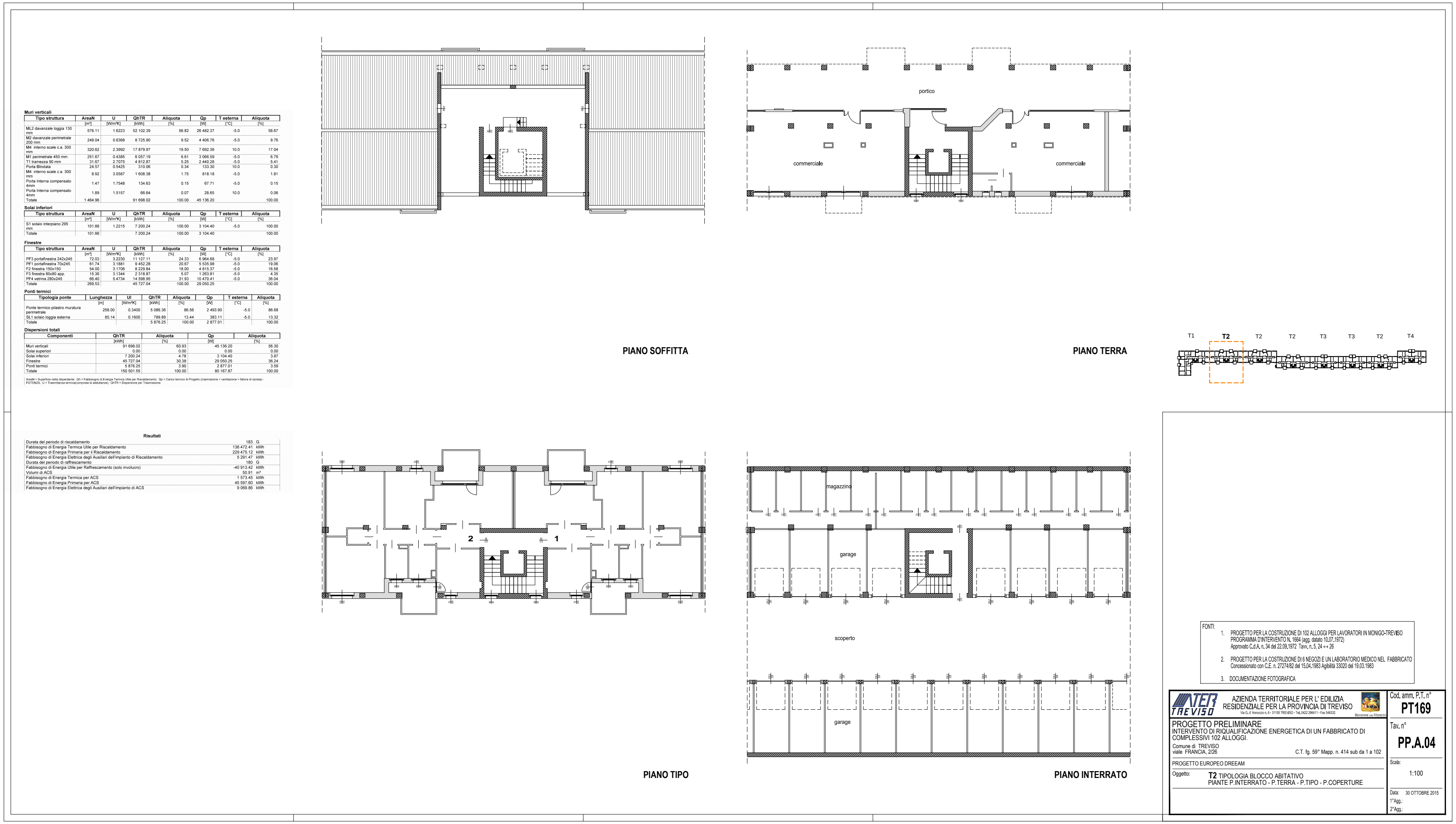


Figure A.2: Blueprint of block T2. Source: [43]

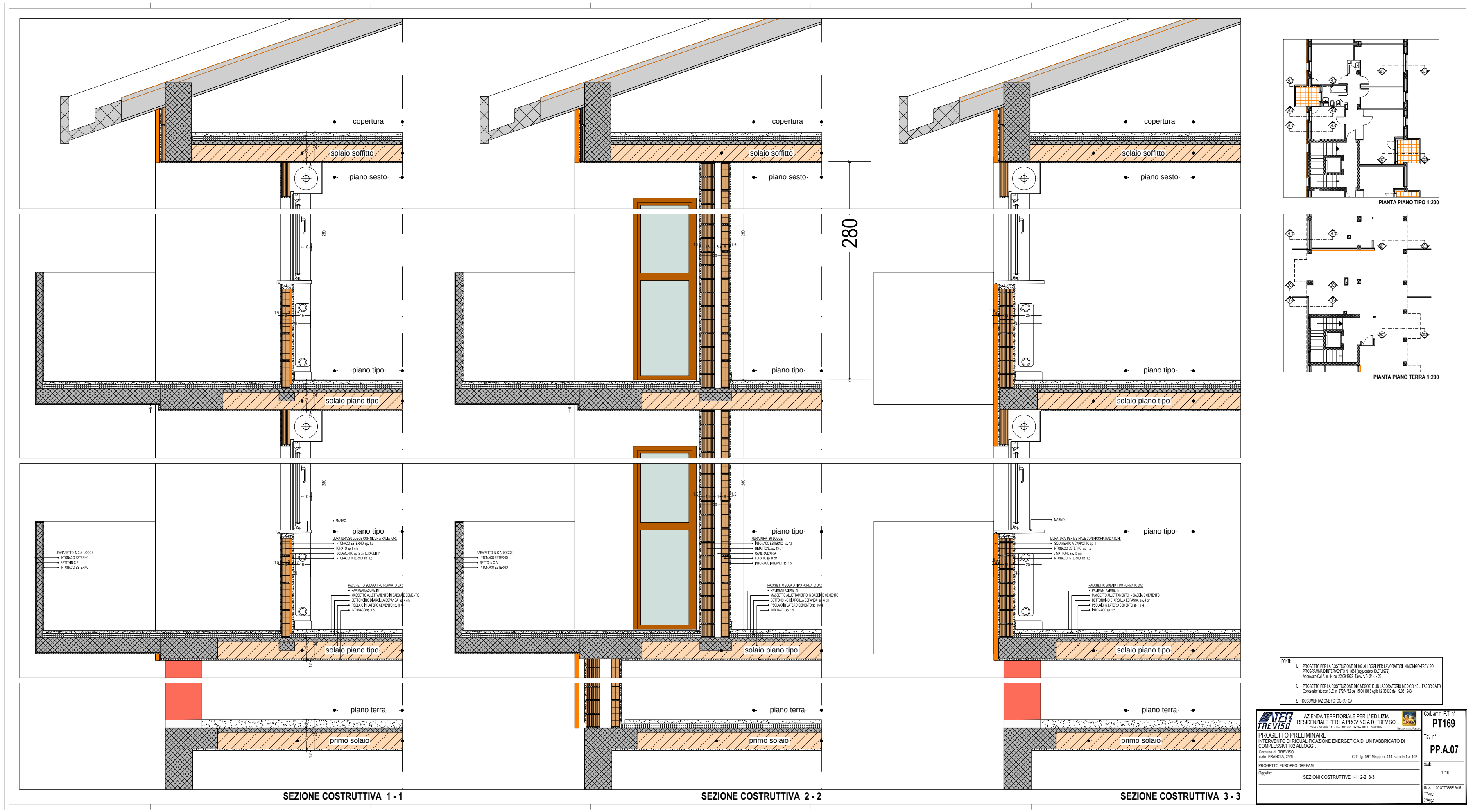


Figure A.3: Cross section of the building. Source [43]

