Strategies in electricity load shifting for building's heating energy usage optimization using price signal
A case of a single-family house in Denmark



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SYNOPSIS:

Denmark's plan is to become 100% fossil fuel independent by 2050. The fluctuations in renewable energy sources like wind and solar gain dictate a need for introducing more flexible systems to manage demands according to the produced energy.

Since around 40% of energy is used in the building sector, the load shift potentials in the residential buildings should be investigated to minimise the dependency of the heating systems during electricity consumption Peak-load periods.

To reach this goal, the paper investigates load shifting in the heating system for an existing Danish single-family house built in 2021, located in Egernsund. The focus of the project is to propose the best switching profile for the heating system according to the electricity signal prices for a particular building to provide the required DHW and space heating with the lowest running costs.

Furthermore, analysing the best strategy proposed with optimized component sizes showed more opportunities to improve savings and shift loads to low prices periods.

By signing this document, each group member confirms participation on equal terms in writing the project. Thus, each member of the group is responsible for all contents of the project.

Abstract

The increase in electricity generation by renewable energy sources stimulated the implementation of new strategies and solutions such as demand side management (DSM), which were introduced to ensure the stability of the grid. In other words, these practices are applied to balance renewable energy production with electricity consumption.

Based on a single-family house located in Egernsund, this master thesis focuses on the investigation of the load-shifting possibilities using DSM. It deep-dives into an analysis of an impact on the amount of energy load shifted to off-peak hours, and possible savings potential with a help of a heat pump, domestic hot water tank and buffer tank. Furthermore, the size of components and their dependence on the energy produced, the electricity consumption, temperature for domestic hot water and indoor comfort is investigated.

The goal of this thesis is to present different simulations of the system configurations and heating setpoints, including electrical price signals as well as ‘’building as a battery’’ concept, to increase annual savings through load shifting, still maintaining the comfortable operative temperature as well as withdrawal tap temperatures.

Nomenclature

Symbol	Description
DHW	Domestic Hot Water
UFH	Under Floor Heating
BaB	Building as a Battery
TES	Thermal Energy Storage
RS	Renewable sources
RES	Renewable energy source
HP	Heat Pump
DSM	Demand side management
RC	Resized Components
HVAC	Heating, Ventilation, and Air Conditioning
DMI	Danish Meteorological Institute
API	Application Programming Interface
COP	Coefficient of Performance
IEQ	Indoor Environmental Quality
ROC	Rate of change
PV	Photovoltaic panels

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1. Introduction

In 2020, the share of energy from renewable sources (RS) in gross electricity consumption in Europe was 37,5 % [1]. In comparison, in 2004 the share of RS was at 15,9 % [1]. The increase in using renewable sources, rather than coal, oil, and natural gas, is happening due to the reduced costs of renewable energy technologies, increasingly high electricity demand as well as decarbonization policies and global set targets [2].

In 2021, Denmark had the largest share of electricity generation from wind and solar sources worldwide [3]. In the same year, Scandinavia had 6271 [4] active wind turbines, which covered approximately 43,6% [5] of total electricity consumption. With that being said, the country is making a progress in achieving net-zero emissions by 2050 and eliminating fossil fuel by 2030 [3].

However, the problem with renewable energy sources (RES) is their variability [6]. For instance, production from wind turbines depends on wind power, and production from Photovoltaic panels depends on the sunlight intensity, which in both cases varies from time to time. Those fluctuations have an impact on grid stability, which can cause power outages [2]. Therefore, there needs to be a balance in the grid, meaning the energy consumed must be equal to or less than the energy generated [2].

Increasing electricity generation from renewable sources stimulated the implementation of new strategies and solutions to balance renewable energy production with electricity consumption. Therefore, demand-side management and time-shifting of electricity consumption are the key solutions for ensuring the stability of the grid [7].

When it comes to demand side management (DSM), the strategies involve incorporating four types of components: energy-efficient end-use devices, additional equipment to enable load shaping, standard control systems for turning end-use devices on/off as required as well as communication systems between end users and external parties [8].

Furthermore, heat pumps (energy efficient devices) in combination with the smart grid allow for load management. As stated by Kim et al. [9]. approximately 50% of detached single-family houses in Denmark are located outside the district heating grids and therefore will be equipped with heat pumps (HP) in the near future [9]. HP in combination with the thermal energy storage (load shaping equipment) such as a storage tank, allow shifting the loads from the peak periods to low periods.

Approximately 40 % of global energy consumption is dedicated to buildings [10]. Furthermore, in Denmark, approximately 25% of the energy consumption is used for space heating and hot water in buildings [10]. Therefore, large water and heating demands can be controlled by DSM strategy to decrease electricity consumption to balance the demand with energy production [8].

Furthermore, the time-shifting possibilities can also be achieved on the household level without any additional components, where occupants are key role players. It refers to moving the usage of equipment consumption to the times when the electricity price is low. However, in this case, it is important to investigate the occupancy behaviour concerning the presence in the buildings, activities as well as energy use [11]. The time-shifting opportunities require changes in the temporality of electricity consumption practices in everyday life, which does not always fit into a daily schedule [12]. The potential of load-shifting strategies was already investigated by Friss et. al. [12] and Fotenaki et. al. [11].

2. Literature review

Marini et. al. [13] emphasized that despite a properly designed thermal energy storage system, the occupancy behaviour and preferences are crucial to introduce successful load shifting. Furthermore, occupants have a possibility of controlling the electricity consumption of household appliances by time-shifting from peak hours to non-peak hours, which usually occurs during night-time, which in long term can reduce the electrical bill [12].

Furthermore, research performed by Friis et.al. [12] investigated the flexibility of electricity consumption in houses without Photovoltaic panels. Participants emphasized that with time-shifting extra tasks were added to the morning routine, such as unloading the dishwasher, which was particularly stressful for families with children. Moreover, the occupants stopped using the tumble dryer, which caused noise during the night and resulted in a reduced economy.

Recent studies have proved that heating the building using real-time pricing can be profitable [14] [15]. Marijanovic et. al. [16] concluded that profitability is affected by an available load that can be shifted and price spread. Fitzpatrick et. al. [14] investigated the influence of different types of electricity tariffs and energy flexibility considering a demand response program to control the heat pump coupled with an energy storage system for space heating. The following tariff strategies have been studied: real-time pricing, two-level day-night tariffs as well as critical-peak pricing. Results showed that real-time pricing is capable of offering the largest energy flexibility with the least electricity costs associated with it.

Furthermore, the impact of heat pump over-dimensioning has been researched. A slight increase in the profitability of the exploitation per annum has been found. A study performed on a German building case showed that over-dimensioning of the heat pump by 15% and 30% resulted in an increase of profits by 12% for 15% over-dimension and 22% for 30% over-dimensioning [16].

Furthermore, Masy et. al. [15] investigated shifting the electric load using an air-to-water heat pump coupled with an underfloor heating system and thermal storage whilst using a day-ahead electricity market (powered by nuclear and gas) in the Belgian context. In this study three electricity tariffs have been compared: flat tariff, two-level day-night tariffs and real-time pricing. Results showed that smart grid strategies alongside a real-time pricing tariff can lead up to a 13% reduction in consumer costs compared to the flat tariff.

Building materials can absorb the energy whenever the indoor temperature is high and release it later and are able to flatten out heat flow fluctuations as well as shift the heating time [17]. The absorption and dissipation rates depend on the thermal properties of the materials Johra et. al. [18] showed that considering the thermal inertia capacity of building materials and using the building as a battery to store the energy, shifted the heating-up time of the building to the low-price electricity periods and increased the energy flexibility of the building by 44% and 8% for low and high insulated buildings [19].

Several studies have proved that coupling a heat pump with a thermal energy storage system can allow for increasing the overall thermal inertia of the building system by shifting the heating load, leading to increased energy flexibility [20] [8] [16] [21]. Thermal energy storage tanks have been studied and it has been found that the larger the storage volume the more load can be shifted [20] [16]. Furthermore, Marijanovic et. al. [16] found a relation between profitability and thermal storage volume – they concluded that the larger the tank the more energy can be exploited later leading to overall savings due to larger units of energy being shifted to peak periods. A study performed on a German building case showed that in the case of 4-hour storage capacity savings of around 20% have been registered. Whereas for 8-hour storage, savings was 36% [16].

Control strategies in heating systems play a key role in energy consumption and load shifting. Using occupancy-based control, which is activated by the presence of occupants, decreased the energy consumption of the HVAC system by 5.9 % [22]. Moreover, another study showed that using "Building as battery" resulted in a load-shifting strategy throughout the heating season, which decreased the heating costs by up to 13% compared to the 19°C constant heating setpoint [23].

3. Hypothesis and problem formulation

Variable electricity tariff characterizes a daily spread between minimum and maximum price within every 24 hours. This can influence DSM methods that allow shifting the heating demand from peak hours to off-peak hours at low costs. Figure 1 indicates, the exemplary price schedule for a week period from 17.12.2021 to 24.12.2021 on the Danish intraday market price of electricity (Nord Pool). With an optimal schedule of heat pump operation considering daily electricity spread one can shift, space heating and DHW heating load from Peak Load hours to Low Load hours using DSM methods. The aforementioned method can result in potential monetary savings in running a heat pump throughout the year. The details for all values used in Figure 1 are presented in Annex C.3.

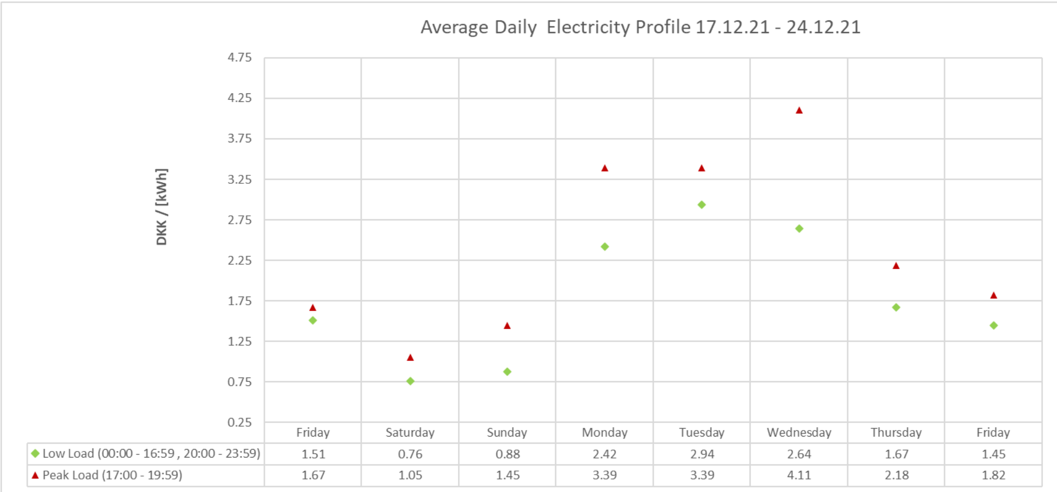


Figure 1. Average Daily Electricity Profile (from 17.1220.21 to 24.12.2021)

The following research questions are addressed throughout the research:

- How does DSM contribute to the stability of the grid?
- How should a heating and DHW strategy be established to bring profits to the household and maintain acceptable indoor comfort and desired domestic hot water withdrawal temperatures?
- How much energy can be shifted implementing proposed strategies throughout the year in Denmark using the following building case?
- What influence does a ‘’building as a battery’’ concept have on shifting energy in comparison to keeping a constant heating setpoint throughout the year using the following building case?
- What are the influence of heat pump and TES sizes on the general savings throughout the year?

4. Methodology

The flexibility of a building energy system refers to its adaptation to dynamic and changing conditions, such as balancing supply and demand on an hourly basis. Investigation of the energy flexibility of the building case will focus on a Danish single-family house constructed in 2021 with Energy Class A 2015. The related document can be found in Annex A.2. Following, the retrospective approach is undertaken in this study using already existing data, rather than future prediction. Therefore, for analysis the Danish reference year 2013 was used to reflect weather conditions as well as the Danish spot market price of electricity (Nord Pool) throughout the year 2021 to reflect load-shifting periods for both heating and domestic hot water. Summarising, this project has the purpose to investigate possibilities and benefits regarding load shifting, assuming the most efficient case to contribute to the future development of control strategy.

This study will investigate a building case in four following concepts, which are elaborated further in this section, having in mind a goal to minimise the overall energy costs to run the heat pump:

- Strategy 1: Reference case (Ref)
- Strategy 2: Reference case with TES (Ref + TES)
- Strategy 3: Electricity Price Signal (BaB + EL. signal)
- Strategy 4: Electricity Price Signal + Building as thermal battery + thermal energy storage tank (El. price signal + BaB + TES)

Figure 2, presents the outline of the project and the following procedures. All strategies and their control methods are explained in each dedicated section. Firstly, all results from strategies are presented, and then results are gathered and compared. Following, the best configuration is investigated to find the impact of taxation and charges that electricity providers demand from the grid which will give a more realistic view of savings. Lastly, a final comparison is made, and then the discussion and conclusions along with the summary are described.

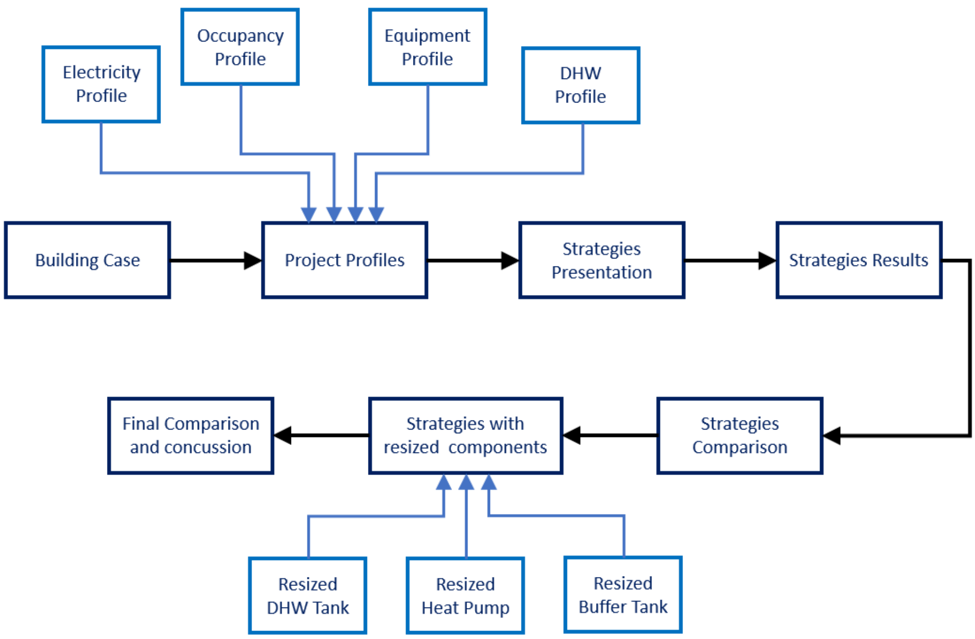


Figure 2. Project Procedure overview

Strategies 1 and 2 will follow a specific order shown in Figure 3.

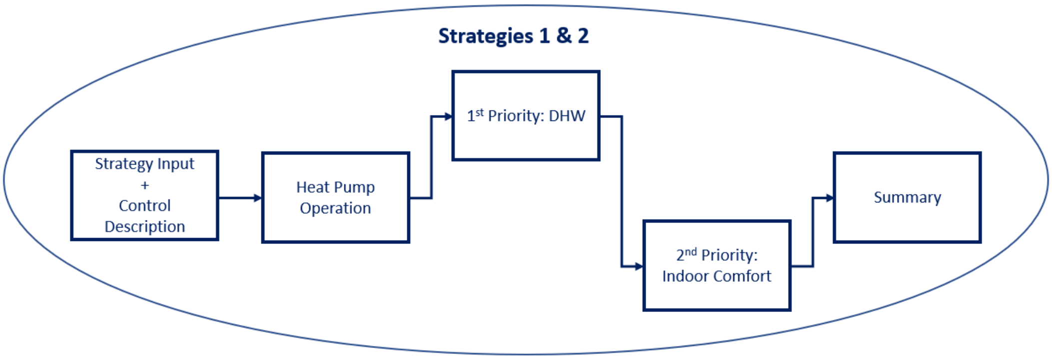


Figure 3. Strategy 1 and 2 Presentation Principle

Figure 4, for strategies 3 and 4, will accommodate different orders, due to the fact that the price signal is influencing the heat pump operation. Once the strategy is described, and the conditional price signal is chosen, the simulation is run, and criteria are checked – when criteria have not been met a process of force running is required. Force running a heat pump is to let the heat pump work during periods when the electricity price is not within the price signal, setting as a priority comfort temperature criterion as well as DHW provision.

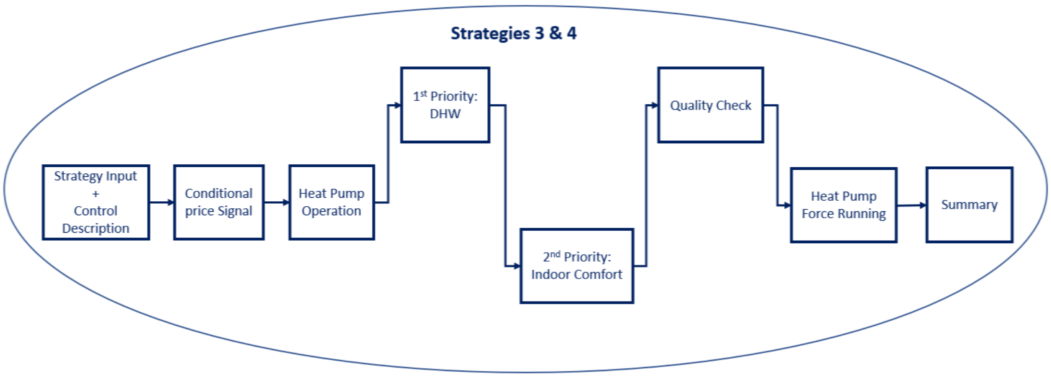


Figure 4. Strategy 3 and 4 Presentation Principle

4.1 Strategy description

For the first strategy, a reference case (Ref) is developed by connecting the heat pump directly to the underfloor heating loop. In this strategy, the heat pump is run continuously to heat the building to the setpoint of 22°C as well as to provide domestic hot water within the temperature range of 40-55°C using a DHW tank as presented in Figure 5.

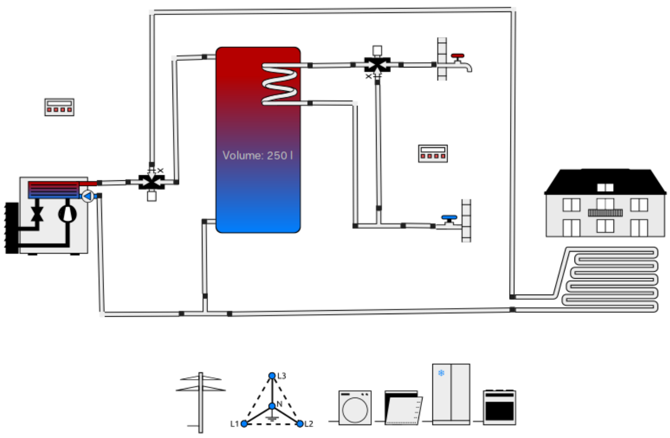


Figure 5. Schematic layout for reference case (Ref)

Following, a second strategy (Ref + TES) was developed by coupling the heat pump and thermal energy storage [Figure 6], where the heat pump is run continuously to heat the building to the setpoint of 22°C as well as to provide domestic hot water within the temperature range of 40-55°C using DHW tank.

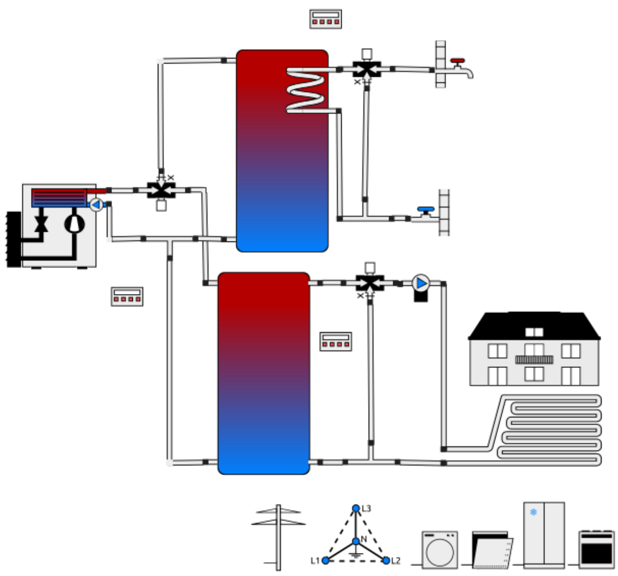


Figure 6. Schematic layout for reference case + TES (Ref + TES)

Reference cases do not consider the electricity price signal to run the heat pump. The heat pump runs at all times regardless of price to satisfy the setpoints – no Demand Side Management (DSM) practice is implemented. The explanatory flowchart of the heat pump operation is presented in Figure 7 and Figure 8 for strategy 1 and strategy 2, respectively.

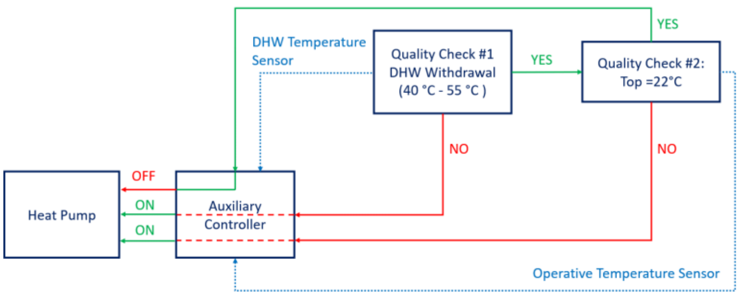


Figure 7. Strategy 1 - Schematic of Control Diagram

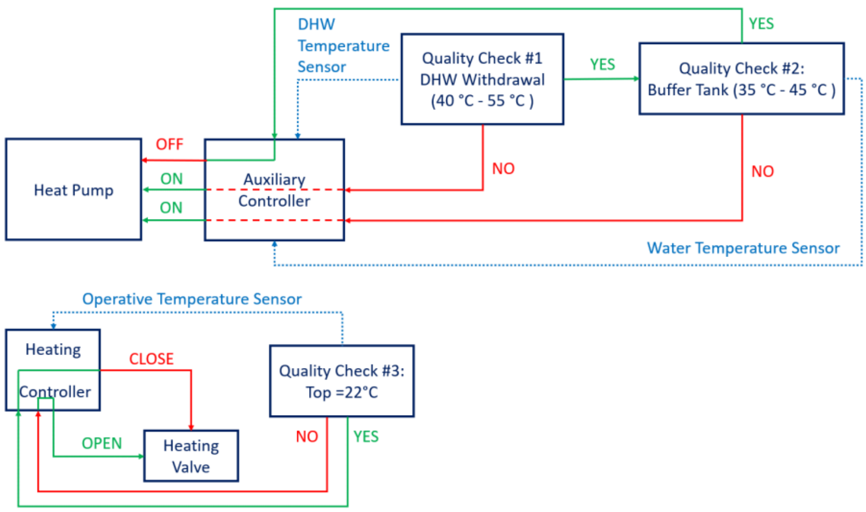


Figure 8. Strategy 2 - Schematic of Control Diagram

Furthermore, the third strategy has the following approach. The heat pump is meant to receive a price signal based on conditional price analysis to provide direct space heating as well as provide satisfactory temperature for domestic hot water withdrawal using a potable water tank - Figure 9 represents the setup.