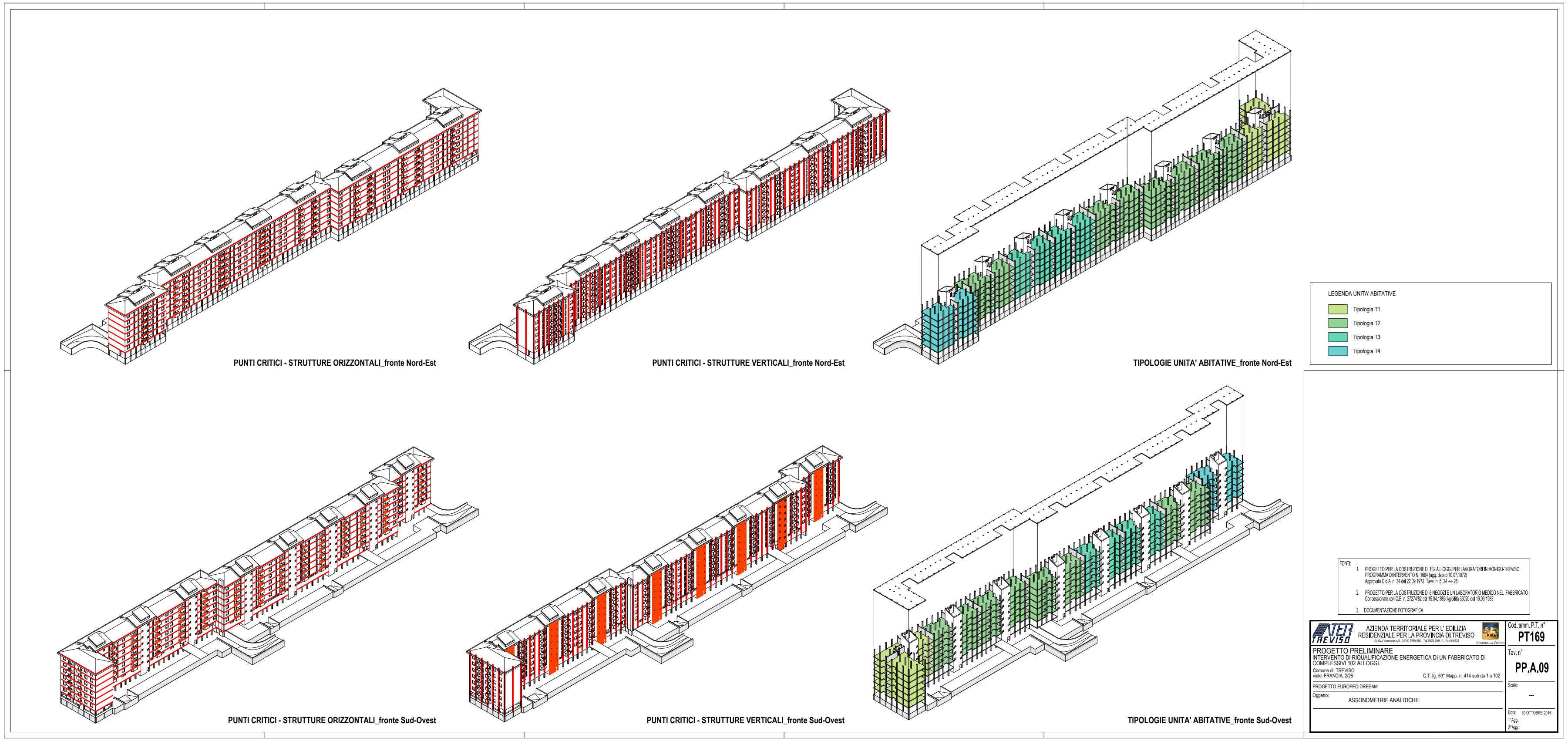


Figure A.4: Axionometrical view of the building and its underlying construction. Source [43]

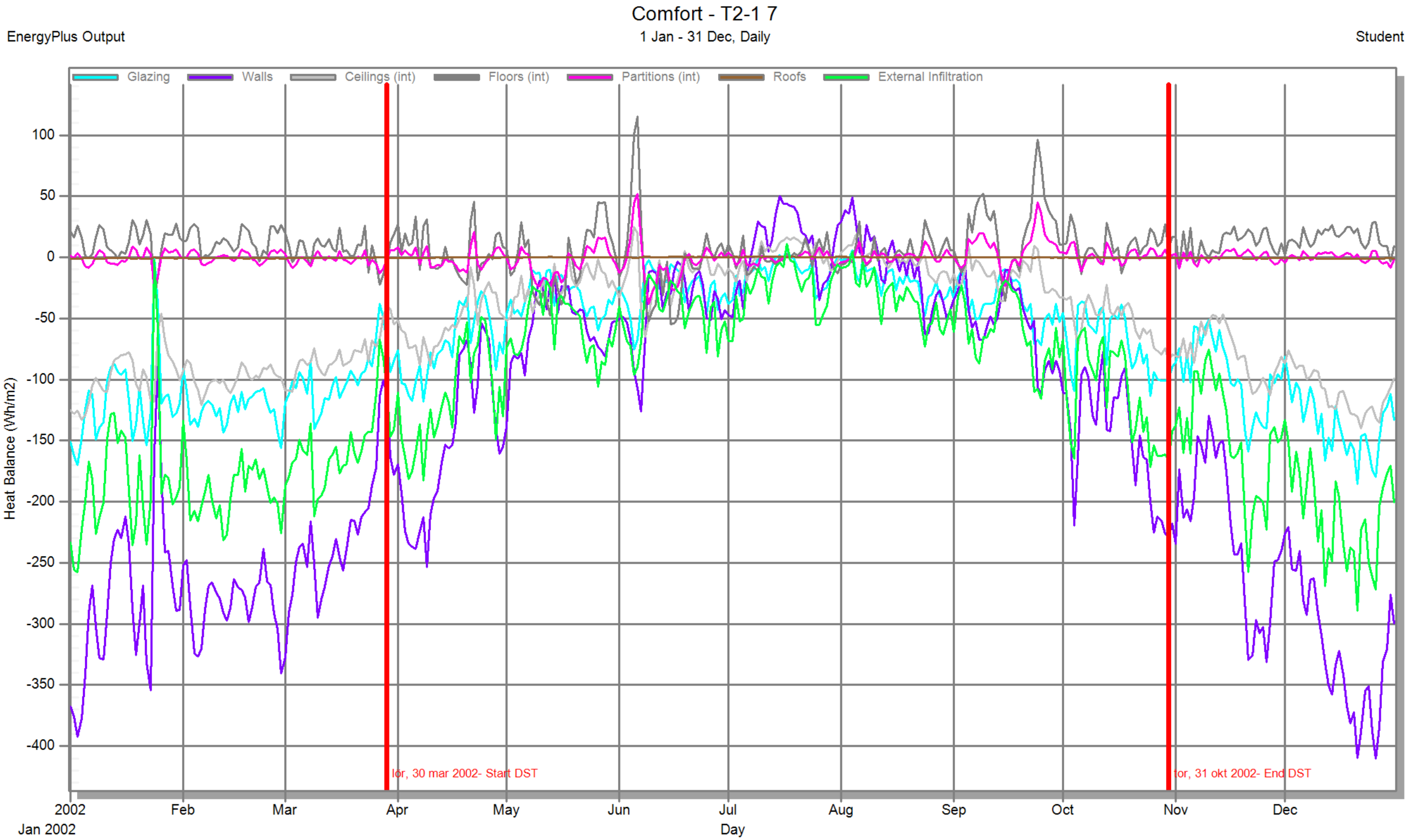


Figure A.5: DesignBuilder fabric heat gains and losses output data for block T2. Source [47]

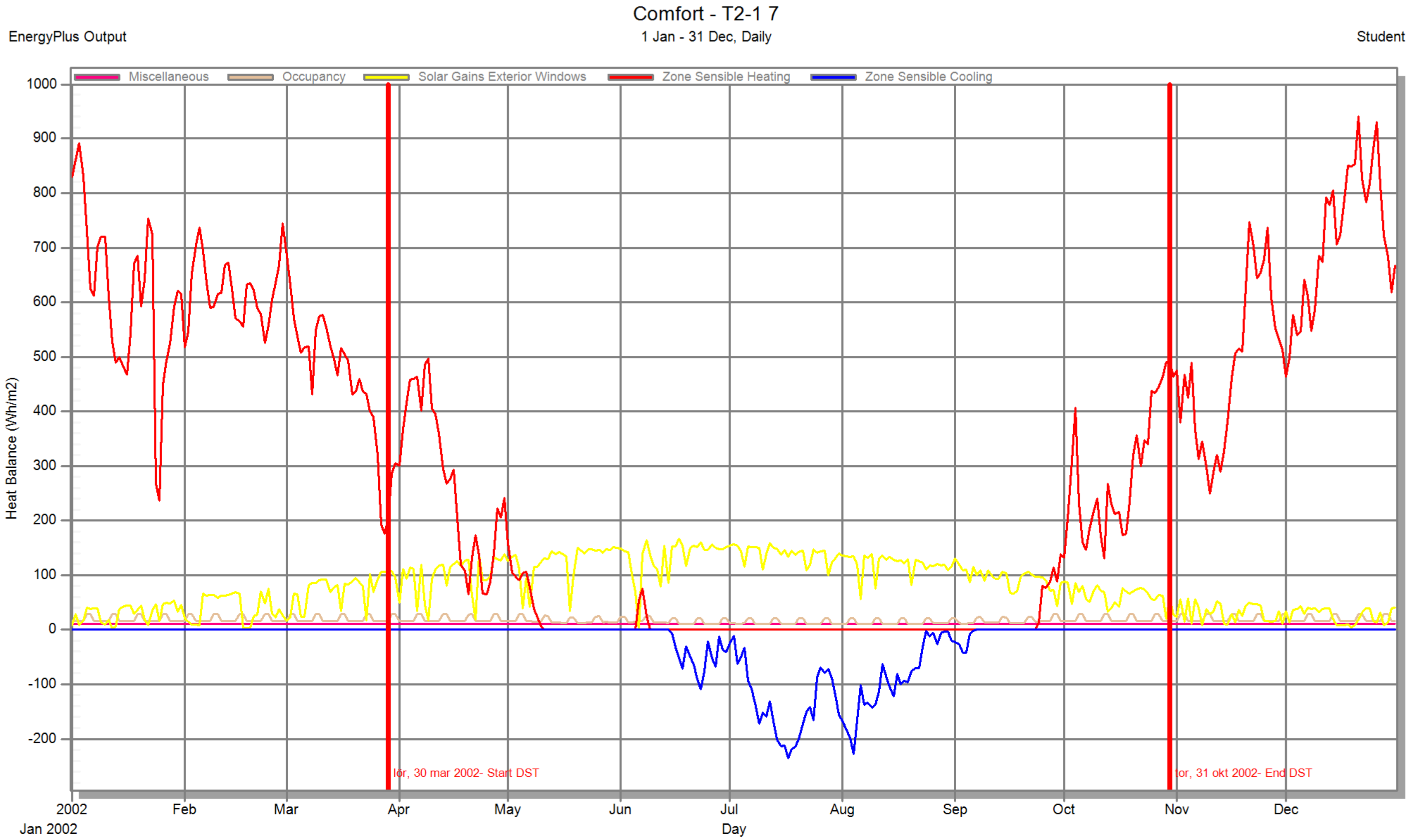


Figure A.6: DesignBuilder heating, cooling and solar gains output data for block T2. Source [47]

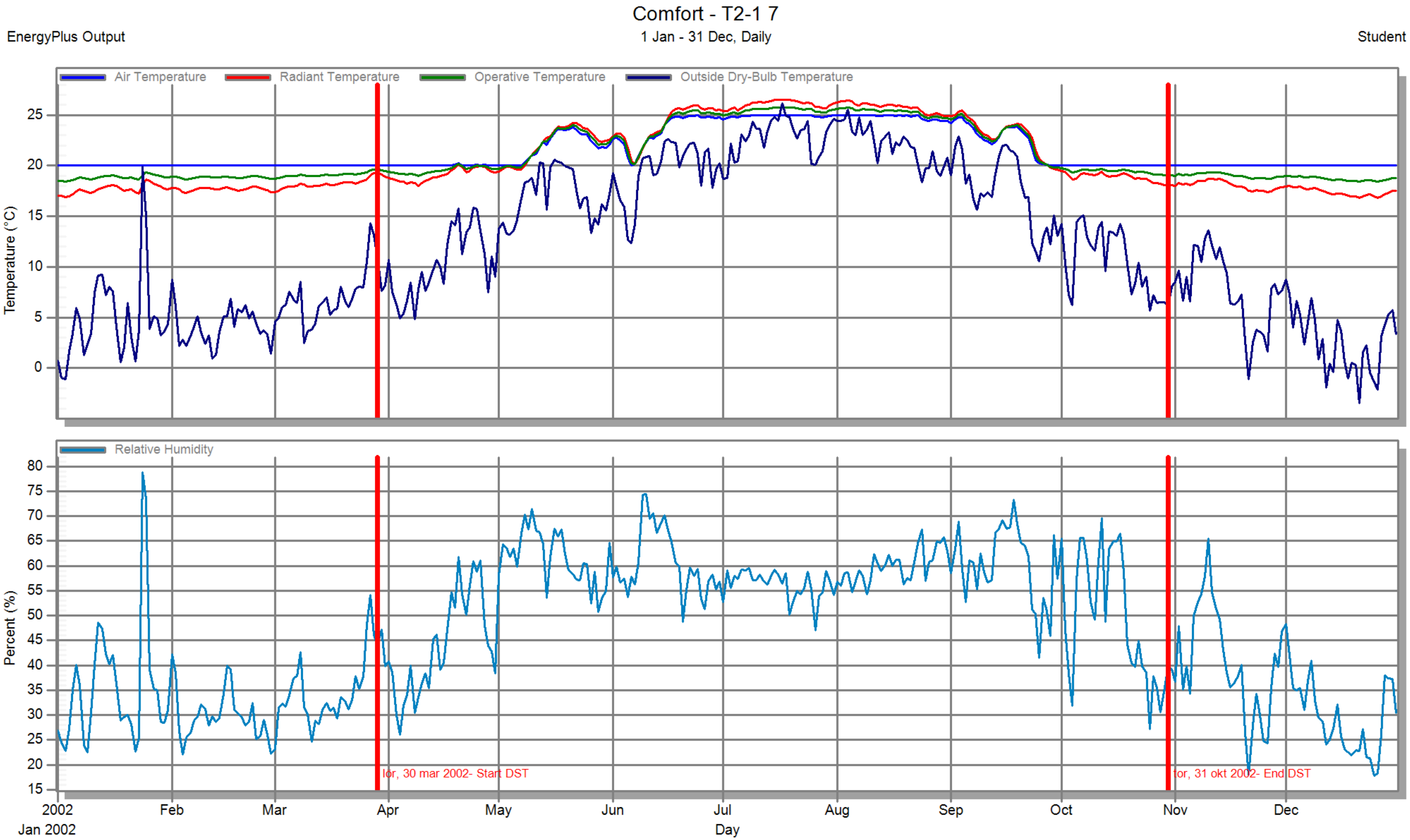


Figure A.7: DesignBuilder comfort output data for block T2. Source [47]