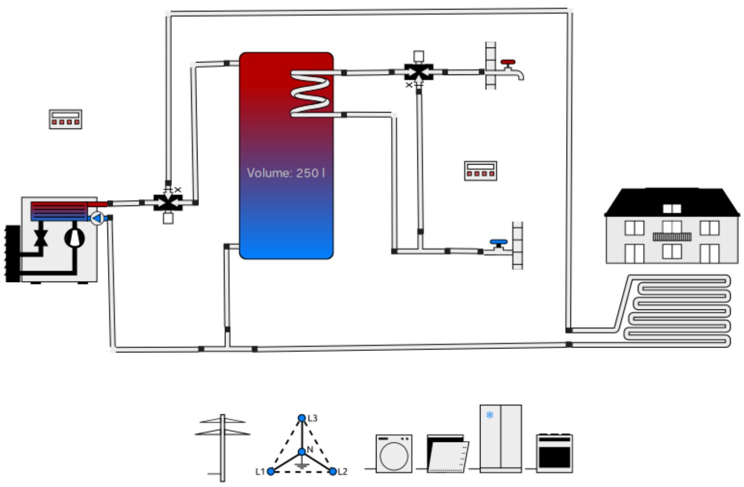


Figure 9. Schematic layout for considering electricity prices signal and BaB (El. signal + BaB)

An explanatory drawing can be seen in Figure 10. Heat Pump runs in two scenarios – using cheap electricity prices alternatively being forced to run despite conditional pricing signal. In this flow chart, electricity signal prices '0' and '1' mean expensive and cheap, respectively.

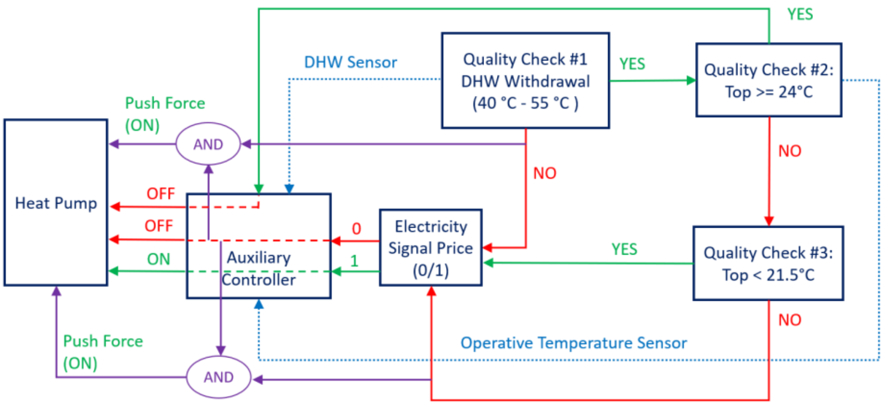


Figure 10. Strategy 3 - Schematic of Control Diagram

Finally, the fourth strategy is simulated, where the heat pump is coupled with a supplementary buffer tank that is used to heat the building using the BaB concept to provide indoor comfort temperature as well as DHW in the temperature range of 40-55°C – setup seen in Figure 11.

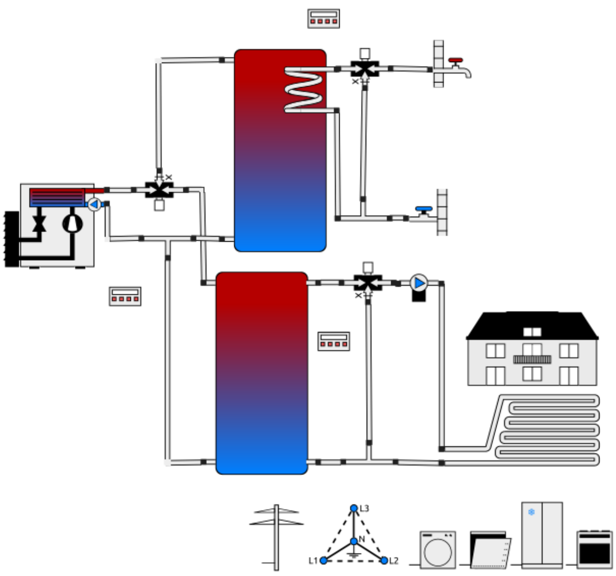


Figure 11. Schematic layout for considering electricity prices signal and Bab + TES (El. signal + BaB + TES)

An explanatory drawing can be seen in Figure 12. Heat Pump runs in two scenarios – using cheap electricity prices alternatively being forced to run despite conditional pricing signal.

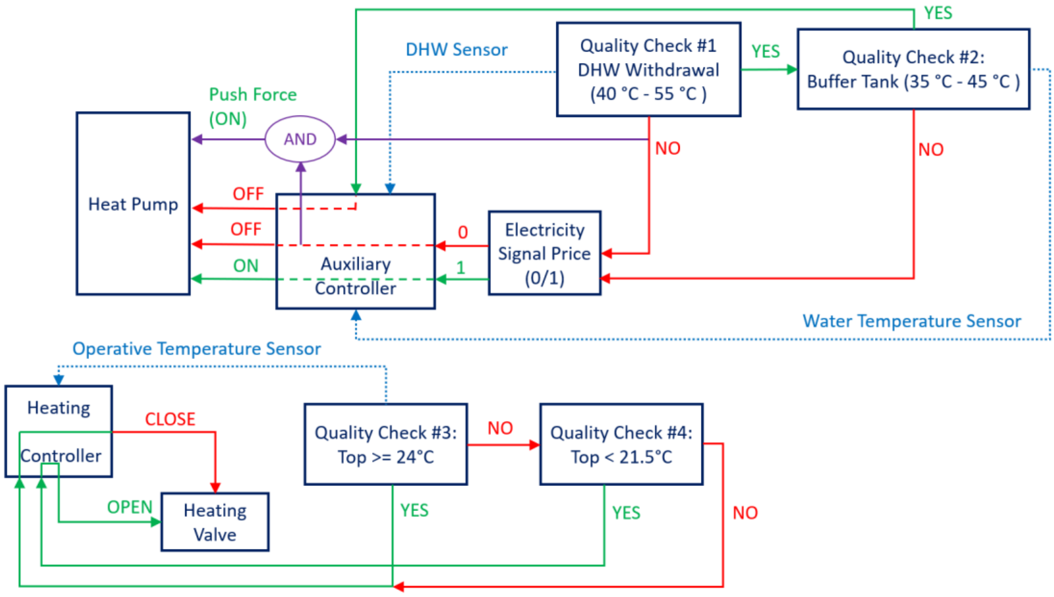


Figure 12. Strategy 4 - Schematic of Control Diagram

5. Building case description

The building in the study case is a two-storey single-family house with a total area of 176.4 m^2. The house was built in 2021 and is located in Egernsund, Denmark. The construction was developed to be a showcase of CleanTechBlock, which is a product consisting of a shell of bricks and a core of foam glass from recycled glass [24]. Furthermore, it is one of the first single-family houses in Denmark with DGNB Platin certification [24].

The constructions of the building components are presented in Table 1 together with their transmission coefficient provided by Sloth Moller company as well as windows and doors specifications from Outrop Vinduer & Dore A/S. Further information is mentioned in Annex A. Furthermore, there are different types of floors covering:

- Wooden floor: all rooms on the first floor (except the bathroom and bedroom
- Brick: corridor, kitchen, and dining area (ground floor rooms)
- Concrete: Bathrooms

Table 1. Building case components

Building components	Construction (starting from inside to outside)	U-value (W/m^2K)
Ground deck	• Floor covering • Concrete • Insulation • Concrete • Insulation	0,07
External wall	• Brick • Insulation (Foam glass) • Brick	0,15
Roof/ceiling	• 1 x Troldtekt • Lightweight concrete • Insulation	0,09
Storey partition	• Wooden floor • Footfall sound insulation • Lightweight concrete • 1 x Troldtekt	0,8
Internal walls	• Brick	-
Windows	• 3 layers energy class • Transmission coefficient (Uw) = 0,83-0,86 W/m^2K • Solar transmittance (Gg) = 0,53 • Glazing part (Ff) = 0,84-0,88 • Light transmittance (Lt) = 0,74	
Doors	• Transmission coefficient (Uw) = 0,73-0,88 W/m^2K • Solar transmittance (Gg) = 0,53 • Glazing part (Ff)= 0,60-0,68 • Light transmittance (Lt) = 0,74	
Skylight	• Transmission coefficient (Uw) = 0,93 W/m^2K • Solar transmittance (g) = 0,47 • Light transmittance (Lt)= 0,58	

Moreover, the building is equipped with two air handling units, two buffer tanks, and two types of heat pumps as well as Photovoltaic panels. The specifications are presented in Table 2.

Table 2. Equipment/Systems in the building case

Equipment/system	Specification
Ventilation	• Two Genvex ECO- 375TS air handling units located on each floor (with Optima 251 control) • Counterflow heat recovery • 82 % heat recovery • SEL at max airflow 1285 J/m^3 • Supply filters class F9 and outlet filter class G4
Heating system	• Two heat pumps: o Air to water with 7 kW o water to water with 5 kW • Floor heating in the entire building
Buffer tank	• 250 L DHW tank • 550 L buffer tank
Photovoltaic panels	• 39 m^2 of PV panels located on the roof (5 kWp)

Furthermore, the building permit submitted on 09/03/2018 stated that the construction must be carried out according to Building Regulations 2015. Therefore, the building is classified as energy class A 2015, and the total energy consumption of the building resulted in 10,2 kWh/m^2 per year, which met the requirement for energy class A 2015. Details can be found in Annex A.2.

To understand the thermal inertia of the house that allows considering the Bab concept in Strategies 3 and 4 the building time constant has been simulated over the year using BSim software. The time constant of the building is the time needed to reach 63.2% of the temperature change between the two steady states [25].

The time constant for the case building was investigated according to the below assumptions and depicted in Figure 13:

- Simulation of the building in BSim with transmission and ventilation heat losses
- Weather data: Denmark Dry 2013
- Heating source power 7 kW
- Indoor temperature set-point: 24°C (High steady-state indoor temperature)
- The minimum steady-state indoor temperature: 20°C
- The heating system stops working at 24:00 (12 A.M) the day before investigated days

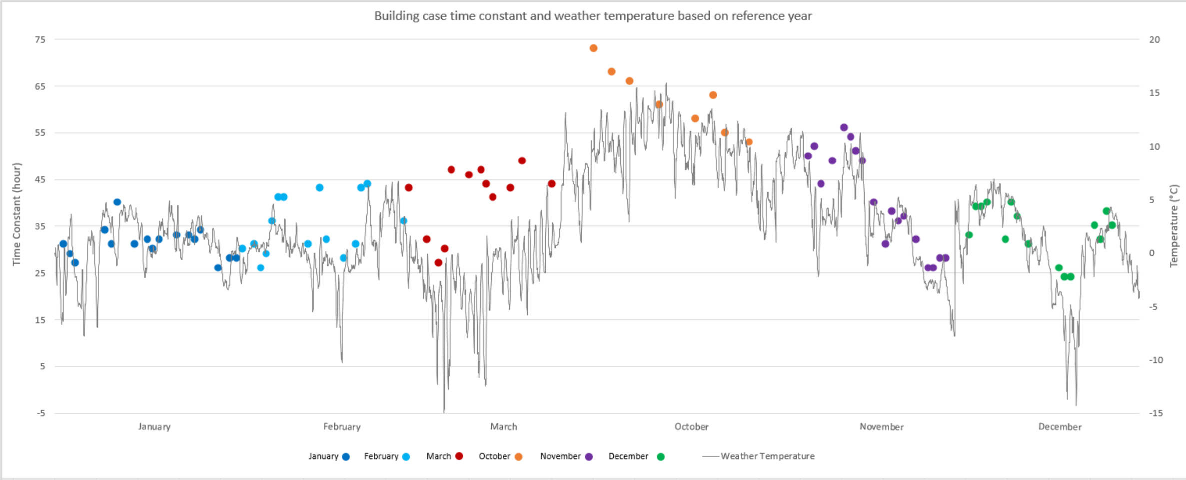


Figure 13. Building case time constant and weather temperature based on the reference year

In addition to the critical day in each month with the lowest recorded air temperature, more days were investigated to find the behaviour of the building and time constant. It is concluded that the time constant is heavily affected by the outdoor temperature. The lowest time constants of the building are on December 19th and 20th with 24 hours followed by February 4th, November 26th, and January 28th with 26 hours.

Other useful data for the building case behaviour is the time needed to increase the operative temperature to the heating setpoint. For this investigation, the reverse procedure for time constant was done using BSim and the time needed to heat the building from 21.5°C to 24°C. The result of this investigation is depicted in Figure 14. Details of these simulations are mentioned in Annex B.

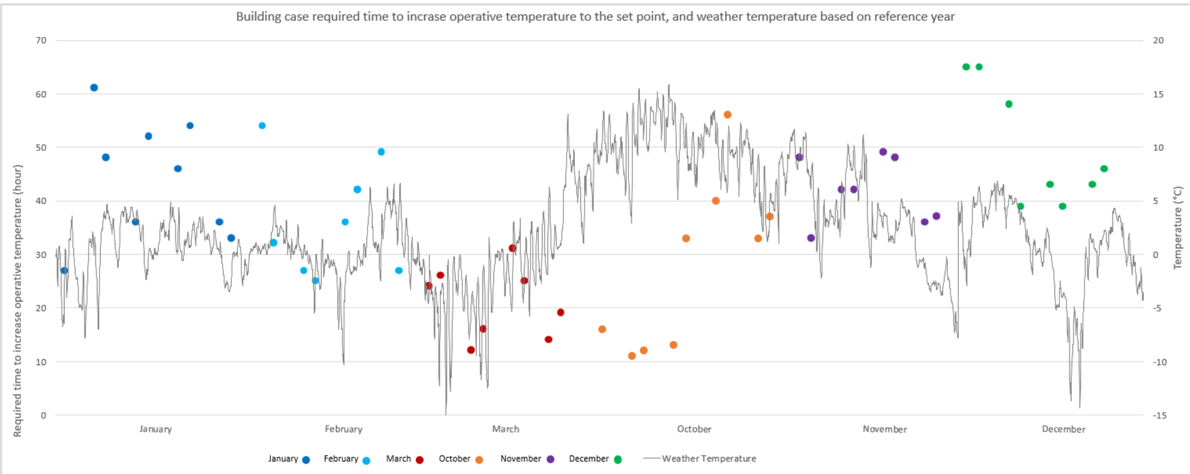


Figure 14. Building case required time to increase the operative temperature to the set point, and weather temperature based on the reference year

6. Project profiles

In this section, project profiles are investigated, that were considered in the Polysun simulation. The following topics are the focus of this section:

- Electricity Price Profile
- Electricity Price treatment
- Occupancy profile
- Appliance's profile
- Domestic Hot Water profile

6.1 Electricity price

Over recent years, a sharp increase in electricity costs is observed. Figure 15 represents the spot electricity prices for the years 2018-2022 with the division for every month. The data was gathered from the Nord Pool website as the monthly average price [26]. As can be observed, between the years 2018-2020 the spot electricity prices per month were in the range approximately of 0,11– 0,41 DKK per kWh. However, from May 2021 until now, the price started to increase. By the end of the year 2021, the price was at 1,4 DKK per kWh, which was 4 times bigger than by the end of the year 2018. Moreover, the year 2022 presents a sharp increase in almost all months compared to all other years. All data used to generate Figure 15 is presented in Annex C.1.

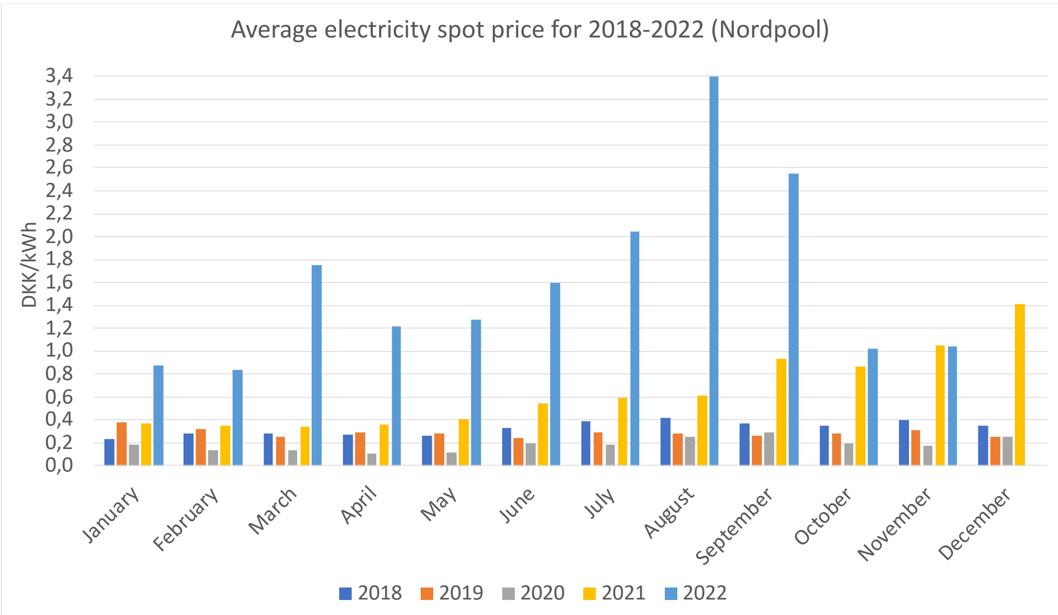
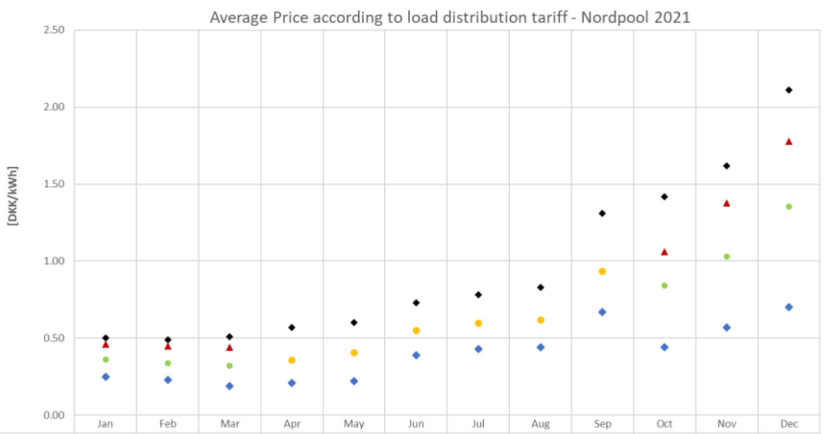


Figure 15. spot electricity prices for years 2018-2022 with the division for every month

Due to the lack of tools for the prediction of future market prices of electricity, the investigation was based on a retrospective approach, using historical data from Nord Pool. Moreover, due to the sharp increase in the years 2021 and 2022 compared to previous years, the retrospective approach was narrowed down to the year 2021.

The hourly data for each day of the year 2021 from Nord Pool was analysed to present the minimum, maximum and average prices for each month. Furthermore, the network tariffs for the year 2021 were included in the calculation. Therefore, as presented in Figure 16, the calculation of the average price was divided into low and peak load for the winter season and low load for the summer season. One can see that the spread from January to March was very similar to each other with maximum and minimum monthly average prices at approximately 0,5 DKK/kWh and 0,22 DKK/kWh, respectively. From April until August, the monthly average values started slowly increasing. However, one can see a sharp rise in September, with the maximum monthly average price exceeding 1 DKK/kWh. By the end of the year 2021, the maximum monthly average price was exceeding 2 DKK/kWh. Data used for Figure 16 can be found in Annex C.2.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ Maximum Monthly Average Price	0.50	0.49	0.51	0.57	0.60	0.73	0.78	0.83	1.31	1.42	1.62	2.11
● Average price Low Load (00:00 - 16:59 , 20:00 - 23:59)	0.36	0.34	0.32							0.84	1.03	1.36
▲ Average price Peak Load (17:00 - 19:59)	0.46	0.45	0.44							1.06	1.38	1.78
● Average price Low Load (00:00 - 00:00) - Cooling Season				0.36	0.40	0.55	0.60	0.62	0.93			
◆ Minimum Monthly Average Price	0.25	0.23	0.19	0.21	0.22	0.39	0.43	0.44	0.67	0.44	0.57	0.70

Figure 16. Average, Minimum and Maximum monthly prices in 2021

With that being said, the spread throughout the entire year 2021 varies from month to month. The gathered data provided insight into the peak times in electricity prices and when to operate the heat pump (low prices), which have an impact on the overall savings for the project case. In Annex C.1 hourly prices for each month in the year 2021 are presented.

6.1.1 Composition of electricity price

One of the big exchanges in Denmark, where electricity is traded is Nord Pool. Here the electricity suppliers buy the amount of electricity they expect to sell to consumers and business companies [26]. The price is set for every hour over the day due to variations in supply and demand [27].

The total electricity price that can be seen on household electricity bills can vary due to different grid areas, due to differences in grid tariffs and grid subscriptions. The electricity price also varies between over 100 electricity suppliers that consumers can choose from and between Eastern and Western Denmark [28].

In Denmark typically the price of electricity consists of various elements, as presented in Figure 17, such as payment for the electricity, distribution, taxes to the state, and VAT. The pure electricity that is traded on the market accounts for approximately 50% of the price per unit of electricity, and the price depends on the agreement with the electrical supplier and is usually affected by the electricity exchange (Nord Pool) [29]. The remaining 50% is distributed as Electricity Tax to the state and VAT (35%), followed by distribution costs (13%), and transmission costs (2%).

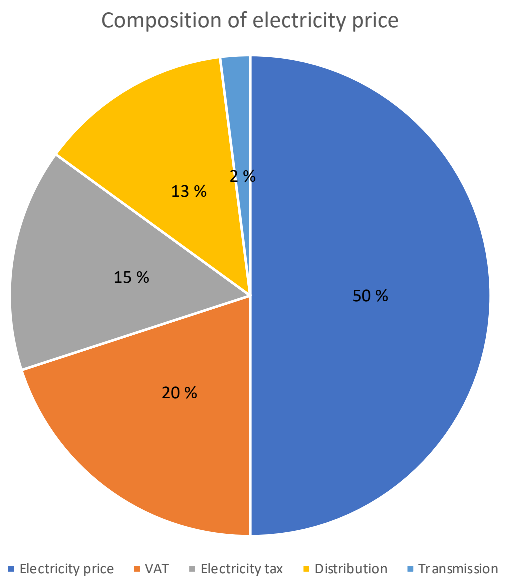


Figure 17. Composition of electricity price in 2021 [30]

The VAT accounts for 20% of the total price and it is a payment to the state. VAT is imposed on all the items from the electricity bill, which includes payment for electricity, transport, and taxes to the state [29]. Electricity tax represents 15% of the total electricity price and it is a fee charged on behalf of the Danish state and is imposed as an amount per kWh consumed [29].

Transmission costs, which account for 2 % of the total electricity price, cover costs for the operation and maintenance of the international connections as well as the overall high-voltage grid in Denmark, which is state-owned by Energinet [29]. According to the Energinet website, for the year 2021, the transmission costs were 4.9 øre/kWh [31].

The distribution section covers costs associated with receiving electricity from the grid as well as it covers the costs of operating the electricity network. This section accounts for 13% of the total electricity price and includes costs related to the network tariff and network subscription. The first part depends on how much power is used and covers costs for the operation maintenance and installation of the network and the electricity meter [29]. Furthermore, the tariff varies throughout the day depending on what time of the day the electricity is used [32]. On top of that, as mentioned before, there is a network subscription that has a fixed price (typically per month), which covers settlement costs and other costs for the electrical supplier [29]. Therefore, this is the competitive parameter between the electrical suppliers.

6.1.2 Electricity price taxation

The raw electricity prices per hour per day are obtained from Nord Pool, further in the project those prices are considered with taxes, distribution, and transmission costs once the most optimised case is investigated. Furthermore, the impact of additional costs derived from taxation, subscription charges etc. is investigated from the angle of total annual savings. Since the market prices were used for the year 2021 due to the retrospective approach, the network tariffs and subscriptions were also used for the same year to avoid data mismatch. Costs associated with the tariff rates are found on the Radius Elnet website and are used throughout this project [33].

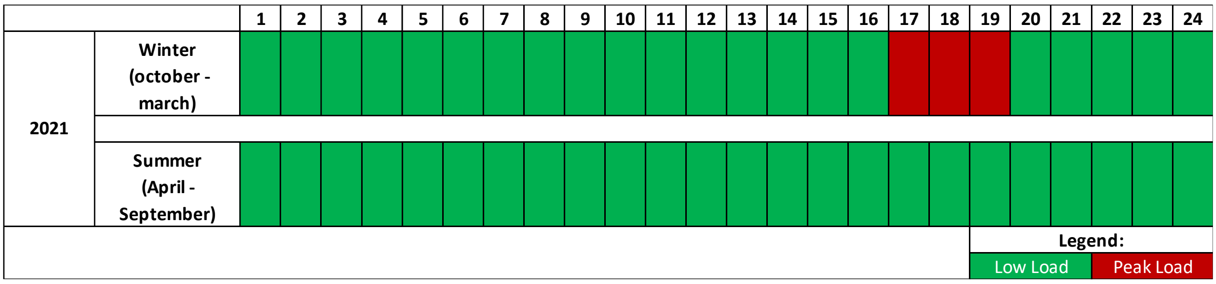
The first step of the development of the market price was adding the network tariff and network subscription as mentioned before. As presented in Table 3, for the winter season there are low and peak tariffs, which price depends on the time during the day when the electricity is used. For the summer season, there is only one low load tariff, disregarding the time when electricity is used. Therefore, for each hour of the market price, the correct tariff prices were added. The network subscription per month was also included, which was 21 DKK excluding VAT [33].

Table 3. Network tariff 2021 [Radius Elnet]

Season	Load period	C-tariff (Øre/kWh)
Winter rate	Low load	23,63
(October-March)	Peak load	63,07
Summer rate (April- September)	Low load	23,63
	Network subscription	
	21 DKK / month	

Table 4 depicts the load distribution from the year 2021 with the division into hours per day. It is assumed that during the summer rate, the PV overproduction in the grid causes the load period to be Low Load.

Table 4. Load distribution in the year 2021 [Radius Elnet]



In the next step, the transmission costs are added. According to Energinet [31] in the year 2021 the transmission cost was 4,9 øre/kWh. According to Elforsyningen [34], the electricity tax was 90 øre/kWh. On top of all the costs mentioned above, a 20% of tax was added to the price. In Table 5, one can see the summary of the development of the electricity price for the project.

Table 5. development of the electricity price

Composition of total electricity price	Elements	Source	Values
50%	Raw electricity price	Nord Pool	Price per hour per day
13 %	Network tariff	Radiuselnet	Division for 2 seasons for low and peak loads
	Network subscription	Radiuselnet	21 DKK per month [33]
2%	Transmission costs	Energinet	4,9 øre per kWh [31]
15%	Electricity tax	Elforsyningens	90 øre per kWh [34]
20%	VAT	State	20% of the price

6.2 Occupancy profile

The occupancy schedule plays an important role in understanding energy use in the household. It is essential to know the occupant's presence in the building, activities as well as the use of appliances [11]. The building in the study case has 176,4 m^2 and consists of three rooms and a bedroom. Therefore, taking into consideration the size of the house as well as the number of rooms, it was concluded that the single-family house is designed for a family of 5 (2 adults and 3 kids).

The occupancy schedules were based on predefined profiles for a household size of 5 people created by Jensen et al. [35]. The profile was divided into weekdays and weekends due to different occupancy hours. The schedule is presented in Figure 18. As can be observed, the unoccupied hours were between 9-16 from Monday- Thursday and on Friday from 9 to 14, due to 37 hours of work per week. The data used to draw Figure 18 is mentioned in Annex C.5.

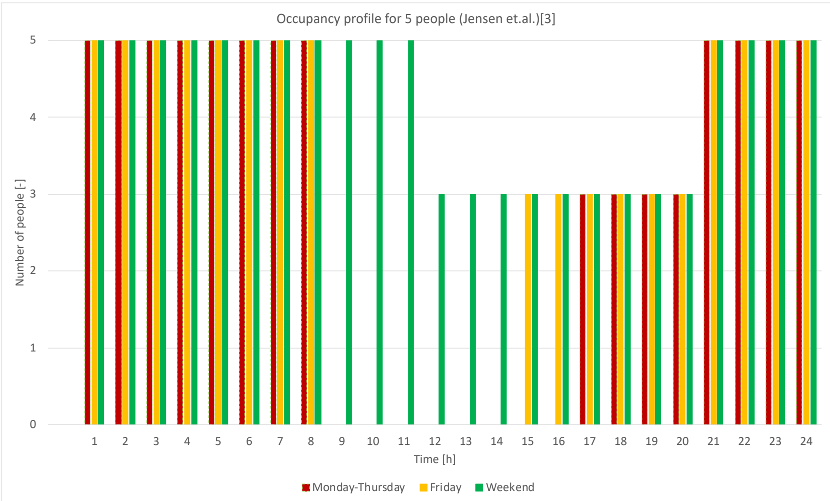


Figure 18. Occupancy profile for 5 people

However, simplifications had to be made in the Polysun software due to its limitation regarding the occupancy schedule. Polysun does not allow a user to specify a more detailed schedule of occupancy, like the one presented in Figure 18. Therefore, the simplification of the occupancy profile was required to be made. The unoccupied times were specified between 9-16 from Monday until Friday and during the weekends the house was specified as fully occupied at all times, disregarding the fraction of people occupancy per hour.

6.3 Equipment profile

Jensen et. al. [35] created an electricity consumption profile for a household size of two and five persons. Since the occupancy schedule was made for a household size of five persons, the equipment profile was matched to it. According to the Jensen et. al research [35], the electricity consumption for a family of 5 was divided into the low, medium, and high profiles as presented in Table 6. The gains from the equipment have an impact on the operative temperature since they also dissipate heat. Therefore, to create the worst-case scenario for the building case, the low profile was chosen.

Table 6. Electricity consumption profiles for a family of 5

Profile	**Annual consumption (kWh per year)** [35]
Low	4855
Medium	5437
High	7765

However, the profiles created by Jensen et. al. [35] were made in 2010 and therefore, it was crucial to check whether the annual electricity consumption changed over a decade. As presented in Figure 19 from Energy Statistics 2020 from Danish Energy Agency [36] the electricity consumption by appliances in they years 2010 and 2020 did not change. It is assumed that living standards increased and equipment efficiency improved at the same time causing similar electricity consumption from equipment between the years 2010 and 2020. Therefore, the predefined profiles by Jensen et.al. [35] were used.

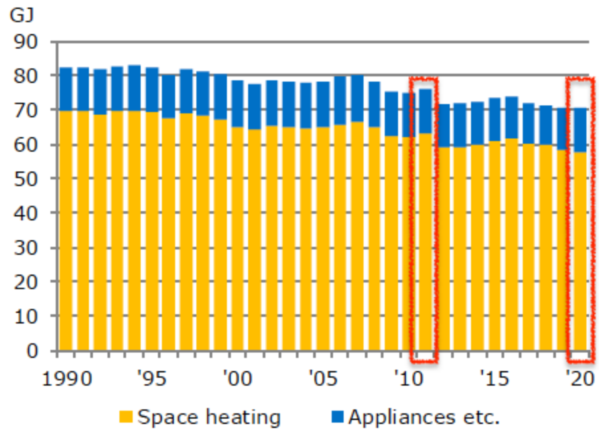


Figure 19. Electricity consumption by appliances from 1990 to 2020

For determining the equipment profile another parameter required was the maximum hourly value of consumption by the appliances. The hourly peak consumption was specified according to the research findings [35] and the values are presented in Table 7. Moreover, to match the annual consumption with the maximum hourly value, the same type of profile was used (low).

Table 7. Maximum hourly value of consumption by appliances

Profile	**Maximum hourly value from 2010 (kWh)** [35]
Low	1,26
Medium	1,41
High	2,01

The relationship between the annual electricity consumption, relative profile and maximum value follows as:

Annual electricity consumption [kWh] = relative profile [-] * equipment consumption [kWh]

Using the relative distribution profile, the equipment consumption over a year resulted in 4831,9 kWh, which differs from the annual electricity consumption specified at the beginning by approximately 23 kWh. The difference was about 0,4 % therefore, the equipment profile was evaluated as accurate and was used in Polysun simulations as a CSV excel file, which was based on calculations presented in Annex C.6. The equipment profile for weekdays is presented in Figure 20 and the weekend profile, as well as calculations, can be found in Annex C.6.

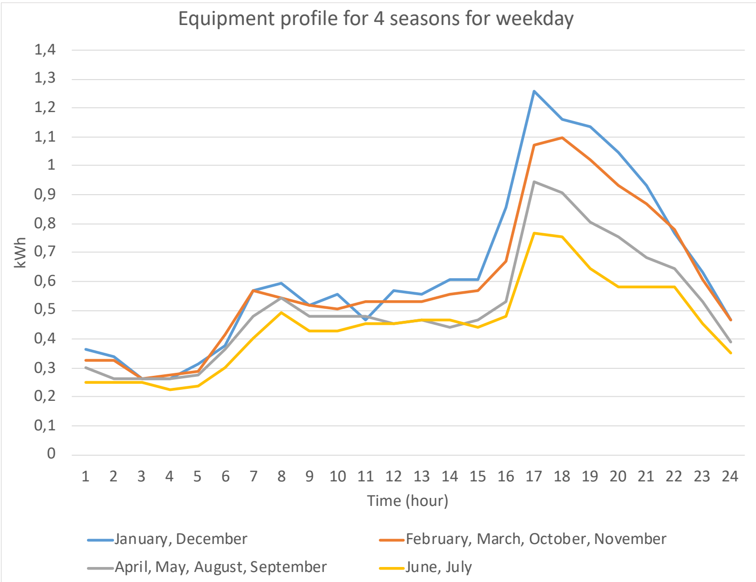


Figure 20. Equipment profile for four seasons for weekday

6.4 Domestic hot water

The domestic hot water profile was based on the schedule defined by Jensen et.al. [35]. However, in contrast to predefined values, the simulation program had no division into weekdays and weekends. Therefore, there was a need for adjustment.

The weekday and weekend values from the relative profile were multiplied by five and two respectively and then added together, which created a weighted factor for each hour of the day. Furthermore, the relative profile values for each hour were summed up separately for both weekdays (952) and weekends (1109) and were used in the next step. The detailed calculations are mentioned in Annex C.7.

In the last step, for each hour the final consumption was calculated, which required previously calculated weighted factor, both total sums and was determined according to the following formula:

$$\boldsymbol{Final = 100 * \frac{Weighted\ factor\ per\ hour}{(5 * X) + (2 * Y)}}$$

X: $sum\ of\ relative\ profile\ for\ weekdays$

Y: $sum\ of\ relative\ profile\ for\ weekends$

The obtained values for the final consumption were inserted in Polysun domestic hot water as the percentage of total consumption, which was specified as 200 L per day (40 l/person/day). In Figure 21 one can see the overview of DHW withdrawal during the day.

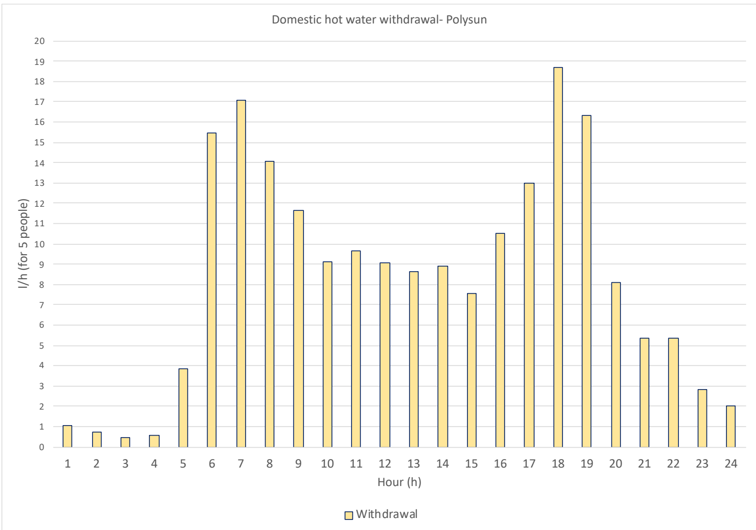


Figure 21. DHW withdrawal profile used in Polysun

7. Study delimitation

In this section, delimitations which reflect the choices being made in terms of the scope and focus of this research, are presented.

7.1 Heat Pump

As section 5. Building Case presents, the building is equipped with two heat pumps – air source heat and ground source. However, the subject of this investigation will focus on air source heat pump technology since this technology is more widespread in Denmark and is expected to become even more in upcoming years [37]. Therefore, a subject of delimitation in this study is the secondary ground source heat pump that is installed in the house.

7.2 Thermal mass

Since there is no information regarding furniture in the building case and to simplify the model and simulation in BSim, furniture has not been considered for the time constant calculation. Furthermore, Johra et.al. [18] argue that indoor elements should be included in lightweight building models. Since the building furniture is varying case by case and considering that will extend the time constant in the lightweight buildings by approximately 8% [18], to analyse the building in the worst condition, the impact of furniture has not been investigated.

7.3 Polysun - limitation

There was no possibility to import variable electricity prices into Polysun. For this reason, economical calculations were done in excel using variable electricity prices for the year 2021. Moreover, since Polysun cannot overwrite new availability times for heat pumps according to the electricity prices, the optimization process to improve DHW temperature was done in excel.

7.4 Recirculation circuit

Since the case is a single-family house, it is assumed that the distance between the mechanical room and the furthest withdrawal point is short and is not needed to consider a recirculation pipe for domestic hot water. Therefore, heat losses for this circuit are not considered in calculations.

7.5 Weather data

In this project, Danish Reference Year 2013 data is being used which is a project delimitation to some extent. The impact of weather can influence the building heating demand, as well as on the spot electricity price. Which can lead to an error, due to data mismatch between years. Wind and solar radiation are one of the energy sources that influence spot electricity prices in Denmark. Nevertheless, gaining access to the weather dataset from Danish Meteorological Institute (DMI) for the year 2021 required creating an Application Programming Interface (API), which is outside of the scope of this project.

8. Introduction to Polysun

As it was stated before, the simulation of strategies was performed in Polysun. In Table 8, one can see the overview of all four simulations.

Table 8. Overview of four strategies simulated in Polysun

	Strategy 1	Strategy 2	Strategy 3	Strategy 4
DHW Tank 250 L	yes	yes	yes	yes
Buffer tank 550 L	no	yes	no	yes
Electricity price	no	no	yes	yes
Building Time constant	no	no	yes	yes

8.1 Input from the building – model of the house

Some information from the building envelope and HVAC systems is needed to create a model in Polysun. The calculated parameters needed as input in Polysun to simulate the building case are mentioned in Table 9. All calculations are mentioned in Annex D.1.

Table 9. Input values for building case in Polysun

Parameter	**Value**
U-value of the building (W/K.m^2)	0.48
Window-to-wall area ratio South	14.33
Window-to-wall area ratio North	31.26
Window-to-wall area ratio East	13.22
Window-to-wall area ratio West	13.94
Air change (1/h)	0.6
Air infiltration (1/h)	0.15
Internal heat gain (people) (W/m^2)	3.36
Internal heat gain (equipment) (W/m^2)	3.14
Heat capacity of the building (kJ/K/m^2)	867

8.2 Heat Pump

A 7 kW air-to-water heat pump was used in polysun simulation to produce heat for both space heating and the DHW water systems. General data for this heat pump is mentioned in Table 10 and detailed technical data is mentioned in Annex E.

Table 10. Air-to-water heat pump in the building case

Nominal heating capacity (kW)	Seasonal COP	Water Flow Rate (l/h)	Refrigerant	Refrigerant amount (kg)	Integrated pump
5.62	4.11	600	R-407C	4	yes

8.3 Temperatures

The temperature setpoint was determined according to DS/EN ISO 16798-2 [38]. The operative temperature criteria are specified as 20-24°C for category II with sedentary activity. With that being said, the setpoint for Strategies 1 and 2, heating setpoint was determined as 22°C. In Strategies 3 and 4, the electricity price signal is considered, therefore operative temperature controller is set to be floating between 21.5°C with the allowance to increase to a maximum of 24°C.

Following the demand, water temperature in all parts of the installation during normal usage does not fall below 50°C and 45°C during peak hours [39]. Furthermore, the temperature set for tapping was set to vary between 40 to 55°C. The volume of the tank is 250 L. In addition, to avoid the risk of too hot water temperature at the tap, the hot water from the tank was mixed with cold water before reaching the tap, as a safety precaution.

Since the supply temperature for the floor heating is 35°C therefore, the temperatures in the buffer tank were set up to be between 35-45°C to ensure the correct temperature at the inlet for heating. Moreover, the volume of the tank is specified as 550 L.

8.4 Thermal Energy Sensor

An investigation has been made regarding the DHW tank sensor position, in the layer of the tank. The sensor has been set at layer 9 and layer 11 respectively, whilst the bottom sensor is located at layer 5. Figure 22 represents the energy deficit [kWh] for both configurations. An energy deficit is a difference between energy demand and its effective consumption. The deficit is calculated as energy [kWh], based on the required setpoint temperature at withdrawal (DHW) and the occurrence at which the temperature is not reaching the demand. As one can see, throughout the year the deficit is larger while having a sensor at layer 11 (150 kWh in total) compared to layer 9 (129 kWh in total). In other words, the average temperature in the tank will be lower once the sensor is placed at layer 11. Consequently, layer 9 will be a consideration throughout the project. Furthermore, the same investigation is made for the strategy 2 setup. According to Figure 22, the deficit is larger while having a sensor at the top layer 11 (137 kWh in total) compared to layer 9 (114 kWh in total). The investigation details are mentioned in Annex F.

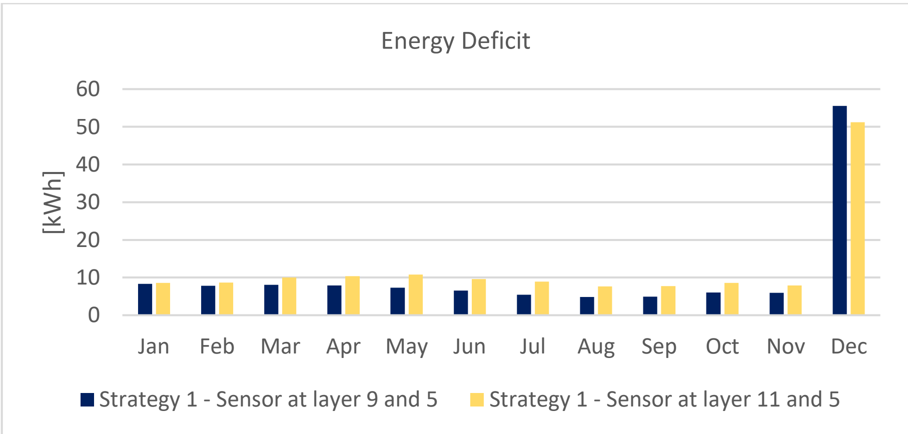


Figure 22. Energy deficit comparison due to different sensor placement

9. Strategies Presentation

In this chapter, all four strategies will be presented and results for operative and DHW temperatures, heat pump COP, operation time, and switch-on times will be shown in figures and tables.

9.1 Strategy 1

The input and configuration of the Strategy 1 are presented in Table 11. The building is heated up to reach the setpoint of 22°C (operative temperature in the building), with the heat pump working cycle to be set as ON/OFF. Meaning, that whenever the operative temperature is reached, the HP automatically shuts off and when the operative temperature is below the mentioned setpoint (22°C) the HP starts working again. The same principle is applied to the DHW. When the temperature in the potable tank is too low, the pump is turned on and when it reached the demand, the pump is shut down.

Table 11. Strategy 1 - Input and Configuration

Configuration	Input
Temperature setpoint in the building	22°C
Storage tank 250 L	yes
Temperature in the hot water tank (between sensors)	40-60°C
Tap water temperature	40 - 55°C
Buffer tank 550 L	no
Temperature in the buffer tank (between sensors)	35 - 45°C
Heat Pump (Air to water)	yes
Supply temp. floor heating	35°C
Considering the time constant of the building	no
Considering the electricity price	no
Computation priority 1	Domestic hot water (DHW)
Computation priority 2	Operative temperature

The configuration of the system in Polysun for Strategy 1 is presented in Figure 23. Sensors in the tank are located in layers 5 and 9.

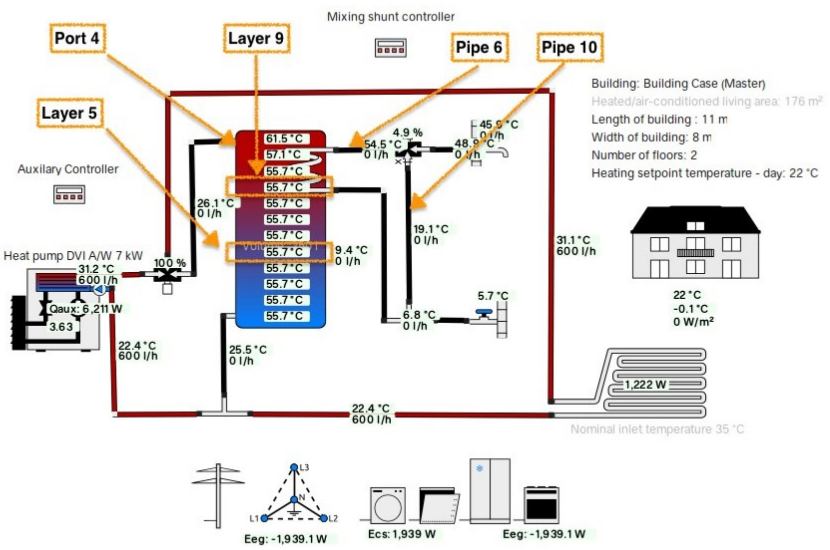


Figure 23. Overview of the system configuration in strategy 1

Following, a control strategy of the auxiliary heating controller can be seen in Table 12. The strategy is set to reach a set point (22°C) in the building. The controller is using the sensor in the building to measure operative temperature, as well as water in the DHW tank in layer 9 for the heat pump to switch on and layer 5 to switch off. Reference to the temperature sensor in the tank layer 5 is set to +10 °C to cut-off differential for the DHW setpoint of 50°C. Therefore, if tank layer 5 reaches 60°C it will stop feeding hot water to the tank. If the temperature drops below 40°C, the sensor sends a signal to the HP to start heating again. Based on all of these information, a switching valve decides its position (0% or 100%) to supply enough water to reach setpoints. The availability of the heat pump is set as always. In Table 12 and Table 13, the controller settings as well as input and output values, for the auxiliary heating controller and mixing valve controller, are mentioned respectively.