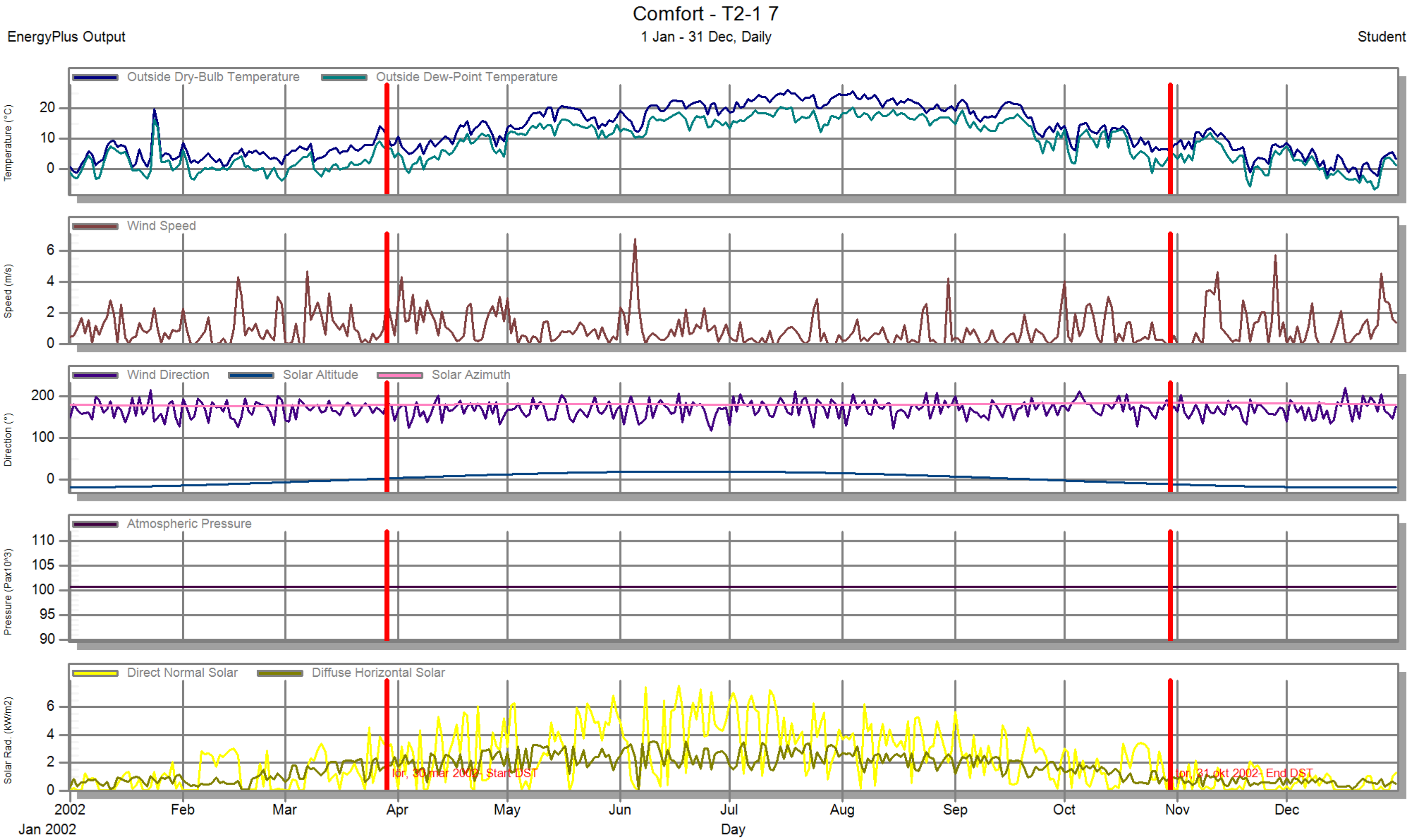
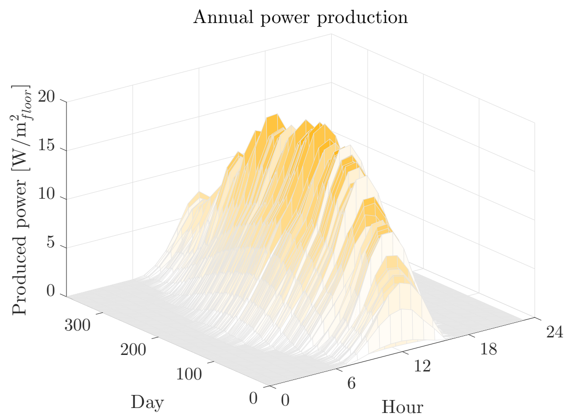
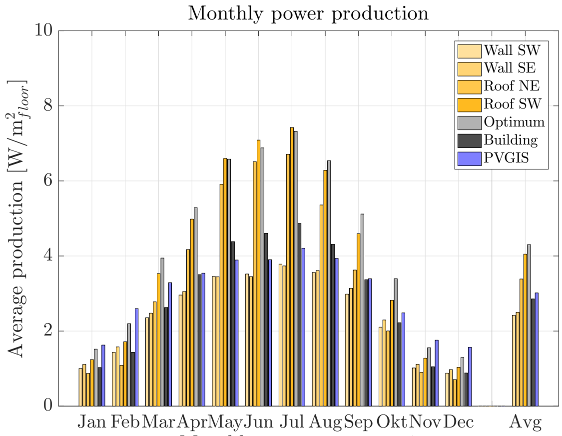


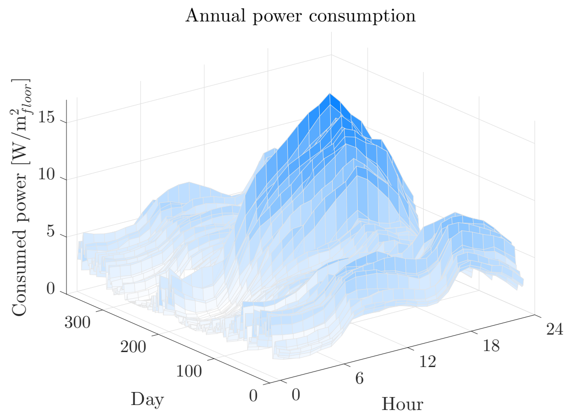
Figure A.8: DesignBuilder site data for block T2. Source [47]

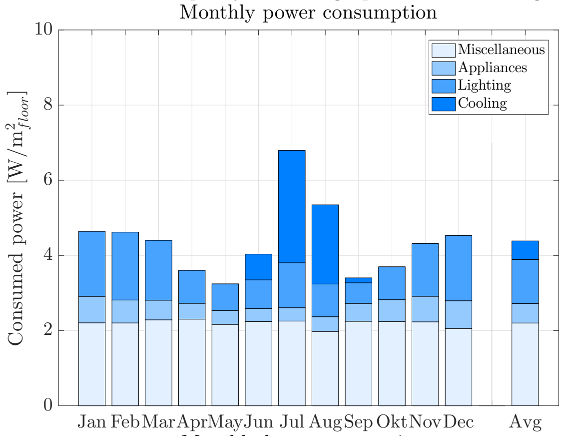
B

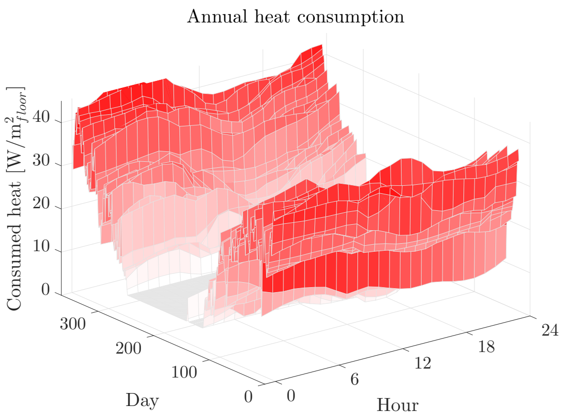
Model data

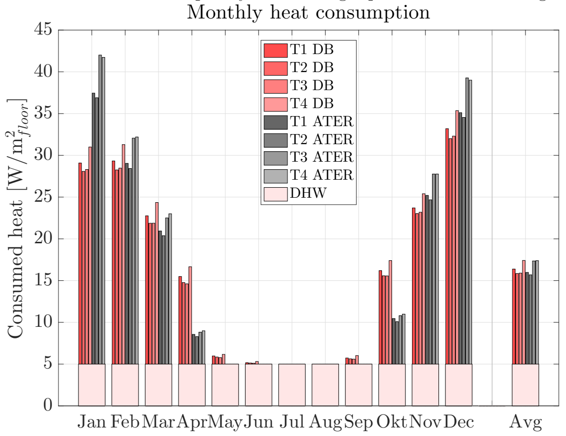

Annual power production
Produced power [W/m^2_{floor}]
20
15
10
5
0
300
200
100
0
Day
0
6
12
18
24
Hour