Table 12. Strategy 1 - Auxiliary heating controller

Name	Value	Unit
Computation priority	1	-
Logic relation temperature sensor 1	OR operation	-
Reference for temperature sensor 1	Variable value	-
Cut in differential 1	0	dT (°C)
Cut-off differential	10	dT (°C)
Reference for temp. sensor 2	Variable value	-
Cut-in differential 2	0	dT (°C)
Cut-off differential 2	0	dT (°C)
Minimum operation time	15	Minutes
Maximum downtime	20	Minutes
Control inputs		
Layer temperature sensor on 1	DHW tank: Layer 9	(°C)
Layer temperature sensor off 1	DHW tank: Layer 5	(°C)
Temperature sensor 1	Hot water demand: temperature setting	(°C)
Layer temperature sensor on 2	Building temperature	(°C)
Layer temperature sensor off 2	Building temperature	(°C)
Temperature sensor 2	Building: setpoint room temp.	(°C)
Control outputs		
On/off heating device	Heat pump: on/off	%
On/off heating loop pump	Three-way valve: switching valve	-
Operation: Always		

Table 13. Strategy 1 – Mixing valve controller

Name	Value	Unit
Computation priority	2	-
Definition temperature setting	Variable value	-
Temperature shift	5	dT (°C)
Control inputs		
Upper temperature level	Pipe 6: Temperature	(°C)
Lower temperature level	Pipe 10: Temperature	(°C)
Variable temperature setting	Hot water demand: temperature setting	(°C)
Control outputs		
Mixing valve	Three-way valve: Valve position	%
Operation: Always		

9.1.1 Domestic Hot Water

Figure 24 visualizes results for DHW temperature at withdrawal points scattered throughout the year. As can be seen, the setpoint is met and varies between 40°C and 55°C. Hourly data used for DHW withdrawal temperature in Figure 24 is mentioned in Annex G.1.

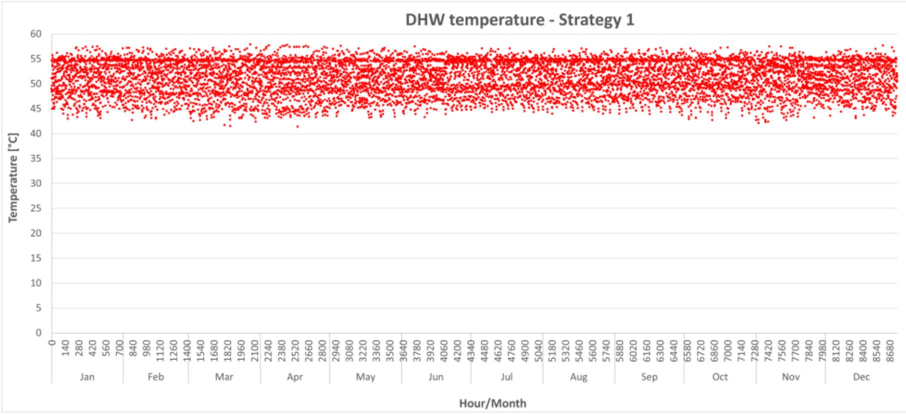


Figure 24. Strategy 1 - DHW temperature

9.1.2 Indoor Comfort

According to Figure 25, the indoor temperature remained around 22°C throughout the whole heating season (January to April and October to December), except for late December. Between December 17th and 23rd, the heat pump could not provide sufficient heating energy to the building so the operative temperature eventually decreased to 21.3°C at the lowest with respect to the set point value of 22°C. All data used to generate Figure 25 for operative temperature in Strategy 1 is presented in Annex G.1.

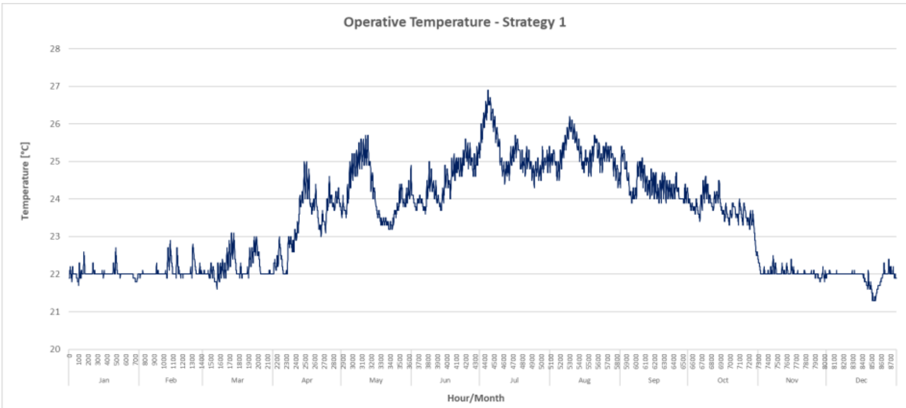


Figure 25. Strategy 1 - Operative temperature

9.1.3 Heat Pump

Figure 26 depicts the average, minimum, and maximum coefficient of performance (COP) of the heat pump throughout the year 2021. Based on this curve it can be concluded that the heat pump is the least efficient during the heating season, therefore it is expected for the system to encounter difficulties reaching certain setpoints. The highest average COP is in June and September with 4 while the maximum COP occurred in November with 5.9. According to Figure 26, the heat pump works more even during the non-heating season compared to the heating season since it fluctuates less in terms of performance and has the lowest difference between the minimum and maximum COP. The calculated average, minimum and maximum heat pump COP throughout the year 2021 for Strategy 1 is mentioned in Annex G.7.

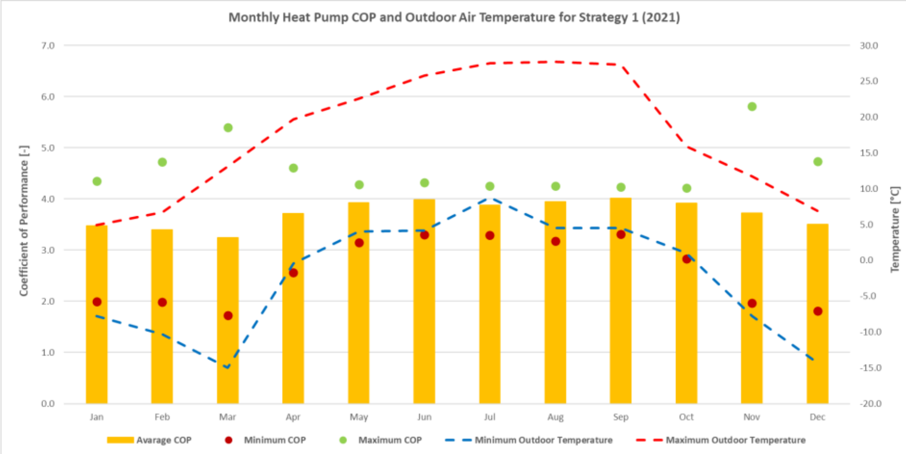
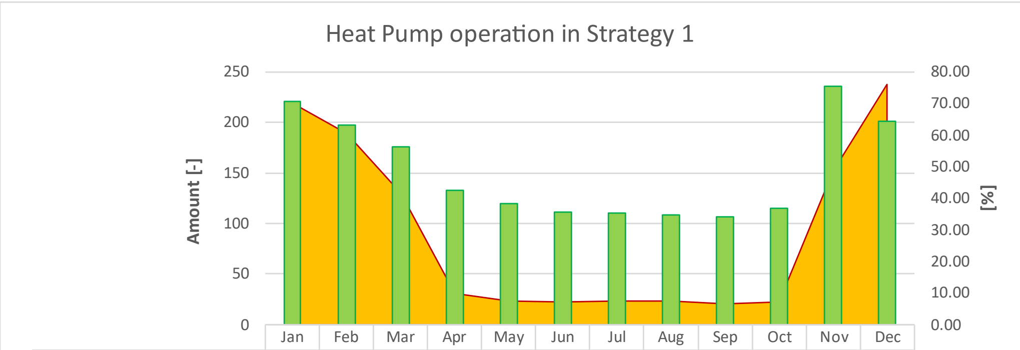


Figure 26. Strategy 1 - Monthly heat pump COP, and outdoor temperature in 2021

Switch-on times as well as overall operation time can be seen in Figure 27. During the non-heating season, the frequency of switch-on times is large in comparison to operation time, unlike during the heating season. The reason for the more often switch-on times of the heat pump is the volume of the DHW tank. Withdrawal intensity is affecting the temperature in the tank, and it is forcing the heat pump to work more often to compensate for DHW demand and reach setpoints set for tank layers. The annual operation time is 2529 hours with 1838 switch-on times. The details for all values used in this figure are presented in Annex G.4.



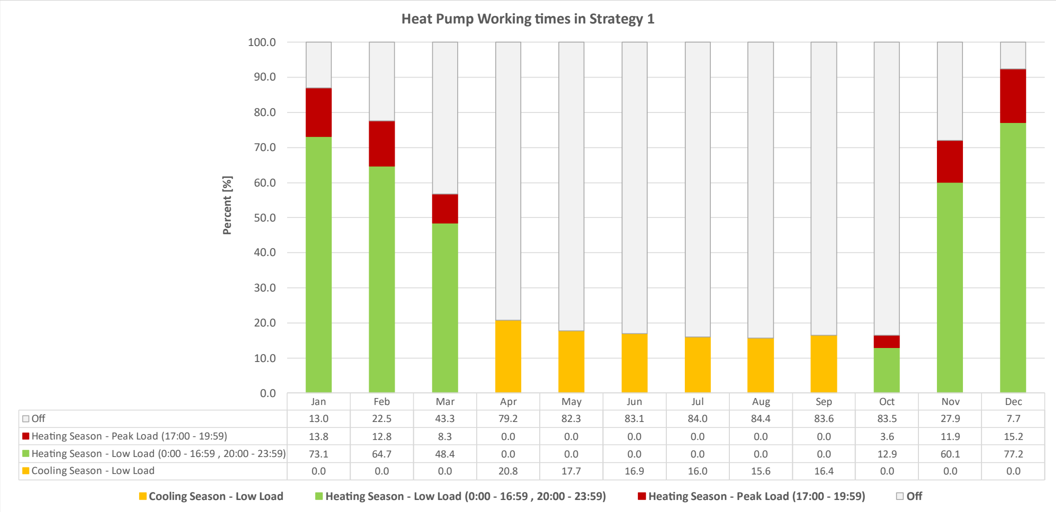
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Operation % of month	70.16	60.57	41.59	9.85	7.31	7.17	7.34	7.40	6.61	6.93	48.39	75.97
Number of switch-on times [-]	221	197	176	133	120	111	110	108	106	115	236	201

Figure 27. Strategy 1 - Monthly heat pump operation time and switch-on times in 2021

Data analysis has been performed to investigate the operation time of the heat pump within different periods. Since the case is a single-family house, C-tariff is considered for price analysis. Each month in the heating season from October to March is divided into two different timing periods; low and peak load, while there is no peak load during the cooling season: [40]

- Cooling Season - Low Load (24h)
- Heating Season - Low Load (0:00 - 16:59, 20:00 - 23:59)
- Heating Season - Peak Load (17:00 - 19:59)

Figure 28 shows heat pump working times during the year divided into months. Each column represents a fraction of the time in percentage in which the heat pump works as well as times when the heat pump is off. Where one can see that the share of hours is distributed in a way that the heat pump operates always longer during Low Load periods throughout the year. The reason for that is the classified period within 24 hours to be considered as Peak Load happens less often than the Low Load period. Nevertheless, the heat pump is expected to consume more electricity during the Peak Period. This fact indicates that there are savings to be gained by reducing that share of heat pump working hours at Peak Load periods and shifting it to preferably Low Load periods during the heating season. Data used to generate this figure for heat pump working times in Strategy 1 is presented in Annex G.3.

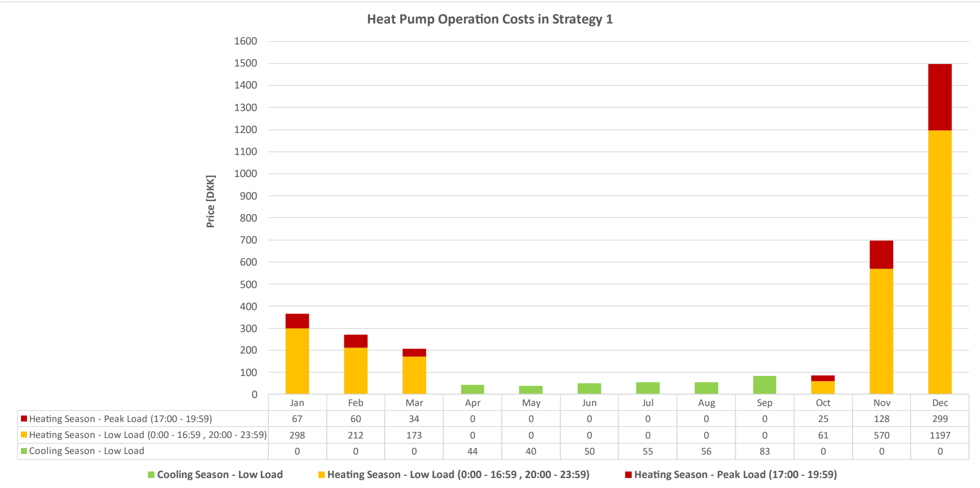


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Off	13.0	22.5	43.3	79.2	82.3	83.1	84.0	84.4	83.6	83.5	27.9	7.7
Heating Season - Peak Load (17:00 - 19:59)	13.8	12.8	8.3	0.0	0.0	0.0	0.0	0.0	0.0	3.6	11.9	15.2
Heating Season - Low Load (0:00 - 16:59 , 20:00 - 23:59)	73.1	64.7	48.4	0.0	0.0	0.0	0.0	0.0	0.0	12.9	60.1	77.2
Cooling Season - Low Load	0.0	0.0	0.0	20.8	17.7	16.9	16.0	15.6	16.4	0.0	0.0	0.0

Figure 28. Strategy 1 - Heat pump monthly working time in different load periods

9.1.4 Summary

The cost of running a heat pump in before mentioned configuration, using a variable electricity tariff is depicted in Figure 29. Annual cost reaches 3451 DKK for the whole year without costs affiliated with Danish taxes as well as distribution and monthly subscription. The largest savings potential is expected to happen during November and December due to a larger share of operating costs to run a heat pump during the Peak Period. Data used to draw Figure 29 for energy costs in Strategy 1 is mentioned in Annex G.6.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating Season - Peak Load (17:00 - 19:59)	67	60	34	0	0	0	0	0	0	25	128	299
Heating Season - Low Load (0:00 - 16:59 , 20:00 - 23:59)	298	212	173	0	0	0	0	0	0	61	570	1197
Cooling Season - Low Load	0	0	0	44	40	50	55	56	83	0	0	0

Figure 29. Strategy 1 - Heat pump operation costs in 2021

9.2 Strategy 2

The input and configuration of the Strategy 2 are presented in Table 14. In this scenario, the system is equipped with a buffer tank, which is used for underfloor heating. Whenever the operative temperature in the building drops below the setpoint (22°C), the heat pump starts working or the buffer tank discharges using stored energy. The heat pump works constantly as an on/off to maintain the temperature in the storage tank for domestic hot water as well as to charge the buffer tank whenever the temperature drops below 35°C.

Table 14. Strategy 2 - Input and Configuration

Configuration	Input
Temperature setpoint in the building	22°C
Storage tank 250 L	yes
Temperature in DHW tank	40-60°C
Tap water temperature	40 - 55°C
Buffer tank 550 L	Yes
Temperature in the buffer tank	35-45°C
Heat Pump (Air to water)	yes
Supply temp. floor heating	35°C
Considering the time constant of the building	no
Considering the electricity price	no
Computation priority 1	Domestic hot water
Computation priority 2	Operative temperature

The configuration of the system in Polysun for Strategy 2 is presented in Figure 30. Sensors for both tanks are located in layer 5 and layer 9.

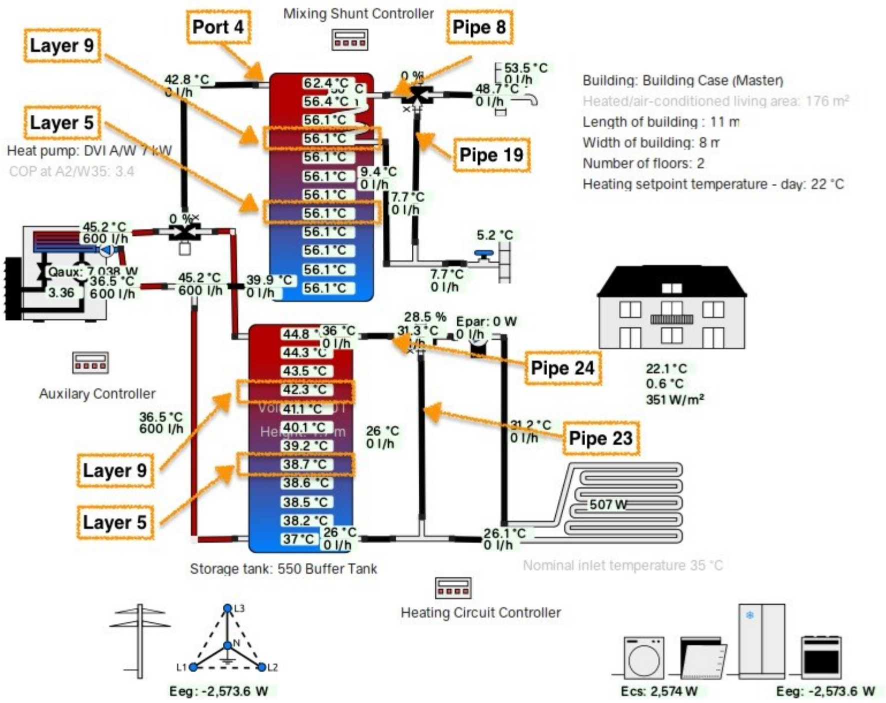


Figure 30. Overview of the system configuration in strategy 2

Following, a control strategy of the auxiliary heating controller can be seen in Table 15. The strategy is set to reach a setpoint (22°C) temperature in the building. The controller is using a sensor in the DHW tank in layer 9 for the heat pump to switch on, and the sensor in layer 5 to switch off. Reference to the temperature sensor in the tank is set to +10°C to cut-off differential to the DHW setpoint of 50°C. The buffer tank for the space heating controller is using sensors in layer 9 and layer 5. Reference to the temperature sensor in the space heating tank is set to 0°C for cut-in and +10°C cut-off differential with reference to the inlet setting of the underfloor heating (UFH) system of 35°C. Based on all that information, a switching valve decides its position (0% or 100%) to supply enough water to reach setpoints. The availability of the pump is set as always. The heating circuit controller (Figure 30) is established to activate the circulation pump and switching valve to mix return water with inlet water in case of too large supply temperatures.

The controller settings as well as input and output values, for the auxiliary heating controller, heating loop controller and mixing valve controller, are mentioned in Table 15, Table 16, and Table 17, respectively.

Table 15. Strategy 2 - Auxiliary heating controller

Name	Value	Unit
Computation priority	1	-
Logic relation temperature sensor 1	OR operation	-
Reference for temperature sensor 1	Variable value	-
Cut-in differential 1	0	dT (°C)
Cut-off differential 1	10	dT (°C)
Reference for temperature sensor 2	Variable value	-
Cut-in differential 2	0	dT (°C)
Cut-off differential 2	10	dT (°C)
Minimum operation time	15	Minutes
Minimum downtime	20	Minutes
Control inputs		
Layer temperature sensor on 1	DHW tank: Layer 9	(°C)
Layer temperature sensor off 1	DHW tank: Layer 5	(°C)
Temperature sensor 1	DHW demand: Temperature setting	(°C)
Layer temperature sensor on 2	Buffer tank: Layer 9	(°C)
Layer temperature sensor off 2	Buffer tank: Layer 5	(°C)
Temperature sensor 2	Heating inlet temperature	(°C)
Control outputs		
ON/OFF heating device	Heat pump: On/off	%
ON/OFF feedwater pump	Three-way switching valve	-
Operation - ALWAYS		

Table 16. Strategy 2 - Heating circuit controller

Name	Value	Unit
Computation priority	3	-
Activation of the heating loop	10	(°C)
Cut-in differential	0	dT (°C)
Cut-off differential	0	dT (°C)
Control inputs		

Outdoor temperature	Outdoor temperature	(°C)
Room temperature setting	Setpoint room temperature	(°C)
Actual room temperature	Temperature	(°C)
Flow rate setting	Total nominal inlet flow	l/h
Variable temperature setting	Inlet temperature setting	(°C)
Upper temperature level	Pipe 24: Temperature	(°C)
Lower temperature level	Pipe 23: Temperature	(°C)
Control outputs		
ON/OFF heating device	Circulation pump heating loop: On/off	%
Mixing valve	Three-way valve: Space heating loop	%
Flow rate setting	Circulation pump heating loop: Flow rate	l/h
Operation - ALWAYS		

Table 17. Strategy 2 – Mixing valve controller

Name	Value	Unit
Computation priority	2	-
Definition temperature setting	Variable value	-
Temperature setting	5	dT (°C)
Control inputs		
Variable temperature setting	DHW demand: Temperature setting	(°C)
Upper temperature level	Pipe 8: Temperature	(°C)
Lower temperature level	Pipe 19: Temperature	(°C)
Control outputs		
Mixing valve	Three-way valve DHW	%
Operation - ALWAYS		

9.2.1 Domestic Hot Water

According to Figure 31, the DHW at the withdrawal point is always within the acceptable range throughout the whole year. The temperature is more widespread than the temperature depicted in DHW temperature in Strategy 1. Hourly data used in Figure 31 for DHW withdrawal temperature is mentioned in Annex H.1.

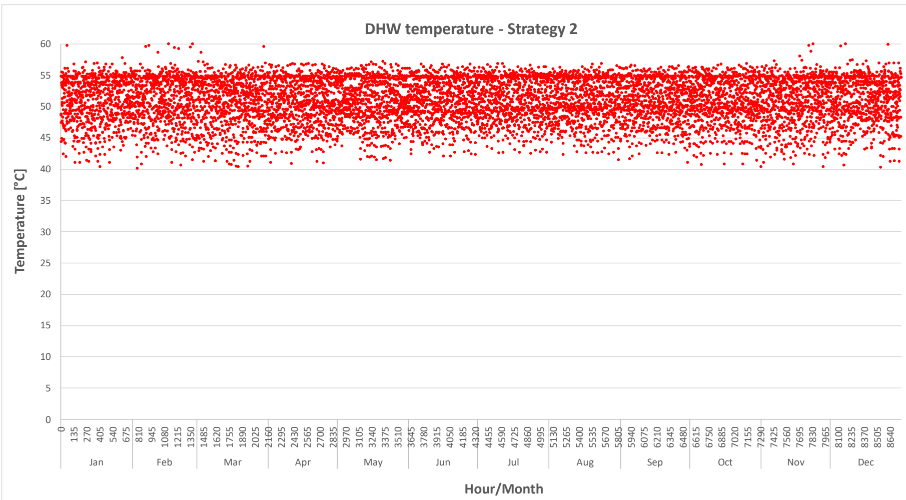


Figure 31. Strategy 2 - DHW temperature

9.2.2 Indoor Climate

According to Figure 32, the operative temperature remained around 24°C throughout the whole heating season (January to April and October to December), except for December. Between December 17th and 23rd, the heat pump could not provide sufficient heating energy to the building so the operative temperature eventually decreased by 21.4°C at the lowest with respect to the set point value of 22°C. The hourly details for all values used in Figure 32 are presented in Annex H.1.

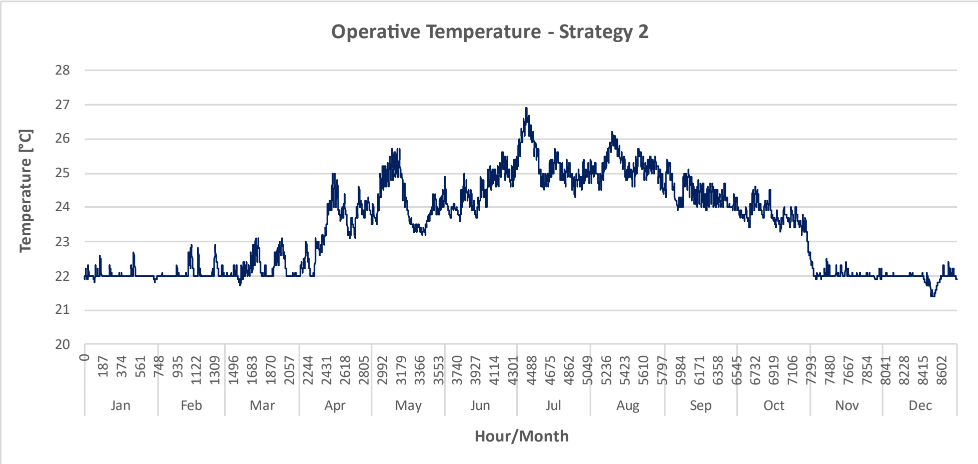


Figure 32. Strategy 2 - Operative temperature

9.2.3 Heat Pump

Figure 33 depicts the average, minimum, and maximum coefficient of performance (COP) of the heat pump throughout the year 2021. Based on this bar chart it can be concluded that the heat pump is the least efficient during the heating season, therefore it is expected for the system to encounter difficulties reaching certain setpoints. The highest average COP is in May, June, and September with 4.1 while the maximum COP occurred in March and November with 5.9 and 5.4. According to Figure 33, the heat pump works evenly during the non-heating season compared to the heating season since it fluctuates less in terms of performance and has the lowest difference between the minimum and maximum COP. Data used for Figure 33 can be found in Annex H.7.

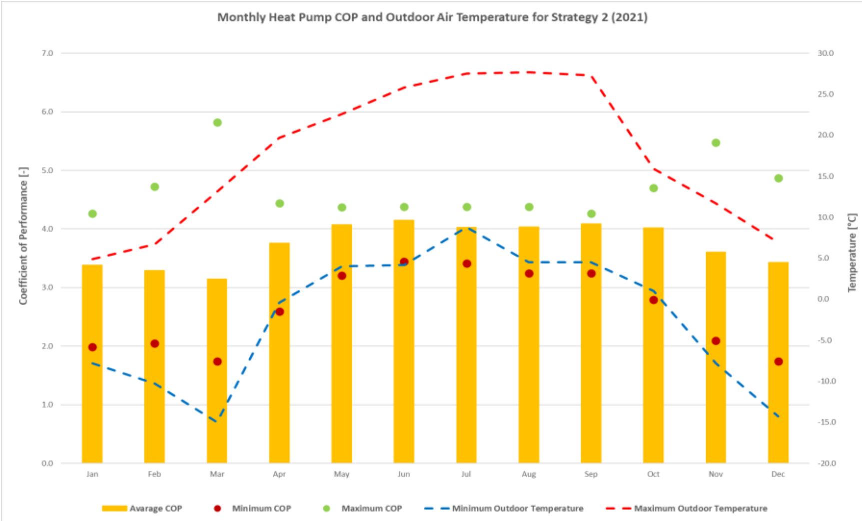


Figure 33. Strategy 2 - Monthly heat pump COP, and outdoor temperature in 2021

Switch-on times as well as overall operation time can be seen in Figure 34. On the contrary, the number of switch-on times is distributed equally throughout the year, it can be noticed that the number of switch-on times throughout the heating season is reduced. The reason for a large share of the switch-on times during non-heating season can be the volume of the DHW tank. Withdrawal intensity is affecting the temperature in the tank, and it is forcing the heat pump to work more often to compensate for DHW demand. The annual operation time is 2479 hours with 1456 switch-on times. Operation time is 55 hours less comparing Strategy 1 whilst being switched on 382 times less, which indicated lesser wear of the heat pump over time. The details for all values used in Figure 34 are presented in Annex H.4.

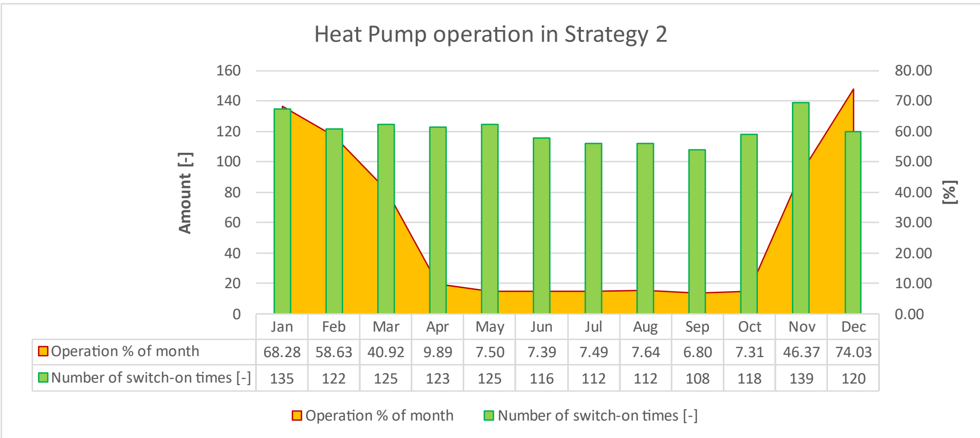


Figure 34. Strategy 2 - Monthly heat pump operation time and switch-on times in 2021

Figure 35 shows heat pump working times during the year divided into months. Each column represents a fraction of the time in percentage in which the heat pump works as well as times when the heat pump is off. Where one can see that the share of hours is distributed in a way that the heat pump operates always longer during Low Load periods throughout the year. The reason for that is the classified period within 24 hours to be considered as Peak Load happens less often than the Low Load period. Nevertheless, during the Peak Period heat pump is expected to consume more electricity. This fact indicates that there are savings to be gained by reducing that share of heat pump working hours at Peak Load periods and shifting it to preferably Low Load periods during the heating season. All data used to draw Figure 35 is presented in Annex H.3.

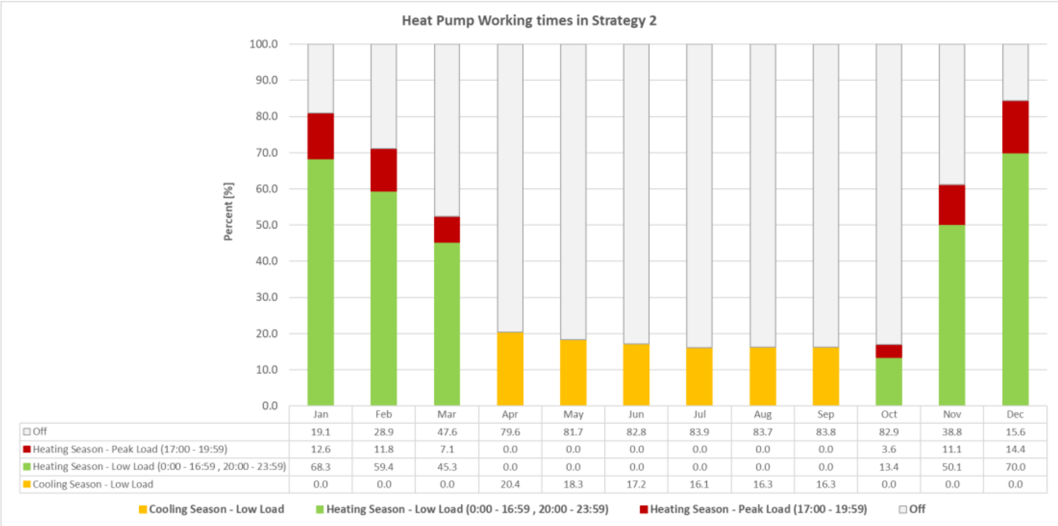


Figure 35. Strategy 2 - Heat pump monthly working time in different load periods

9.2.4 Summary

Figure 36 shows heat pump running costs in the configuration mentioned at the beginning of this section. Annual cost reaches 3466 DKK for the whole year without costs affiliated with Danish taxes as well as distribution and monthly subscription. Final costs are comparable to Strategy 1, therefore largest savings potential is expected to happen during November and December due to the larger share of operating costs to run a heat pump during the Peak Period. It is assumed that savings are similar in Strategies 1 and 2, due to the lack of control strategy in heat pump operation. Data used to create Figure 36 for heat pump operation costs in Strategy 2 is mentioned in Annex H.6.

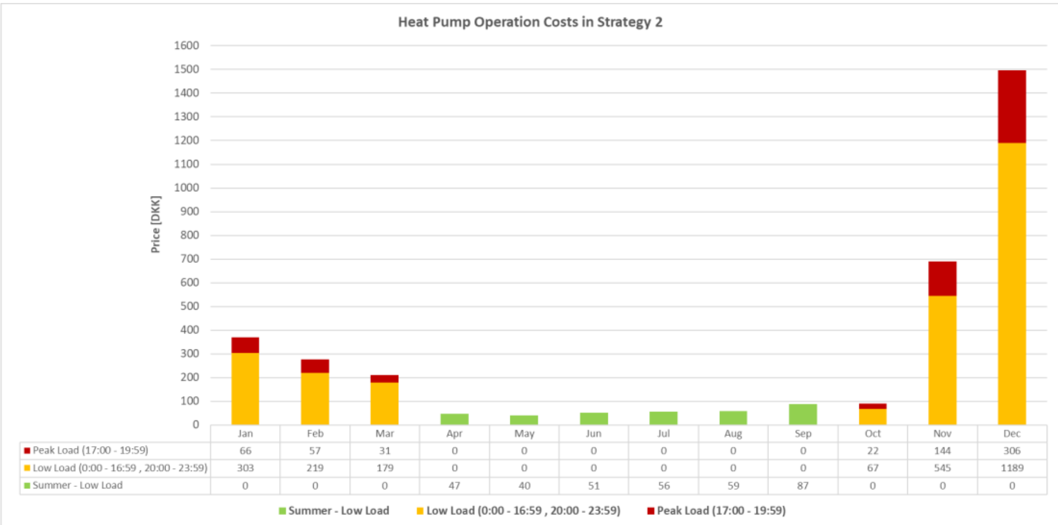


Figure 36. Strategy 2 - Heat pump operation costs in 2021

9.3 Strategy 3

The input and configuration of the Strategy 3 are presented in Table 18. The layout principle of the system was the same as in the first strategy. However, in this scenario, the electricity price signal is included in the simulation. The goal is to operate the heat pump during the Low Load period as well as avoid operation in the Peak Load period for both DHW and space heating, still maintaining the required operative temperature as well as fulfilling DHW withdrawal temperatures. On certain occasions, if the price signal fails, a push forcing of the heat pump is expected to happen to fulfil comfort criteria for indoor temperature and DHW temperatures. For that purpose, an analysis of the electricity prices from Nord Pool was performed to find the best optimal case for the operation of the pump. Furthermore, the time constant of the building construction is influencing the heating controller.

Table 18. Strategy 3 - Input and Configuration

Configuration	Input
Operative temperature upper setpoint in the building	24°C
Operative temperature lower setpoint in the building	21.5°C
DHW tank 250 L	yes
Temperature in DHW tank (between sensors)	40-60°C
Tap water temperature	40 - 55°C
Buffer tank 550 L	no
Temperature in buffer tank (between sensors)	35 - 45°C
Heat Pump (Air to water)	yes
Supply temp. floor heating	35°C
Considering the time constant of the building	yes
Considering the electricity price	yes
Computation priority 1	Domestic hot water
Computation priority 2	Operative temperature

The configuration of the system in Polysun for Strategy 3 is presented in Figure 37. Sensors in the tank are located in layers 5 and 9.

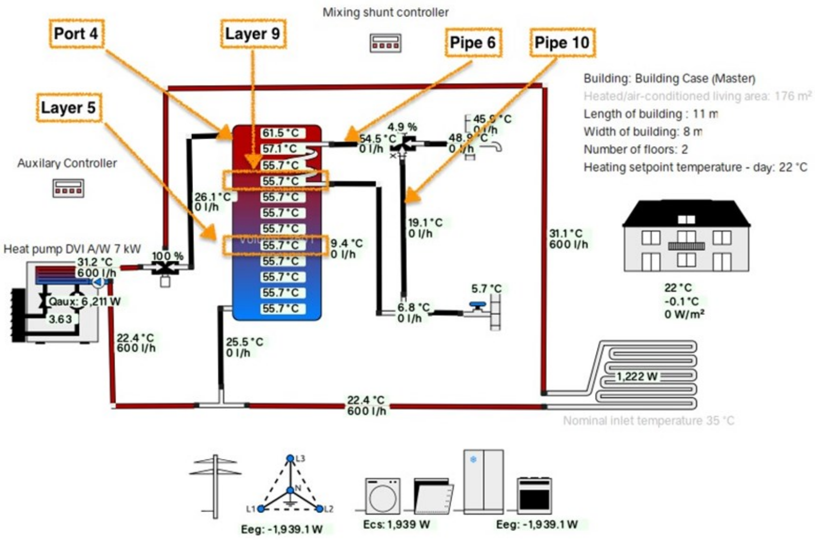


Figure 37. Overview of the system configuration in strategy 3

Following, a control strategy of the auxiliary heating controller can be seen in Table 19. The controller is using a sensor in the building to measure operative temperature, as well as water in the DHW tank in layer 9 for the heat pump to switch on and layer 5 to switch off. For the operative temperature, a floating controller is set to vary between 24°C and 21.5°C. Cut in differential is set to -0.5°C and cut off as 2°C with the reference to the operative temperature setpoint of 22°C. Therefore, the maximum operative temperature is allowed to reach 24°C and a minimum of 21.5°C. Reference to the temperature sensor in the tank layer 5 is set to +10 °C to cut-off differential for the DHW setpoint of 50°C. Therefore, if tank layer 5 reaches 60°C it will stop feeding hot water to the tank. If the temperature drops below 40°C, the sensor sends a signal to the HP to start heating again Based on all that information, a switching valve decides its position (0% or 100%) to supply enough water to reach setpoints. The availability of the pump is based on the price signal. The controller settings as well as input and output values, for the auxiliary heating controller and mixing valve controller, are presented in Table 19 and Table 20, respectively.

Table 19. Strategy 3 - Auxiliary heating controller

Name	Value	Unit
Computation priority	1	-
Logic relation temperature sensor 1	OR operation	-
Reference for temperature sensor 1	Variable value	-
Cut in differential 1	0	dT (°C)
Cut-off differential	10	dT (°C)
Reference for temp. sensor 2	Variable value	-
Cut-in differential 2	-0.5	dT (°C)
Cut-off differential 2	2	dT (°C)
Minimum operation time	15	Minutes
Maximum downtime	20	Minutes
Control inputs		
Layer temperature sensor on 1	DHW tank: Layer 9	(°C)
Layer temperature sensor off 1	DHW tank: Layer 5	(°C)
Temperature sensor 1	Hot water demand: temperature setting	(°C)
Layer temperature sensor on 2	Building temperature	(°C)
Layer temperature sensor off 2	Building temperature	(°C)
Temperature sensor 2	Building: setpoint room temp.	(°C)
Control outputs		
On/off heating device	Heat pump: on/off	%
On/off heating loop pump	Three-way valve: switching valve	-
Operation: Price Signal		

Table 20. Strategy 3 – Mixing valve controller

Name	Value	Unit
Computation priority	2	-
Definition temperature setting	Variable value	-
Temperature shift	5	dT (°C)
Control inputs		
Upper temperature level	Pipe 6: Temperature	(°C)
Lower temperature level	Pipe 10: Temperature	(°C)
Variable temperature setting	Hot water demand: temperature setting	(°C)
Control outputs		
Mixing valve	Three-way valve: Valve position	%
Operation: Always		

9.3.1 Price Signal and force running of Heat Pump

Since the priority of this project is providing DHW at withdrawal within the temperature range of 40-55°C, **13 different possibilities** for the heat pump switching profiles have been investigated. The first option for the data treatment for electricity prices was to take the minimum price per day and add 15% on top of that. Then 20%, 25%, and 30% are added to the minimum electricity price to create the next switching times for the heat pump. The following three options for switching time were created by adding 5%, 10%, and 15% on top of the daily average electricity price. So, the heat pump is available at times when the prices are lower than 55%, 60%, and 75% of the average electricity price. Next switching profiles were created based on average daily prices with -5%, -10%, and -15% deductions. Finally, two other possibilities for the heat pump switching profiles were created according to the price spread (between the minimum and maximum daily prices). In the first profile, all hours with electricity price lower than 50% was considered as availability times for the heat pump and in the second one, availability times were considered for prices lower than 75%. Table 21 summarizes all possibilities considered. Hourly data of 13 Switching profiles used in Strategy 3 are mentioned in Annex J.

Table 21. Different heat pump switching profiles created according to the hourly signal price

Switching profiles												
a)	**b)**	**c)**	**d)**	**e)**	**f)**	**g)**	**h)**	**i)**	**j)**	**k)**	**l)**	**m)**
+15% of MIN. daily price	+20% of MIN. daily price	+25% of MIN. daily price	+30% of MIN. daily price	Below AVG. daily price	+5% of AVG. daily price	+10% of AVG. daily price	+15% of AVG. daily price	-5% of AVG. daily price	-10% of AVG. daily price	-15% of AVG. daily price	> 50% of the daily spread	> 75% of the daily spread

Legend:
MIN. - minimum
AVG. - average

As can be seen in Figure 38 and Table 22, the bigger value added to the minimum electricity price, the better results for domestic hot water temperatures. Furthermore, the bigger value added to the average electricity prices per day showed fewer fluctuations in domestic hot water temperatures compared to the previous options. The last profile considering more than 75% of daily spread, enhanced DHW withdrawal temperatures compared to all previous ones. All data used to generate these figures for DHW withdrawal temperature in Strategy 3 is presented in Annex J.

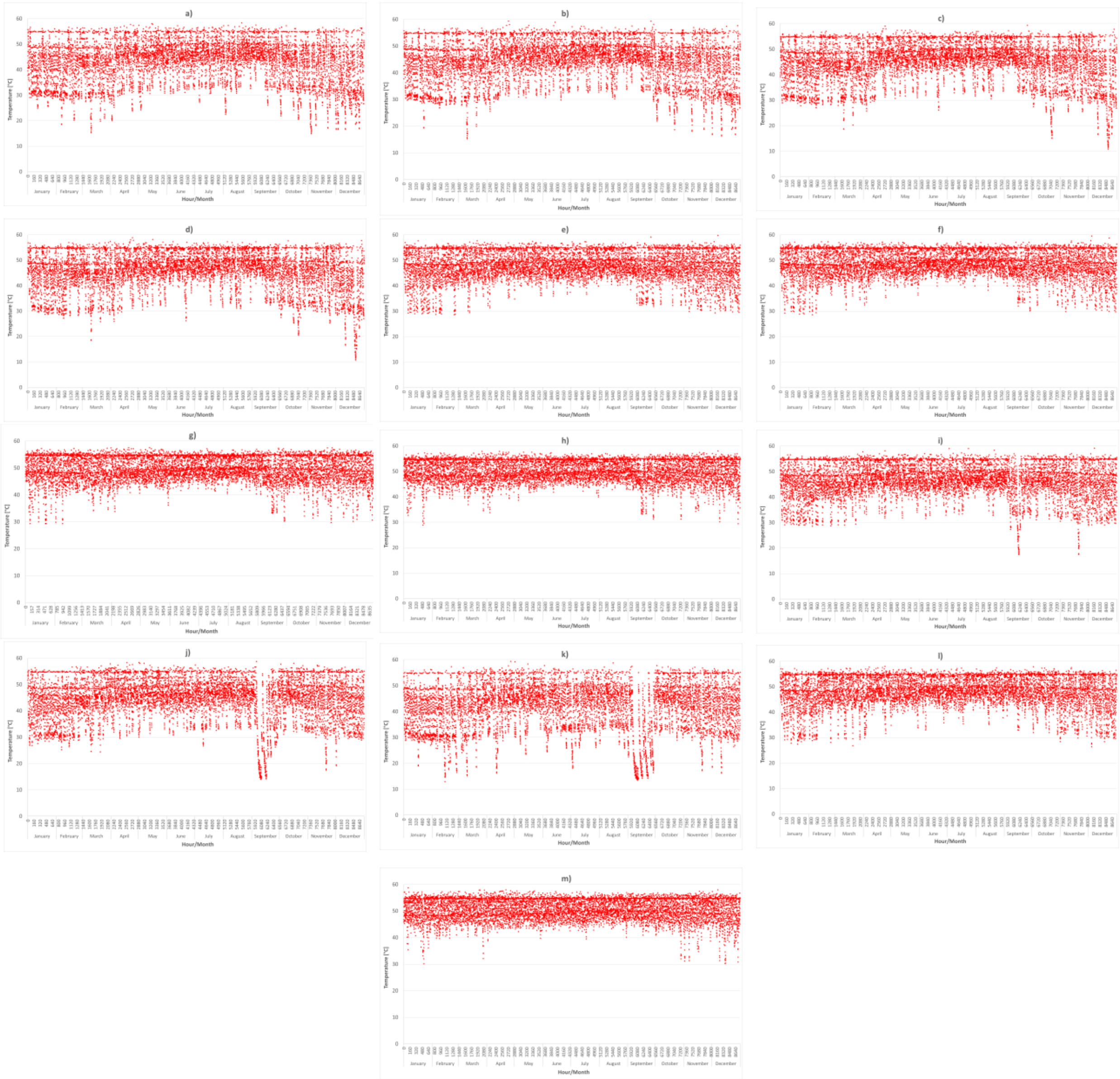


Figure 38. Strategy 3 - DHW temperature with different heat pump switching profiles

Table 22. Strategy 3 – Number of hours that DHW temperature lower than 40°C with different heat pump switching profiles

Switching profile	a)	b)	c)	d)	e)	f)	g)	h)	i)	j)	k)	l)	m)
Number of Hours (T_{DHW}<40°C)	3012	2495	2165	1930	798	554	306	191	1339	2200	3401	821	116

The other criteria in the building case is operative temperature. Figure 39 shows operative temperatures fluctuate between 23°C and 11°C during heating periods (January-April and October-December). According to EN16798-2 to meet indoor comfort for a residential building, operative temperatures should be between 20°C and 25°C. Since the goal for this project is meeting IEQ Category II, the only switching times which have considerable results to work with are h) and m). Hourly data used in Figure 39 is presented in Annex J.16.