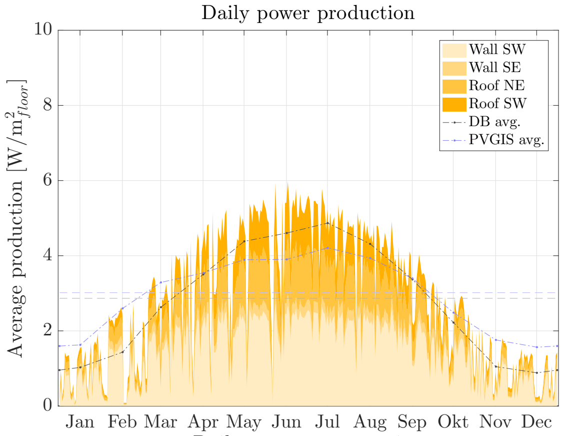

Monthly power production
Average production [W/m^2_{floor}]
10
8
6
4
2
0
Wall SW
Wall SE
Roof NE
Roof SW
Optimum
Building
PVGIS
Jan Feb Mar Apr May Jun Jul Aug Sep Okt Nov Dec Avg

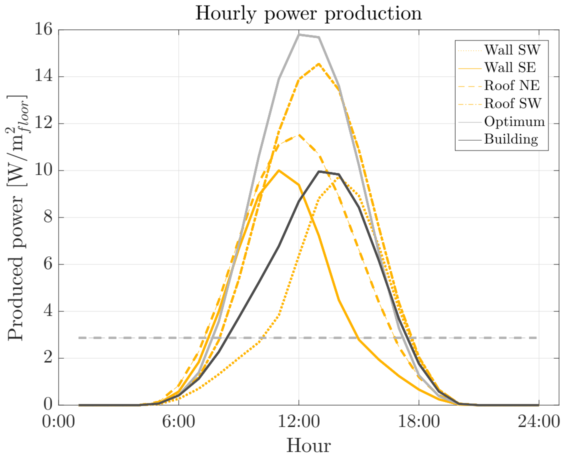

Annual power consumption
Consumed power [W/m^2_{floor}]
15
10
5
0
300
200
100
0
Day
0
6
12
18
24
Hour

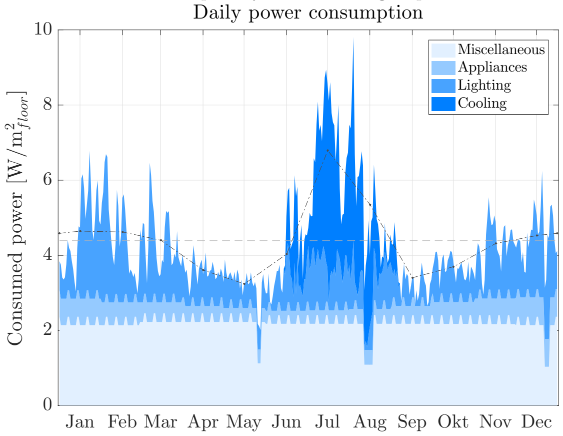

Monthly power consumption
Consumed power [W/m^2_{floor}]
10
8
6
4
2
0
Miscellaneous
Appliances
Lighting
Cooling
Jan Feb Mar Apr May Jun Jul Aug Sep Okt Nov Dec Avg

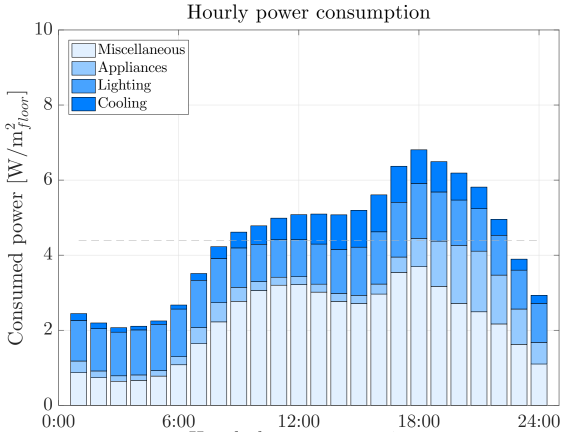

Annual heat consumption
Consumed heat [W/m^2_{floor}]
40
30
20
10
0
300
200
100
0
Day
0
6
12
18
24
Hour

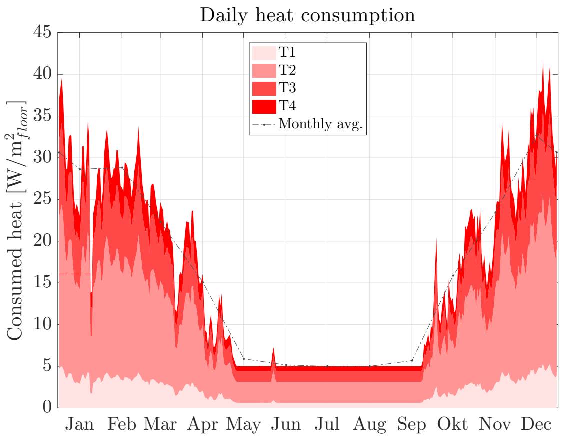

Monthly heat consumption
Consumed heat [W/m^2_{floor}]
45
40
35
30
25
20
15
10
5
0
T1 DB
T2 DB
T3 DB
T4 DB
T1 ATER
T2 ATER
T3 ATER
T4 ATER
DHW
Jan Feb Mar Apr May Jun Jul Aug Sep Okt Nov Dec Avg

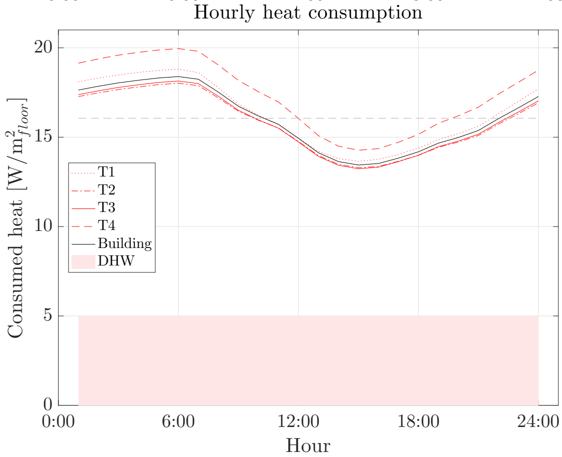

Daily power production
Average production [W/m$^2_{floor}$]
Wall SW
Wall SE
Roof NE
Roof SW
DB avg.
PVGIS avg.
0
2
4
6
8
10
Jan Feb Mar Apr May Jun Jul Aug Sep Okt Nov Dec


Hourly power production
Produced power [W/m$^2_{floor}$]
Wall SW
Wall SE
Roof NE
Roof SW
Optimum
Building
0
2
4
6
8
10
12
14
16
0:00 6:00 12:00 18:00 24:00
Hour

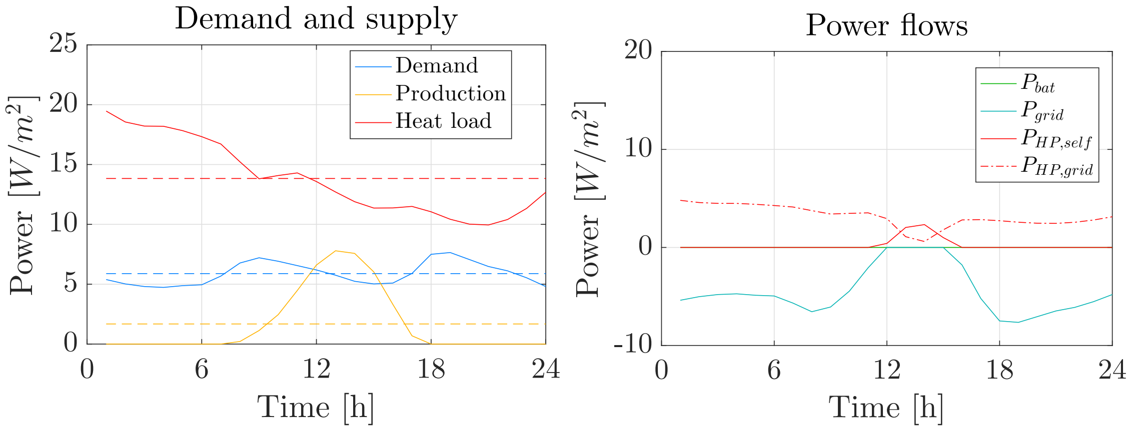

Daily power consumption
Consumed power [W/m$^2_{floor}$]
Miscellaneous
Appliances
Lighting
Cooling
0
2
4
6
8
10
Jan Feb Mar Apr May Jun Jul Aug Sep Okt Nov Dec