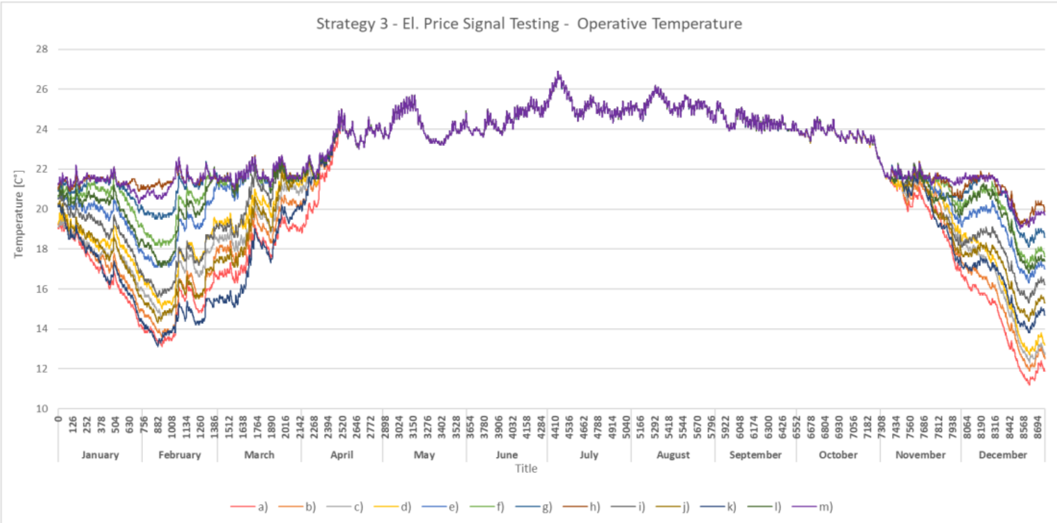


Figure 39. Strategy 3 - Operative temperature with different heat pump switching profiles

In Table 23 the number of hours in which operative temperature is lower than 20°C for different heat pump switching profiles is mentioned.

Table 23. Strategy 3 – Number of hours that operative temperature lower than 20°C with different heat pump switching profiles

Switching profile	a)	b)	c)	d)	e)	f)	g)	h)	i)	j)	k)	l)	m)
Number of Hours (T_{op}<20°)	3243	2887	2768	2589	1588	760	571	170	2543	2799	3058	1064	282

The best possible switching profiles according to Table 22 and Table 23 are h) and m). These two switching profiles were investigated and compared in terms of total electricity consumption of the heat pump, number of hours with domestic hot water temperature lower than 40°C and meeting indoor comfort considering the operative temperature. The electricity consumption and related price in Table 24 were calculated only for the operation of the heat pump.

Table 24. Strategy 3 - Comparison between the best two switching profiles

Switching Profile	h) +15% of AVG. daily price	m) < 75% of daily spread
Electricity consumption (kWh)	4251	4239
Energy Price (DKK)	2678	2727
Heat pump working hours	2266	2271
Switching on times	1012	1074
Number of Hours (T_{op}<20°C)	170	282
Number of Hours (T_{DHW}<40°C)	191	116

Further push forcing of the heat pump will be considered for switching profiles that are based on +15% of AVG. daily price [h)] and 75% of daily spread [m)]. Due to these switching profiles being not able to provide the availability to meet DHW and operative temperature demand the process of improvement of the profiles was made. The improvement procedure was done manually in which the heat pump runs by force whilst the heat pump is turned off in the current hour and domestic hot water temperature is lower than 40°C or operative temperature is lower than 20°C. After data treatment, another simulation was performed, and the results can be seen in Table 25. Data for the new switching profiles used push force the heat pump are mentioned in Annex J.15.

Table 25. Strategy 3 - Comparison between the best two switching profiles with heat pump push forcing

Switching Profile	h) Push Forcing +15% of AVG. daily price	m) Push Forcing < 75% of daily spread
Electricity consumption (kwh)	4404	4419
Energy Price (DKK)	2969	2986
Heat pump working hours	2340	2349
Switching on times	1103	1159
Number of Hours (T_{op}<20°C)	0	0
Number of Hours (T_{DHW}<40°C)	0	0

According to Table 25, the switching profile h) Push Forcing in which +15% of AVG. daily price is considered, has better results in terms of electricity consumption and price. Furthermore, the heat pump works 9 hours less, and the switch-on time is 56 times less than m) Push Forcing.

9.3.2 Domestic Hot Water

As a result of the heat pump force running, one can see that the DHW mostly fluctuates between 40°C and 56°C. The data used for Figure 40 is mentioned in Annex I.1.

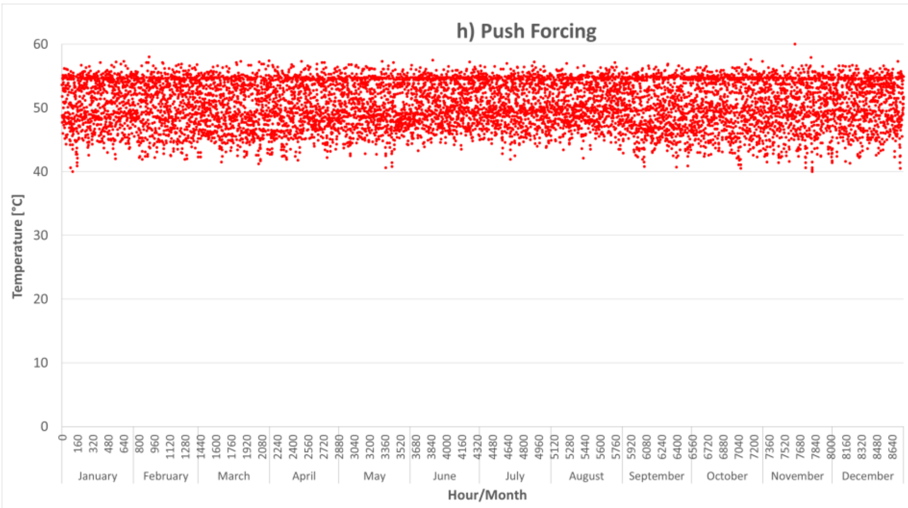


Figure 40. Strategy 3 - DHW temperature with h) push force switching profile

9.3.3 Indoor Climate

The impact of heat pump push force can be seen by comparing operative temperature throughout the year depicted in Figure 41. The operative temperature throughout the heating season improved and oscillates around 22°C with downfalls to 20°C. Data used for Figure 41 can be found in Annex J.15.

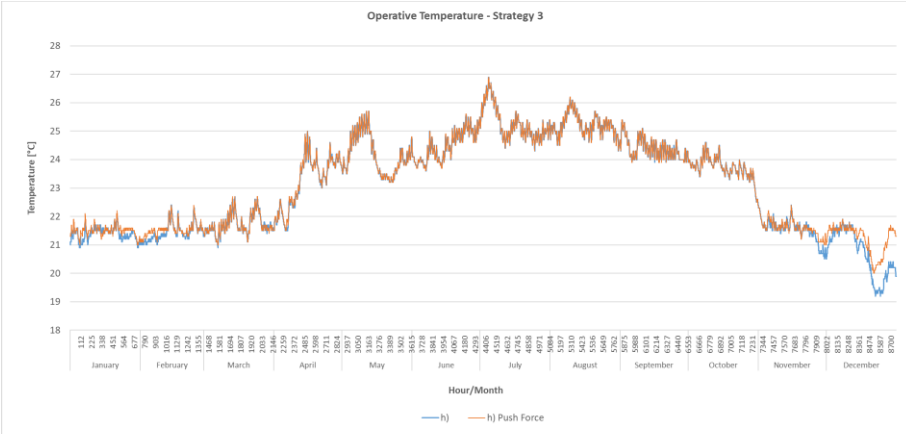


Figure 41. Strategy 3 - Operative temperature comparison between switching time profile h) and h) Push Force

9.3.4 Heat Pump

Figure 42 depicts the average, minimum, and maximum coefficient of performance (COP) of the heat pump throughout the year 2021. Based on this bar chart it can be concluded that the heat pump is the least efficient during the heating season, therefore it is expected for the system to encounter difficulties reaching certain setpoints. The highest average COP is in May, June, and September with 4 while the maximum COP occurred in March and November with 5.8 and 6.1 respectively. According to Figure 42, the heat pump works evenly during the non-heating season compared to the heating season since it fluctuates less in terms of performance and has the lowest difference between the minimum and maximum COP. All data for the heat pump COP throughout the year 2021 used in Figure 42 is mentioned in Annex I.7.

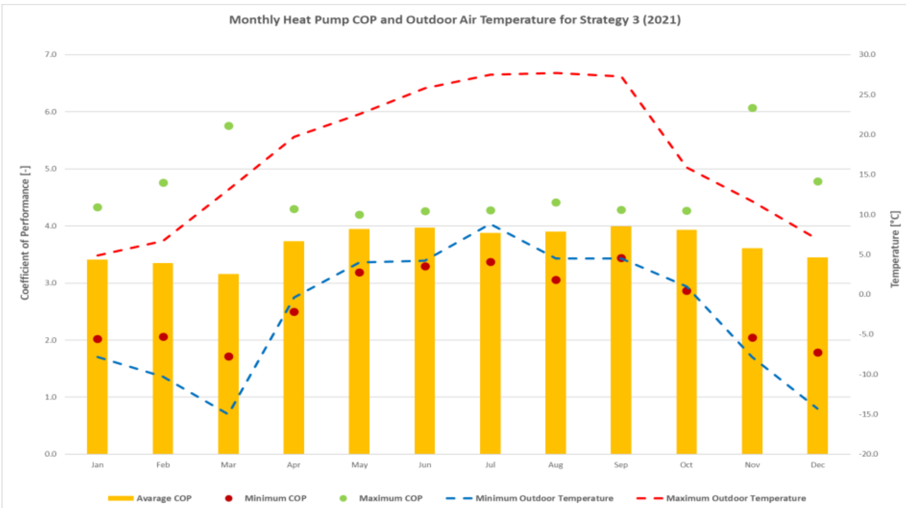


Figure 42. Strategy 3 - Monthly heat pump COP, and outdoor temperature in 2021

Switch-on times as well as overall operation time can be seen in Figure 43. During the non-heating season, the frequency of switch-on times is large in comparison to operation time, unlike during the heating season. The reason for the more often switch-on times of the heat pump can be the low volume in the DHW tank. Withdrawal intensity is affecting the temperature in the tank, and it is forcing the heat pump to work more often to compensate for DHW demand. The annual operation time is 2340 hours with 1103 switch-on times. Data used in Figure 43 is presented in Annex I.4.

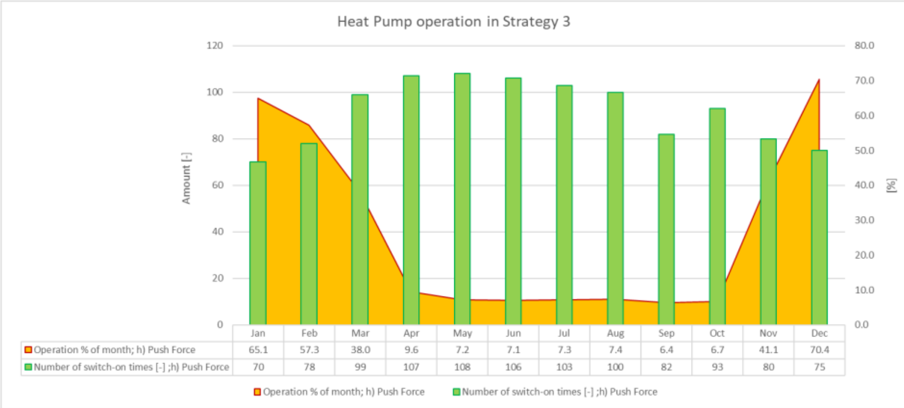


Figure 43. Strategy 3 - Monthly heat pump operation time and switch-on times in 2021

Figure 44 shows heat pump working times during the year divided into months after considering electricity price signal as well as the Bab concept where force running of the heat pump was included to meet stipulated setpoints and criteria. Each column represents a fraction of the time in percentage in which the heat pump works as well as times when the heat pump is off. Summarising, the price signal allows for a decreased operation in the peak load. Nevertheless, total peak load shaving is not within the capabilities of such a configuration. The details for all values used in Figure 44 are presented in Annex I.3.

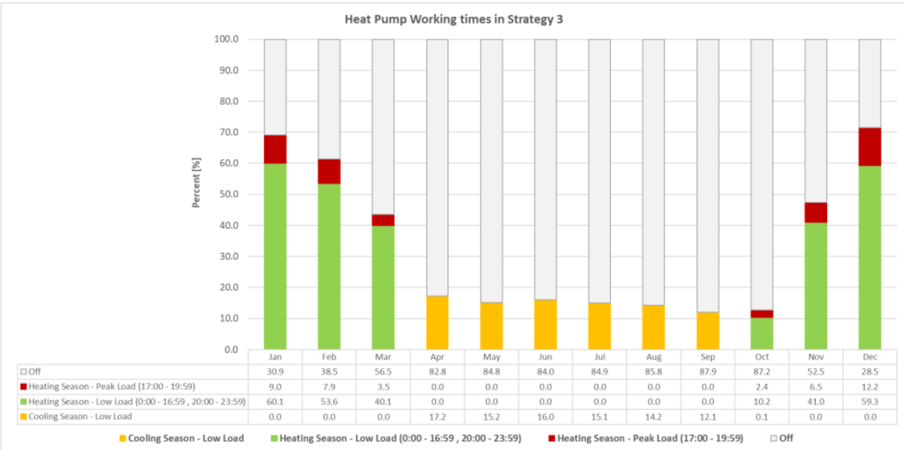
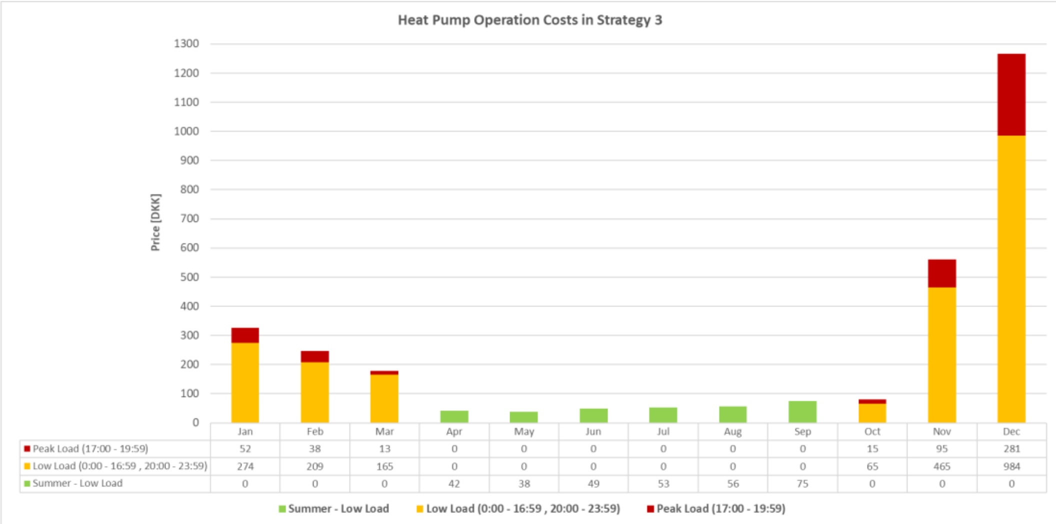


Figure 44. Strategy 3 - Heat pump monthly working time in different load periods

9.3.5 Summary

The running costs of the heat pump accordingly to the optimised configuration method, where a variable electricity tariff is being used to calculate costs, depicted in Figure 45. As the electricity costs rise in the 4th quarter of the year, an increase in the price can be seen. The annual cost reaches 2969 DKK for the whole year without costs affiliated with Danish taxes as well as distribution and monthly subscriptions. Data used in Figure 45 can be found in Annex I.6.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Peak Load (17:00 - 19:59)	52	38	13	0	0	0	0	0	0	15	95	281
Low Load (0:00 - 16:59 , 20:00 - 23:59)	274	209	165	0	0	0	0	0	0	65	465	984
Summer - Low Load	0	0	0	42	38	49	53	56	75	0	0	0

Figure 45. Strategy 3 - Heat pump operation costs in 2021

9.4 Strategy 4

The input and configuration of the Strategy 4 are presented in Table 26. The layout principle of the system was the same as in the second strategy, mentioned in Figure 46. However, in this scenario, the electricity price signal is included in the simulation. The goal is to operate the heat pump when the price is low but still maintain the required operative temperature as well as fulfil domestic hot water withdrawal temperatures. For that purpose, an analysis of the electricity prices from Nord Pool was performed to find the best optimal case for the operation of the pump. The goal is to operate the heat pump when the price is low but still maintain the operative temperature as classified in IEQ category II, as well as fulfil DHW withdrawal temperatures. Furthermore, the time constant of the building construction is influencing the heating controller. Detail explanation of the data treatment is presented in the following section.

Table 26. Strategy 4 - Input and Configuration

Configuration	Input
Temperature upper setpoint in the building	24°C
Temperature lower setpoint in the building	21.5°C
Storage tank 250 L	yes
Temperature in the hot water tank (between sensors)	40-60°C
Tap water temperature	40-55°C
Buffer tank 550 L	yes
Temperature in the buffer tank (between sensors)	35-45°C
Heat Pump (Air to water)	yes
Supply temp. floor heating	35°C
Considering the time constant of the building	yes
Considering the electricity price	yes
Computation priority 1	Domestic hot water
Computation priority 2	Operative temperature

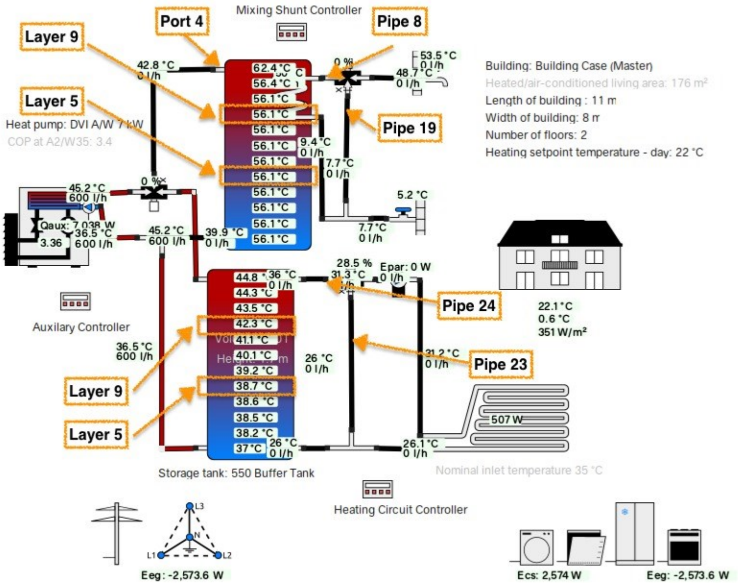


Figure 46. Overview of the system configuration in strategy 4

The control strategy is to heat the building's thermal mass using a price signal for the activation of the heat pump, once the setpoint is met heat pump is off and the building's thermal mass is expected to dissipate the heat from itself, using the Bab concept. Ideally, the control strategy must use the heat stored in the buffer tank, bought using a price signal and discharged whenever a lower setpoint is met and the electricity price is high. The heating circuit controller is set to be floating between 24°C and 21.5°C for the indoor operative temperature, Table 27, Table 28, and Table 29 present the whole configuration. Detail explanation of the data treatment is presented in the following section.

Table 27. Strategy 4 - Auxiliary heating controller

Name	Value	Unit
Computation priority	1	-
Logic relation temperature sensor 1	OR operation	-
Reference for temperature sensor 1	Variable value	-
Cut-in differential 1	0	dT (°C)
Cut-off differential 1	10	dT (°C)
Reference for temperature sensor 2	Variable value	-
Cut-in differential 2	0	dT (°C)
Cut-off differential 2	10	dT (°C)
Minimum operation time	15	Minutes
Minimum downtime	20	Minutes
Control inputs		
Layer temperature sensor on 1	DHW tank: Layer 9	(°C)
Layer temperature sensor off 1	DHW tank: Layer 5	(°C)
Temperature sensor 1	DHW demand: Temperature setting	(°C)
Layer temperature sensor on 2	Buffer tank: Layer 9	(°C)
Layer temperature sensor off 2	Buffer tank: Layer 5	(°C)
Temperature sensor 2	Heating inlet temperature	(°C)
Control outputs		
ON/OFF heating device	Heat pump: On/off	%
ON/OFF feedwater pump	Three-way switching valve	-
Operation – Price Signal		

Table 28. Strategy 4 - Heating circuit controller

Name	Value	Unit
Computation priority	3	-
Activation of the heating loop	10	(°C)
Cut-in differential	-0.5	dT (°C)
Cut-off differential	2	dT (°C)
Control inputs		
Outdoor temperature	Outdoor temperature	(°C)
Room temperature setting	Setpoint room temperature	(°C)
Actual room temperature	Temperature	(°C)
Flow rate setting	Total nominal inlet flow	l/h
Variable temperature setting	Inlet temperature setting	(°C)
Upper temperature level	Pipe 24: Temperature	(°C)
Lower temperature level	Pipe 23: Temperature	(°C)
Control outputs		
ON/OFF heating device	Circulation pump heating loop: On/off	%

Mixing valve	Three-way valve: Space heating loop	%
Flow rate setting	Circulation pump heating loop: Flow rate	l/h
Operation - ALWAYS		

Table 29. Strategy 4 – Mixing valve controller

Name	Value	Unit
Computation priority	2	-
Definition temperature setting	Variable value	-
Temperature setting	5	dT (°C)
Control inputs		
Variable temperature setting	DHW demand: Temperature setting	(°C)
Upper temperature level	Pipe 8: Temperature	(°C)
Lower temperature level	Pipe 19: Temperature	(°C)
Control outputs		
Mixing valve	Three-way valve DHW	%
Operation - ALWAYS		

9.4.1 Price Signal and force running of Heat Pump

Since the priority of this project is providing DHW within the range (40-55°C), 13 different possibilities for the heat pump switching time have been investigated. Figure 47 shows graphs for all investigated switching time profiles. Table 30, summarizes the findings for DHW withdrawal temperatures. The last profile considering more than 75% of the daily spread, showed the best results for DHW withdrawal temperatures compared to all previous ones. All data used in Figure 47 is presented in Annex L.