Hourly power consumption
Consumed power [W/m$^2_{floor}$]
Miscellaneous
Appliances
Lighting
Cooling
0
2
4
6
8
10
0:00 6:00 12:00 18:00 24:00

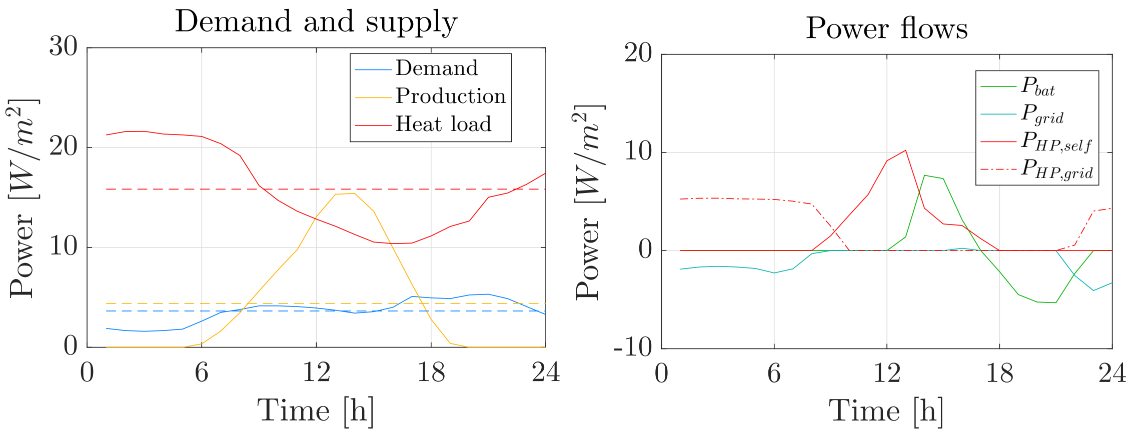

Daily heat consumption
Consumed heat [W/m$^2_{floor}$]
T1
T2
T3
T4
Monthly avg.
0
5
10
15
20
25
30
35
40
45
Jan Feb Mar Apr May Jun Jul Aug Sep Okt Nov Dec


Hourly heat consumption
Consumed heat [W/m$^2_{floor}$]
T1
T2
T3
T4
Building
DHW
0
5
10
15
20
0:00 6:00 12:00 18:00 24:00
Hour