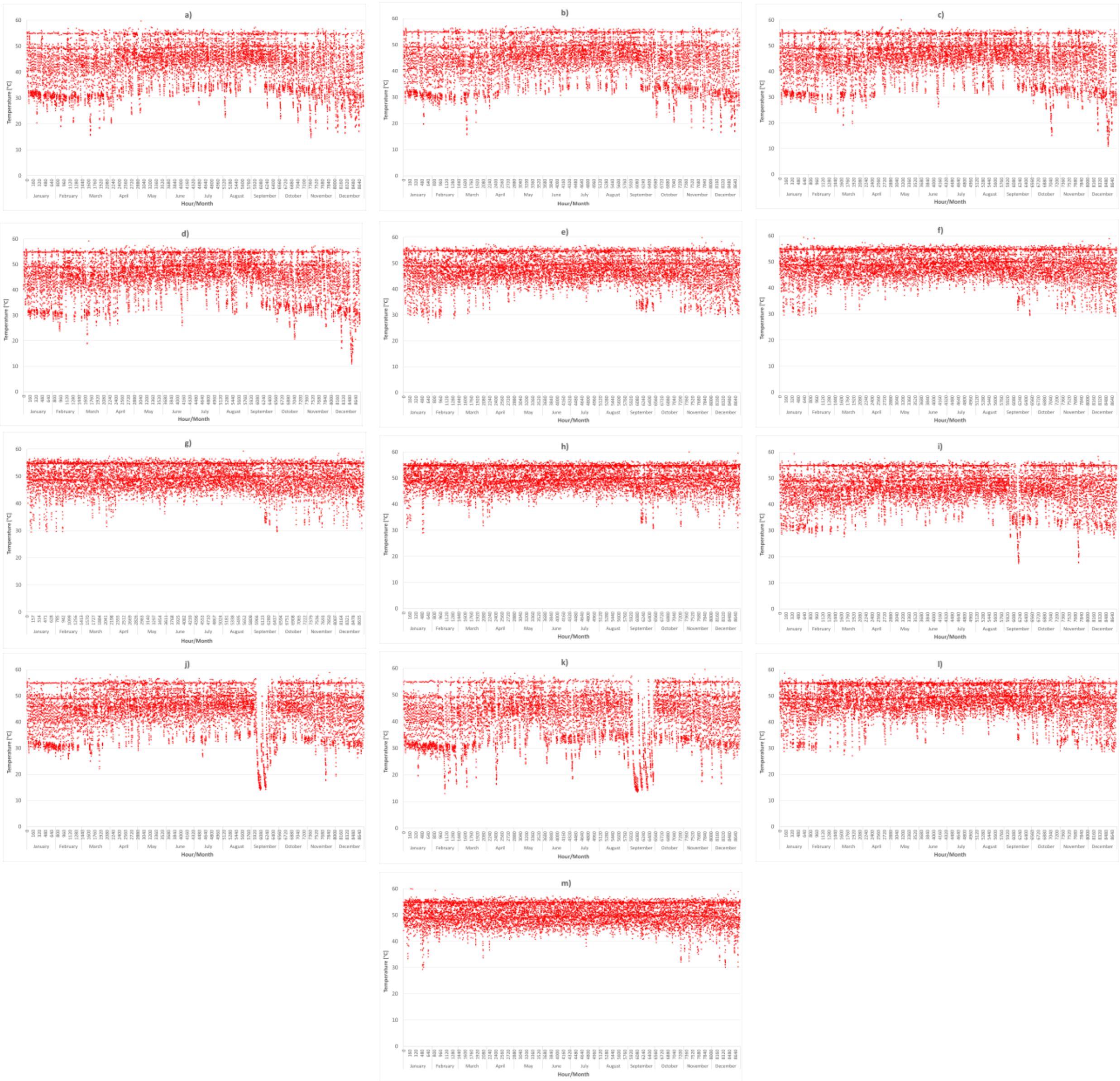


Figure 47. Strategy 4 - DHW temperature with different heat pump switching times

Table 30. Strategy 4 – Number of hours that DHW temperature lower than 40°C with different heat pump switching times

Switching profile	a) +15% of MIN. daily price	b) +20% of MIN. daily price	c) +25% of MIN. daily price	d) +30% of MIN. daily price	e) Below AVG. daily price	f) +5% of AVG. daily price	g) +10% of AVG. daily price	h) +15% of AVG. daily price	i) -5% of AVG. daily price	j) -10% of AVG. daily price	k) -15% of AVG. daily price	l) > 50% of the daily spread	m) > 75% of the daily spread
No. of Hours (T_{DHW}<40 °C)	3108	2558	2221	1959	837	545	334	204	1436	2271	3513	861	129
Legend: MIN. - minimum AVG. – average													

The other criteria that are investigated in the building case are operative temperature. The below curves in Figure 48 show operative temperatures fluctuate between 24°C and 11°C during heating periods (January-April and October-December), of which summary can be seen in Table 31. According to EN16798-2 to meet indoor comfort for a residential building operative temperatures should be between 20°C and 25°C. Since the goal for this project is meeting IEQ Category II, the only switching times which follow this criterion the closest are 75% of daily spread m) and h). Hourly data used in Figure 48 for operative temperatures in 13 different switching profiles is mentioned in Annex L.15.

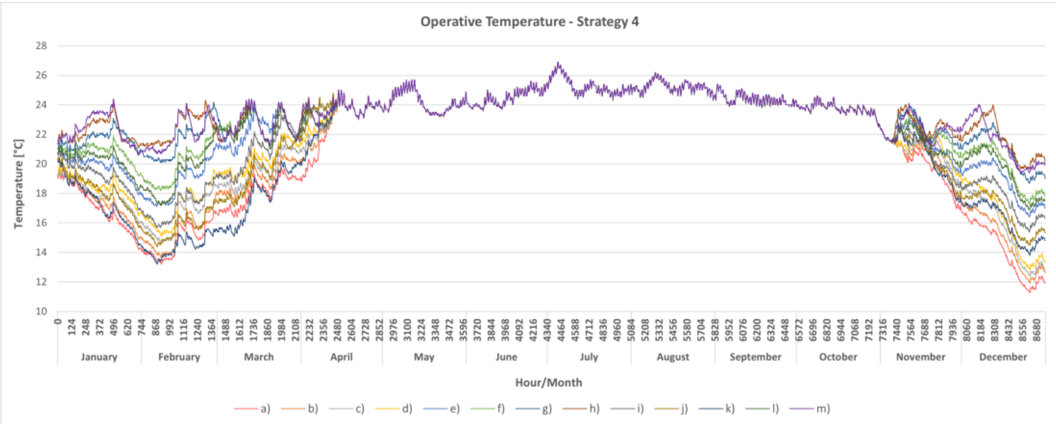


Figure 48. Strategy 4 - Operative temperature with different heat pump switching times

Table 31. Strategy 4 – Number of hours that operative temperature lower than 20°C with different heat pump switching times

Switching profile	a) +15% of MIN. daily price	b) +20% of MIN. daily price	c) +25% of MIN. daily price	d) +30% of MIN. daily price	e) Below AVG. daily price	f) +5% of AVG. daily price	g) +10% of AVG. daily price	h) +15% of AVG. daily price	i) -5% of AVG. daily price	j) -10% of AVG. daily price	k) -15% of AVG. daily price	l) > 50% of the daily spread	m) > 75% of the daily spread
No. of Hours (T_{op}<20° C)	3239	2881	2754	2559	1520	734	256	110	2497	2786	3063	1004	188
Legend: MIN. - minimum AVG. – average													

The best possible switching times according to Table 30 and Table 31 are **h)** and **m)**. These two switching profiles were investigated and compared in terms of total electricity consumption of the heat pump, number of hours with domestic hot water temperature lower than 40°C and meeting indoor comfort considering the operative temperature. The electricity consumption and related price in Table 32 were calculated only for the operation of the heat pump. The data mentioned in Table 32 are presented in Annex L.8 and L.13.

Table 32. Strategy 4 - Comparison between the best two switching time profiles

Switching Profile	h) +15% of AVG. daily price	m) < 75% of daily spread
Electricity consumption (kwh)	4606	4631
Energy Price (DKK)	2754	2928
Heat pump working hours	2445	2458
Switching on times	984	1049
Number of Hours (T_{op}<20°C)	110	188
Number of Hours (T_{DHW}<40°C)	204	129

Following, the push forcing of the heat pump will be considered for switching profiles that are based on +15% of AVG. daily price [**h)**] and 75% of daily spread [**m)**]. Due to these switching profiles being not able to provide the availability to meet DHW and operative temperature demand the process of improvement of the profiles was made. The improvement procedure was done manually in which the heat pump runs by force whilst the heat pump is turned off in the current hour and domestic hot water temperature is lower than 40°C or operative temperature is lower than 20°C. After data treatment, another simulation was performed, and the results can be seen in Table 33. The hourly details for two switching profiles after push forcing the heat pump are presented in Annex L.14.

Table 33. Strategy 4 - Comparison between the best two switching time profiles with heat pump push forcing

Switching Time Profile	h) Push Forcing +15% of AVG. daily price	m) Push Forcing < 75% of daily spread
Electricity consumption (kwh)	4785	4784
Energy Price (DKK)	3132	3106
Heat pump working hours	2636	2538
Switch-on times	1102	1079
Number of Hours (T_{op}<20°C)	0	0
Number of Hours (T_{DHW}<40°C)	0	0

According to Table 33, the switching time profile m) Push Forcing in which 75% of daily spread is considered, shows better results in terms of electricity consumption and price. Furthermore, the heat pump works less by 98 hours, and the switch-on time is 23 times less than h) Push Forcing.

9.4.2 Domestic Hot Water

After the process of force running, one can see that the DHW withdrawal temperatures mostly fluctuate between 42°C and 55°C. Visual results can be seen in Figure 49. Hourly data used in this figure is mentioned in Annex K.1.

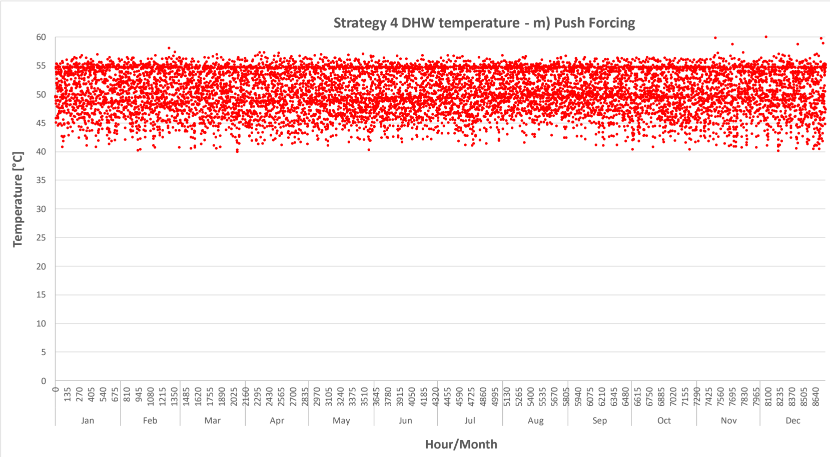


Figure 49. Strategy 4 - DHW temperature with m) Push force switching time profile

9.4.3 Indoor climate

Furthermore, the impact of optimisation can be seen by comparing operative temperature throughout the year depicted in Figure 50. Force running of the profile is successful for the scenario with a pricing signal based on 75% of the daily price spread m). The details for values used in this figure are presented in Annex K.1 and L.13.

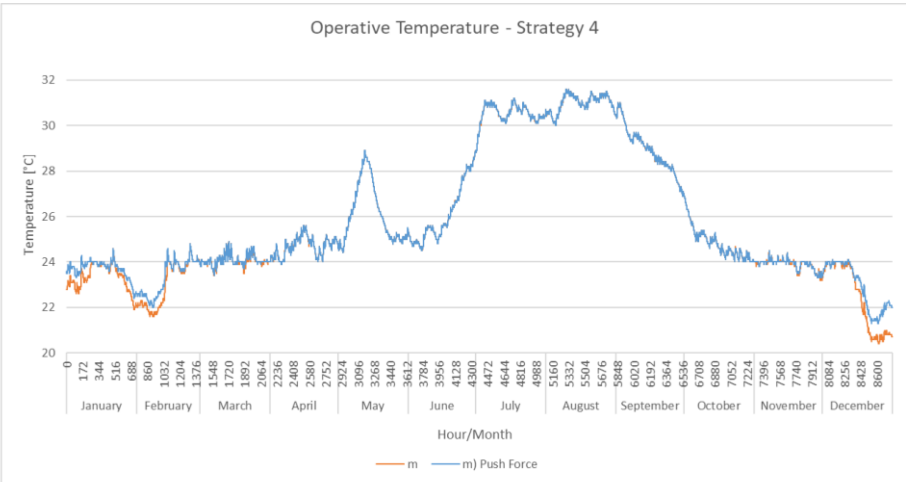


Figure 50. Strategy 4 - Operative temperature comparison between switching time profile m) and m) Push Force

Summarizing all the above results in Table 34, the push-forced switching time profiles are presented for the entire year. One must notice, that after the process of force running, the energy usage increased as well as all other factors to enhance comfort temperatures for DHW and operative temperature. Data mentioned in Table 34 are presented in Annex L.13 and L.14.

Table 34. Strategy 4 - Comparison between the m) and m) push force heat pump switching time profiles

Switching Time Profile	m)	m) Push Forcing
Electricity consumption (kwh)	4631	4784
Energy Price (DKK)	2928	3106
Heat pump working hours	2458	2538
Switch-on times	1049	1079
Number of Hours (T_{op}<20°C)	188	0
Number of Hours (T_{DHW}<40°C)	129	0

9.4.4 Heat Pump

Figure 51 depicts the average, minimum, and maximum coefficient of performance (COP) of the heat pump throughout the year 2021. Based on this bar chart it can be concluded that the heat pump is the least efficient during the heating season, therefore it is expected for the system to encounter difficulties reaching certain setpoints. The highest average COP is in May, June, and September with 4.1 while the maximum COP occurred in November with 5.8. According to Figure 51, the heat pump works evenly during the non-heating season compared to the heating season since it fluctuates less in terms of performance and has the lowest difference between the minimum and maximum COP. The details for calculated average, minimum and maximum heat pump COP throughout the year 2021 for Strategy 4 is mentioned in Annex K.7.

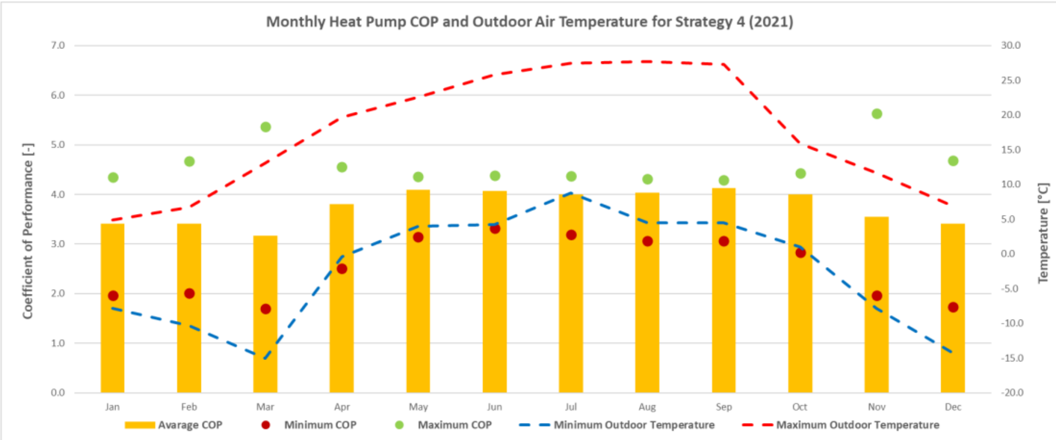


Figure 51. Strategy 4 - Monthly heat pump COP, and outdoor temperature in 2021

Furthermore, in Figure 52 one can see the distribution of heat pump operation using m) forced run switching profile. As can be seen, the heat pump operates for long periods with a low frequency of switch-on times during the heating season. This is a good sign, indicating lesser wear of the heat pump throughout the time. Data used for Figure 52 can be found in Annex K.4.

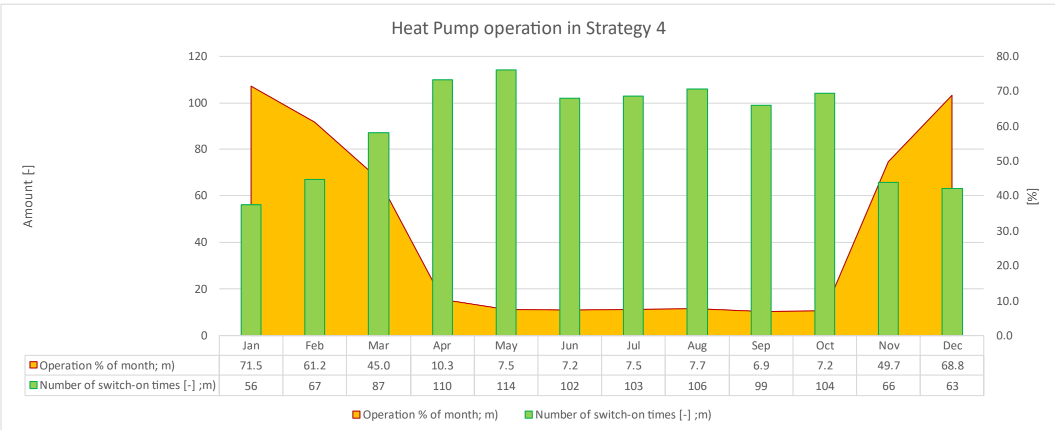


Figure 52. Strategy 4 - Monthly heat pump operation time and switch-on times in 2021

Figure 53 shows heat pump working times during the year divided into months after considering electricity price signal as well as the BaB concept where force running of the heat pump was included to meet stipulated setpoints and criteria. Each column represents a fraction of the time in percentage in which the heat pump works as well as times when the heat pump is off. Data used to generate this figure is presented in Annex K.3.

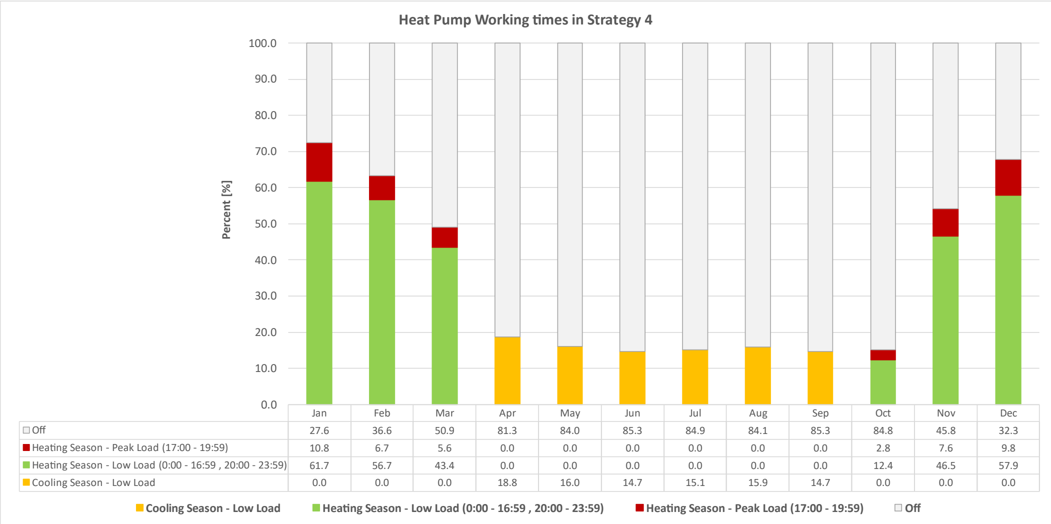


Figure 53. Strategy 4 - Heat pump monthly working time in different load periods

9.4.5 Summary

The running cost of the heat pump accordingly to the optimised configuration method, where a variable electricity tariff is being used to calculate costs, is presented in Figure 54. As the electricity costs rise in the 4th quarter of the year, we can see a price increase. The annual cost reaches 3106 DKK for the whole year without costs affiliated with Danish taxes. The details for all values used in this figure are presented in Annex K.6.

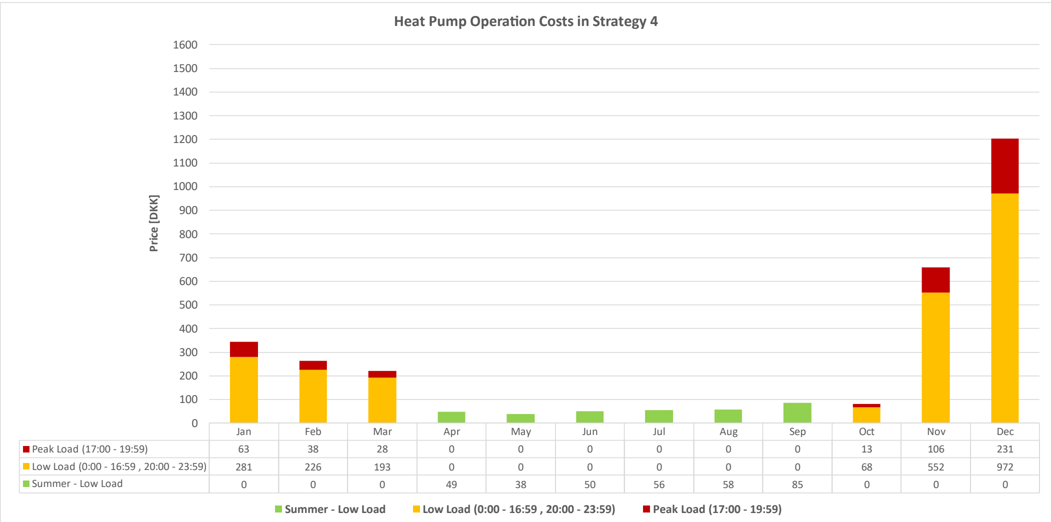


Figure 54. Strategy 4 - Heat pump operation costs in 2021

9.5 Results & Comparison

This section will compare all strategies where the following data is analysed:

- Operative temperature
- DHW temperatures
- Heat pump energy consumption and running costs
- Load Shifting
- Switch on Times
- Savings

9.5.1 Operative and DHW temperature

According to Figure 55, all strategies met operative temperature for category II. Comparing all results show that Strategy 4 provides higher operative temperature during the heating season whereas it has a larger temperature band and fluctuates more in the comfort zone. On the other hand, in Strategies 1 and 2, the operative temperature mostly fluctuates around 22°C and has the smallest temperature band. The lowest operative temperature during the heating season occurred in Strategy 3 in January and December in which the operative temperature drops to category II while it happens only in December for strategy 4. Furthermore, the highest average temperature during the heating season occurred in strategy 4 while the lowest is in strategy 3. Details for values used in Figure 55 are presented in Annex M.1.