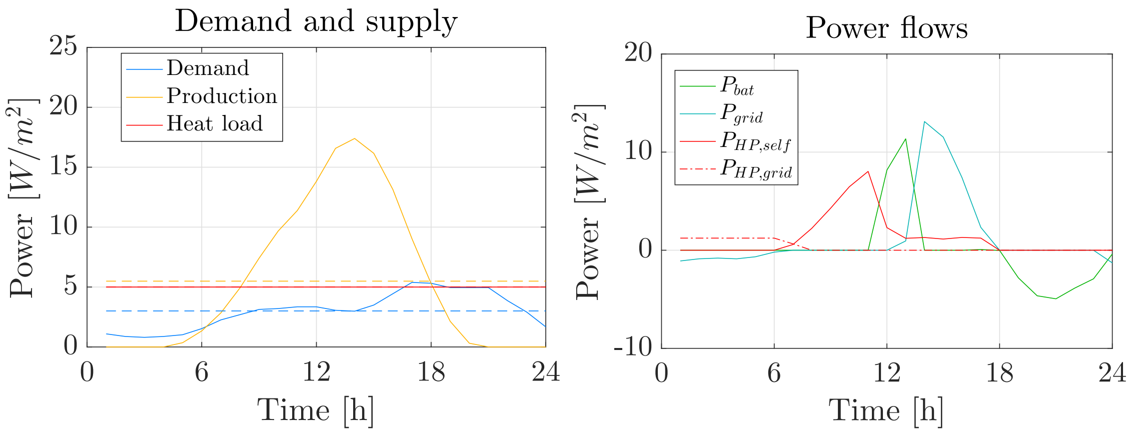
January 24



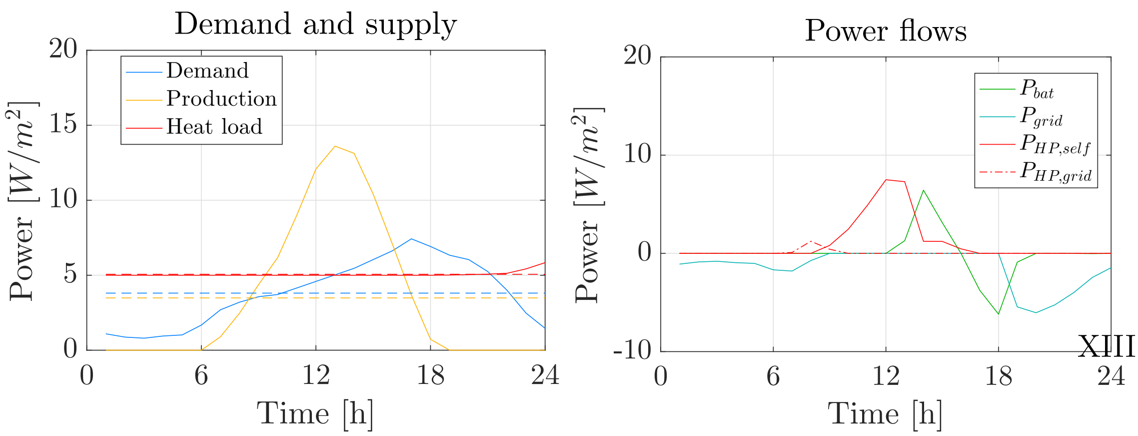
April 13



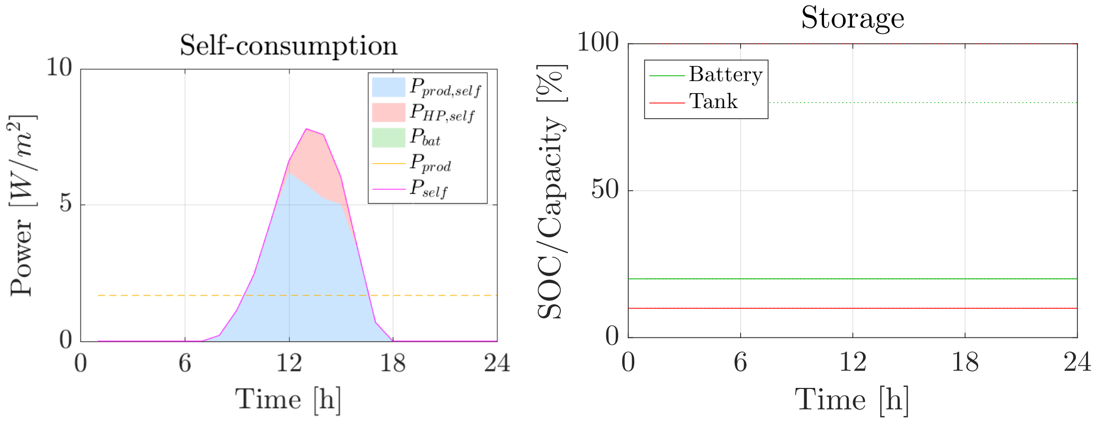
June 13



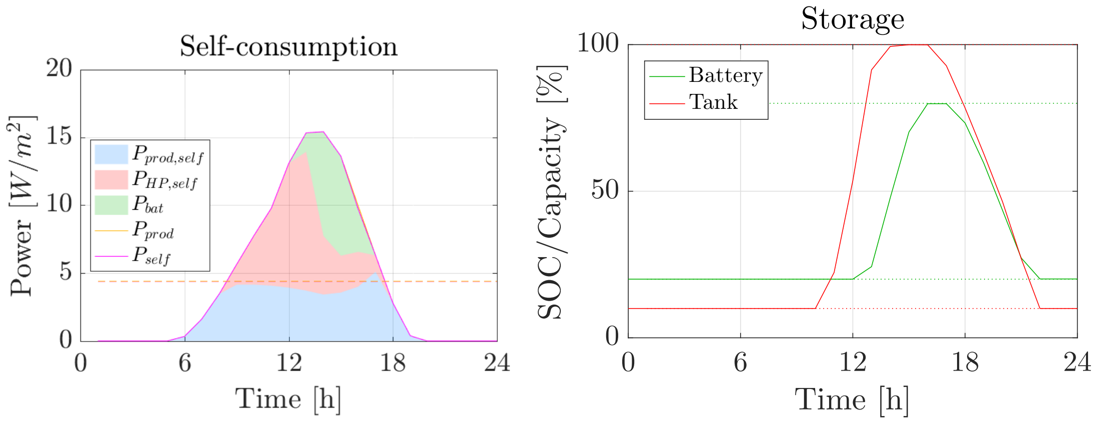
September 23



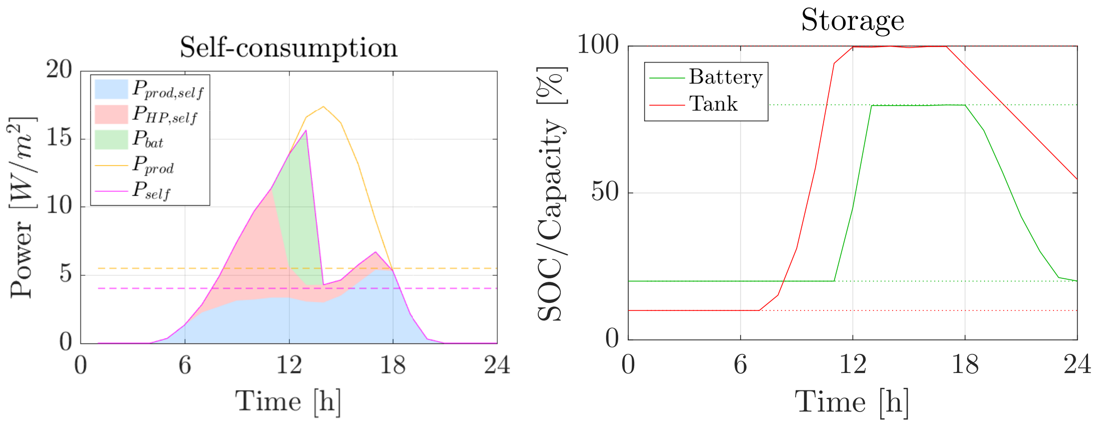
January 24



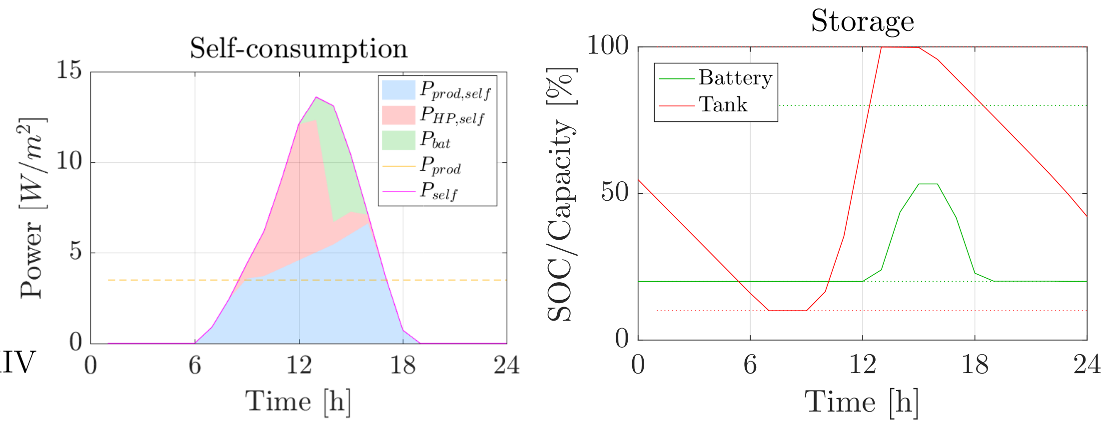
April 13



June 13

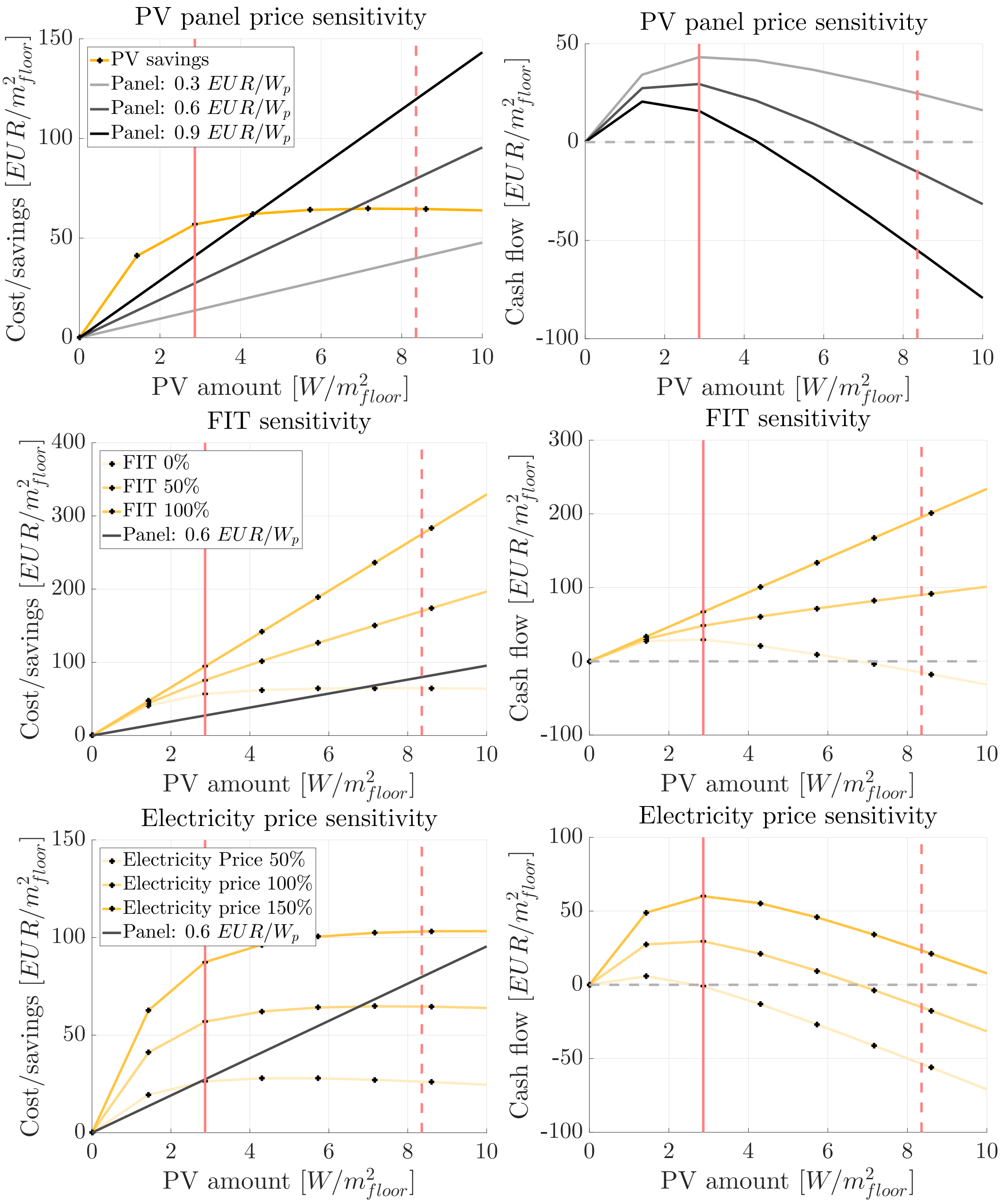


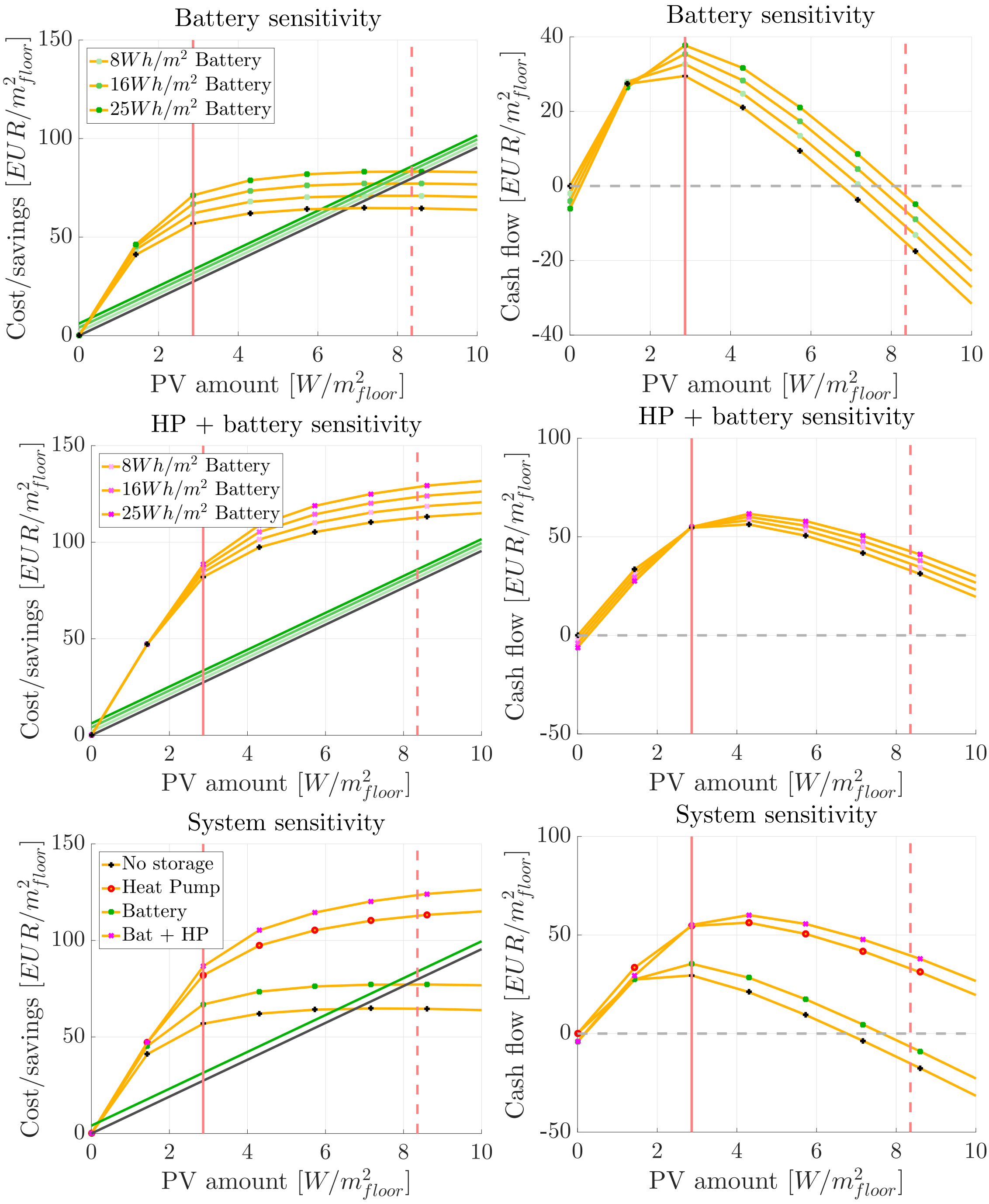
September 23



C

Economical data





Battery sensitivity
Cost/savings [EUR/m^2_{floor}]
$8Wh/m^2$ Battery
$16Wh/m^2$ Battery
$25Wh/m^2$ Battery
PV amount [W/m^2_{floor}]
Battery sensitivity
Cash flow [EUR/m^2_{floor}]
PV amount [W/m^2_{floor}]
HP + battery sensitivity
Cost/savings [EUR/m^2_{floor}]
$8Wh/m^2$ Battery
$16Wh/m^2$ Battery
$25Wh/m^2$ Battery
PV amount [W/m^2_{floor}]
HP + battery sensitivity
Cash flow [EUR/m^2_{floor}]
PV amount [W/m^2_{floor}]
System sensitivity
Cost/savings [EUR/m^2_{floor}]
No storage
Heat Pump
Battery
Bat + HP
PV amount [W/m^2_{floor}]
System sensitivity
Cash flow [EUR/m^2_{floor}]
PV amount [W/m^2_{floor}]

D

Appendix D: Environmental impact

Next to being technically and economically feasible, the system has to make sense from an ecological stance as well. The heat pump has an obvious positive environmental impact due to the enormous savings in gas. For the solar PV panels in combination with Li-ion batteries, the impact is less obvious, as both require significant amounts of energy and materials to produce.

A study that evaluated the life cycle impact of five types of batteries (NiMH, lead-acid, Li-ion, sodium-sulphur and NiCd) found that Li-ion batteries have the most significant environmental impact of all battery types, both in terms of greenhouse gas emissions and metal depletion. [36]

Table D.1: Environmental impact per kg of battery production for various types of batteries. Source: [36]

	Climate change $[kg_{CO_2,eq}]$	Metal depletion $[kg_{Fe,eq}]$	Fossil fuel depletion $[kg_{oil,eq}]$	Cum. energy demand $[MJ/kg]$	Energy Density $[MJ/kg]$
Lead acid	0.9	0.4	0.3	17	0.13-0.18
Lithium ion	12.5	20	1.6	90	0.46-0.72
Nickel cadmium	2.1	1.5	0.7	37	0.14-0.22
Nickel metal hydride	5.3	3.2	1.6	90	0.27-0.34
Sodium sulphur	1.2	3.2	0.4	19	0.72

Li-ion battery production requires 90 MJ and releases 12.5 kg of CO_2 per kg of Li-ion produced. The energy density of a Li-ion battery is between 0.46 and 0.72

MJ/kg, or 0.128 to 0.2 kg/kWh. Energy density is an import consideration for the automotive industry, but not for residential applications. Therefore the lower value of 0.128 kWh/kg is used to calculate the net CO2 emissions resulting from a 1 kWh battery as follows:

$$CO_{2,bat} = \frac{kg_{CO_2}}{kg_{Li\text{-}ion}} \cdot \frac{kg_{Li\text{-}ion}}{kWh_{bat}} = 12.5 \cdot \frac{1}{0.128} = 97.66 \frac{kg_{CO_2}}{kWh_{bat}} \tag{D.1}$$

Where:

$CO_{2,bat}$ is the net CO_2 emission $[kg_{CO_2}/kWh]$

The production of $1m^2$ of polycrystalline solar panel requires approximately $250kWh$ of energy. If the panels are produced in China with an emission rate of $0.97kg_{CO_2}/kWh$, the corresponding CO_2 emissions are $242.5kg_{CO_2}/m^2$.

The average power production of $1m^2$ of solar panel attached to the building is $8.56W$. With an estimated lifetime of 20 years, the total power production will be $1500kWh/m^2$. The greenhouse gas emissions for grid electricity in Italy are equal to $0.41kg_{CO_2}/kWh$. [3] The CO_2 savings will thus amount to $1500 \cdot 0.41 = 615kg_{CO_2}$. This gives a net CO_2 saving of $615 - 242.5 = 372kg_{CO_2}$ per m^2 of solar panel.

Thus, $3.85kWh$ of battery storage can be installed for every m^2 of solar panel in order to achieve a positive CO_2 emission output for the PV-attached battery system. With a total solar panel surface area of $4096m^2$, this means that up to $15.7MWh$, or $1280kWh/m^2$, of battery storage can be installed before reaching a net negative CO_2 impact. This far exceeds the economically viable amount of battery capacity ($< 100Wh/m^2$). The environmental impact of a PV-attached battery system does therefore not pose a noteworthy boundary condition on the optimum system selection.