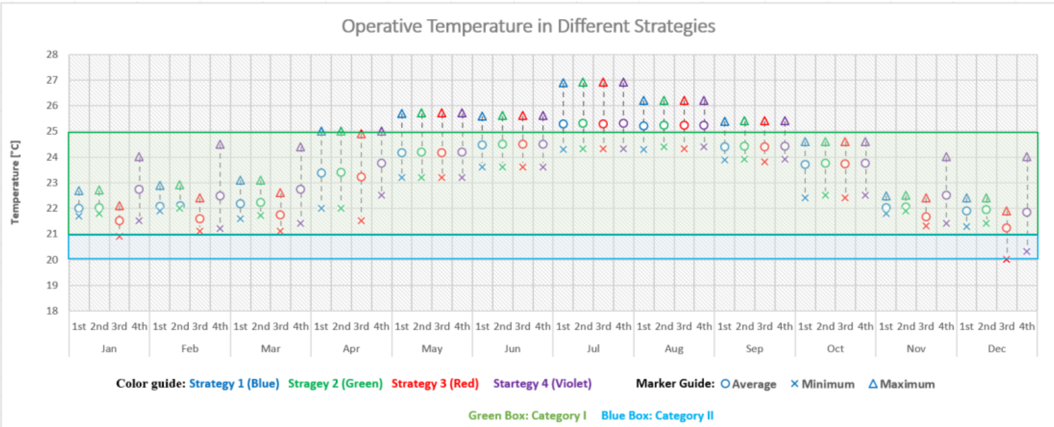


Figure 55. Operative temperature comparison in different strategies

According to Figure 56, all strategies provide the minimum required DHW temperature at the withdrawal point which is defined as 40°C, all over the year. Strategies 1 and 3 have fewer fluctuations compared to other strategies and provide a more even DHW temperature band during the year while Strategies 2 and 4, which include a buffer tank for space heating, provide higher DHW temperature during the heating season. The data used to draw Figure 56 is mentioned in Annex M.2.

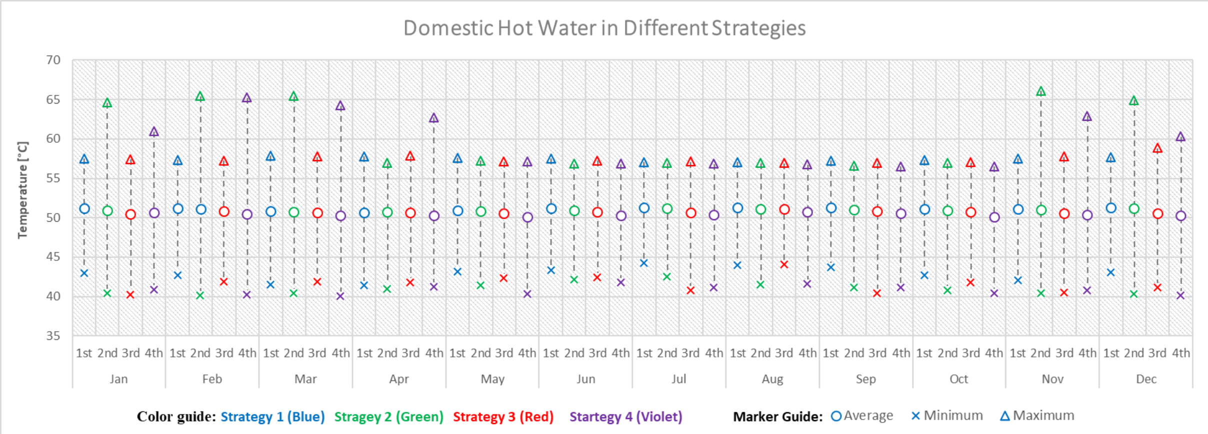


Figure 56. Domestic hot water temperature comparison in different strategies

9.5.2 Heat pump operation and energy consumption

According to Figure 57, systems with two tanks for DHW and space heating have fewer number of switch-on times compared to the systems with only one tank. In Strategies 3 and 4, the heat pump is more likely to work continuously with the lowest number of switch-on times. Since the space heating system in strategy 3 is directly connected to the heat pump, discrete working of the heat pump due to price signal limitations cannot provide sufficient energy to heat the building to the highest desired operative temperature (24°C). Whereas, in strategy 4 there is a buffer tank to store heated water with high temperature during off-peak periods and use it later. Strategy 4 consumes more energy compared to strategy 2 while it has a reduced number of switch-on times and more working hours for the heat pump. Data used for Figure 57 can be found in Annex M.3.

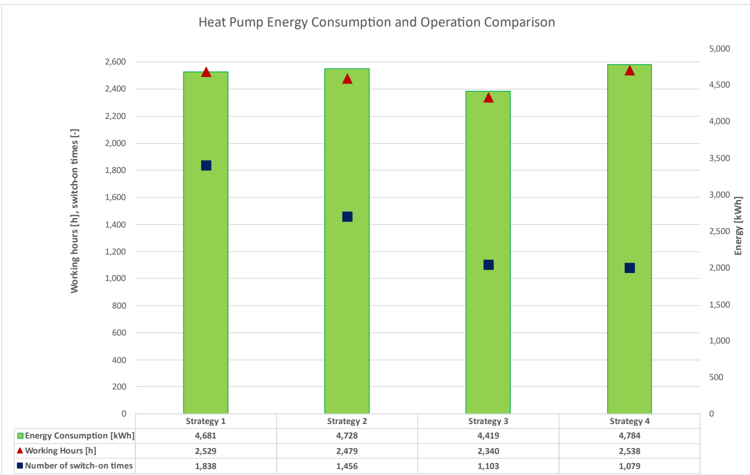


Figure 57. Energy consumption, operation time, and switch-on times for different strategies

Signal prices in Strategies 3 and 4, decreased the heat pump running costs by 14% and 10% compared to their reference cases (Strategy 1 and Strategy 2), respectively. Furthermore, Strategy 4 provides more comfortable conditions in both DHW and operative temperature compared to Strategy 3. To meet these higher comfort levels, the heat pump in Strategy 4 consumes 8.2% electricity more than Strategy 3 with an increased 4.6% running cost in the year 2021.

According to Figure 58, which shows a comparison between Strategies 2 and 4, the number of switch-on times during peak periods for DHW indicates that there is no considerable peak cutting during the heating season. It is assumed that the DHW tank might be too small for a family of 5 people. Therefore, further peak cutting could not be achieved due to the DHW tank size and the hot water withdrawal intensity resulting from the profile. In other words, no warm water is stored long enough to bring profits, using variable electricity tariffs. This matter will be further investigated in this project. The details for all values used in Figure 58 are presented in Annexes M.4, H.5, and K.5.

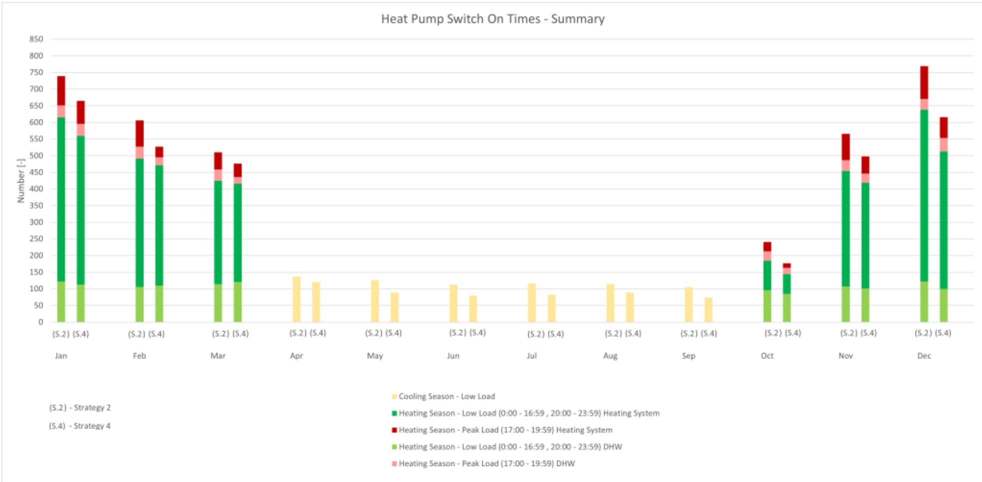


Figure 58. Heat pump switch-on times for DHW and heating systems split into load periods for strategy 2 and strategy 4

9.5.3 Load Shifting Comparison

Following, the load shifting is depicted in Figure 59. It is given as a normalized percentage difference while comparing a change of control logic from Strategy 1 to Strategy 3 and Strategy 2 to Strategy 4. One can see a load shifting as a result of implementing DSM practices as well as electricity price signal, it can be seen that almost the same percentage of the load occurring during the Peak Period in reference strategies (Strategy 1 and Strategy 2) has been distributed over Low Load Period in Strategy 3 and Strategy 4, respectively, resulting in potential savings. The details for all values used in Figure 59 are presented in Annex M.5.

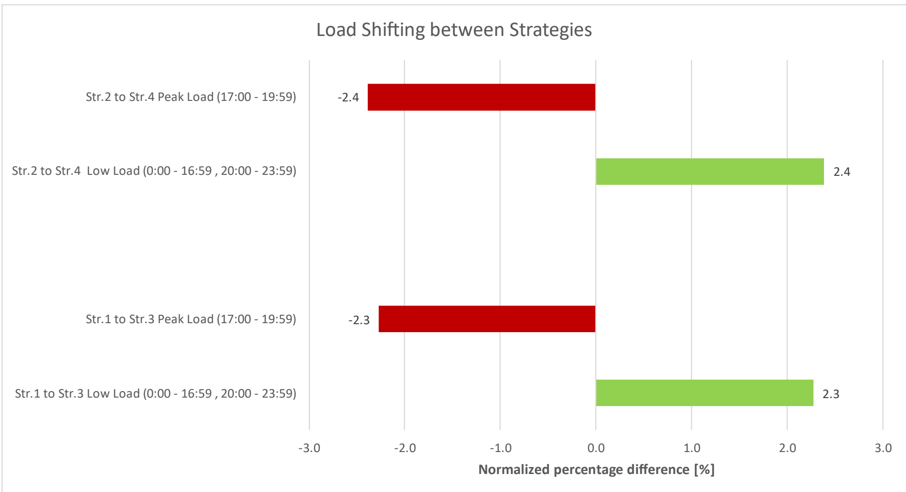


Figure 59. The load shifted from strategy 1 to strategy 3 and strategy 2 to strategy 4

9.5.4 Savings Comparison

Figure 60 depicts savings throughout the year caused by shifting the load accordingly to information presented in Figure 59. Consideration is the transition from Strategy 2 to Strategy 4 and from Strategy 1 to Strategy 3 to conclude savings potential. While looking at both savings curves, one can see a relation of increasing savings due to larger variation in electricity price which confirms the previously stated assumptions. Furthermore, the savings curve in Strategy 3 is fluctuating less over a short period of time in comparison to Strategy 4 indicating that having an extra tank for space heating contributes to increased savings fluctuation over short periods of time. The hourly data used in Figure 60 are presented in Annex M.6.

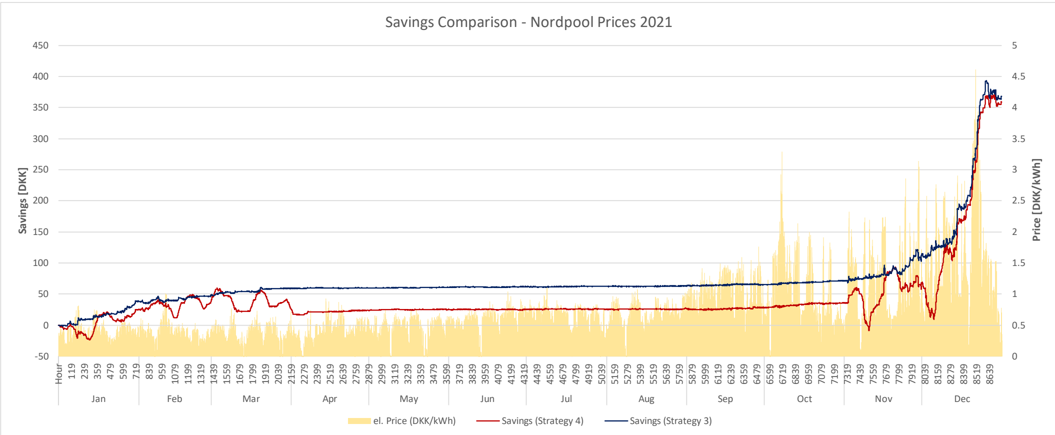


Figure 60. Savings for strategy 3 and strategy 4 with regards to their reference strategies

In Figure 61 and Figure 62, one can see that the linear rate of change in savings is highly dependent on the price spread. The linear rate of change is calculated as follows:

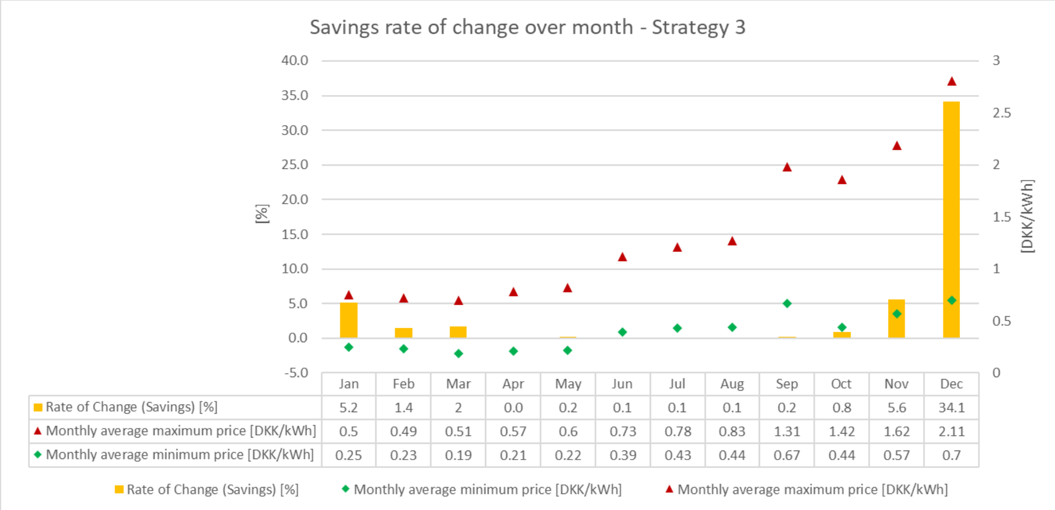
$$\boldsymbol{ROC = 100 * \frac{D2 - D1}{T}}$$

$D2: savings\ at\ the\ end\ of\ period$

$D1: savings\ at\ the\ beginning\ of\ period$

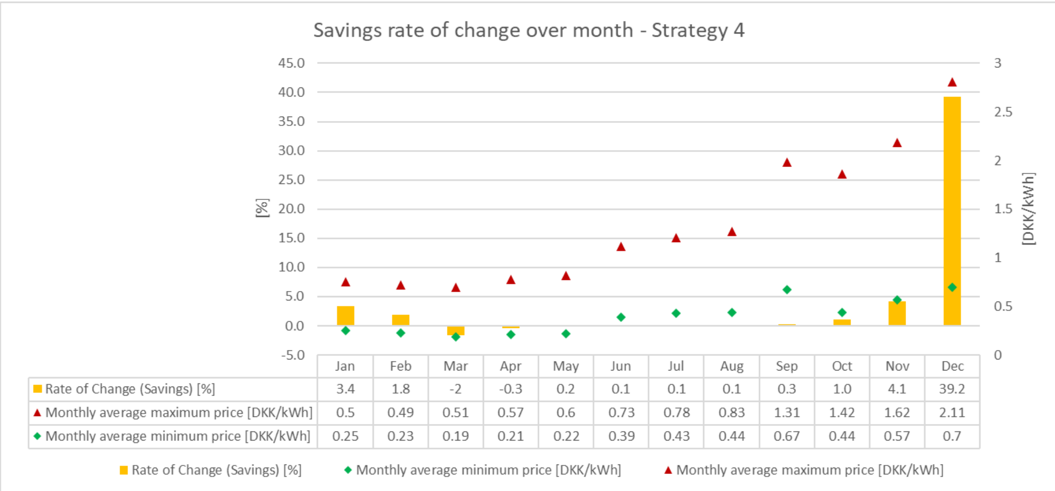
$T: time\ it\ took\ for\ a\ change\ to\ occur$

While comparing savings from Strategy 3 and Strategy 4 throughout the cooling season one can see that no considerable savings are accumulated out of DHW using the price signal to operate the heat pump. Data used to generate Figure 61 and Figure 62 are presented in Annex M.6.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rate of Change (Savings) [%]	5.2	1.4	2	0.0	0.2	0.1	0.1	0.1	0.2	0.8	5.6	34.1
Monthly average maximum price [DKK/kWh]	0.5	0.49	0.51	0.57	0.6	0.73	0.78	0.83	1.31	1.42	1.62	2.11
Monthly average minimum price [DKK/kWh]	0.25	0.23	0.19	0.21	0.22	0.39	0.43	0.44	0.67	0.44	0.57	0.7

Figure 61. Savings rate of change over the month in 2021 - Strategy 3



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rate of Change (Savings) [%]	3.4	1.8	-2	-0.3	0.2	0.1	0.1	0.1	0.3	1.0	4.1	39.2
Monthly average maximum price [DKK/kWh]	0.5	0.49	0.51	0.57	0.6	0.73	0.78	0.83	1.31	1.42	1.62	2.11
Monthly average minimum price [DKK/kWh]	0.25	0.23	0.19	0.21	0.22	0.39	0.43	0.44	0.67	0.44	0.57	0.7

Figure 62. Savings rate of change over the month in 2021 - Strategy 4

Figure 63 depicts the average pricing spread of raw electricity prices. As one can see, the spread has been nearly constant throughout the year until August, therefore shifting the load might be not as beneficial in terms of savings as shifting it in the period from September to December. As an example, shifting 1 kWh of electricity in January from Peak Period to Low Period would be equal to 0.1 DKK of savings, whereas in December it is 0.42 DKK of savings based on the average values presented in Figure 63. Summarising, it is important to analyse pricing spread instead of values itself to successfully shift the load, from the Peak Period to the Low Period. All data used to generate Figure 63 is presented in Annex C.2.

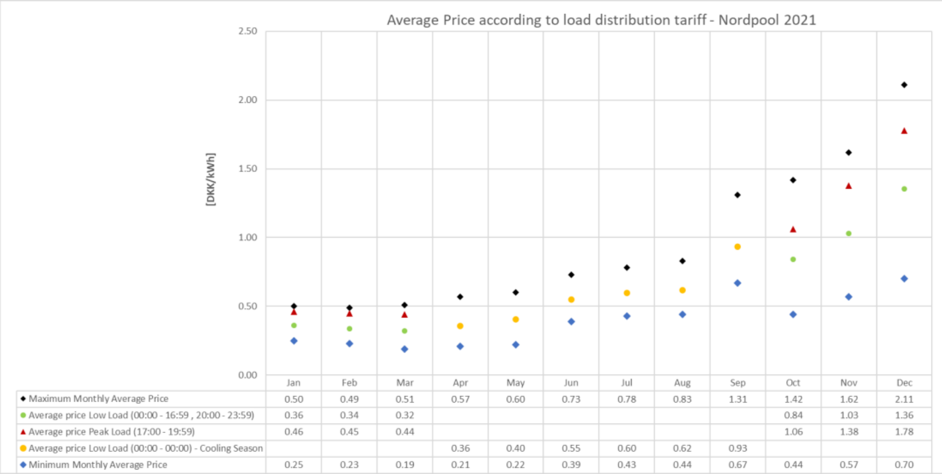


Figure 63. Average price according to load distribution in 2021

Summarising, the highest rate of change in December in Strategy 3 and Strategy 4 indicates that the high daily spread of electricity prices has a great influence over savings in the case of using Bab, the high thermal inertia of the building allows for keeping thermal comfort within the acceptable boundaries while heat pump does not operate. According to Figure 64, it can be concluded that the BaB concept has a high potential to increase savings in periods when prices fluctuate the most as well the 24-h price spread is large, and the average outdoor temperature is low. The data used to draw Figure 64 is mentioned in Annex M.7.

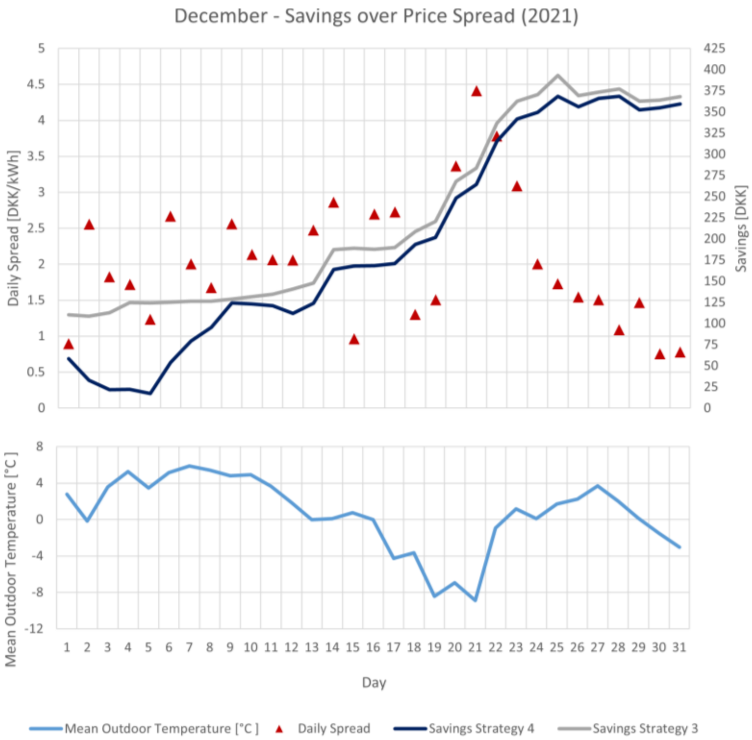


Figure 64. Savings over price spread for Strategy 3 and Strategy 4 in December 2021

9.5.5 Summary

Comparing all strategies in terms of operative and DHW temperatures showed that systems with two separated tanks for space heating and DHW, strategy 2 and strategy 4, have higher average operative temperatures and larger DHW temperature bands. Furthermore, these systems are able to provide higher DHW temperatures compared to Strategy 1 and Strategy 3.

Regarding heat pump operation, the number of switch-on times is more sensitive to the electricity signal prices in such a way Strategy 3 and Strategy 4 have the lowest numbers. Furthermore, while Strategy 4 has the lowest number of switch-on times compared to all other strategies, the heat pump works more and produces the highest amount of heating. In addition, lesser switch-on times led to lesser wear in heat pump parts and maintenance.

Running costs in all strategies showed that the cost of electricity consumed by the heat pump in systems which work based on electricity signal prices is lower than in reference strategies (Strategy 1 and Strategy 2).

Summarizing all points, one can be concluded is Strategy 4 provides better comfort conditions, less maintenance, more working hours, and fairly fewer running costs.

10. Increased capacity of tank and heat pump

Sizes of components for all four strategies were based on components located in a single-family house from the study case. Therefore, after simulating all four strategies, the next step was to investigate the size of the components and their influence on the overall yearly savings and indoor comfort. The base for finding the best components size was based on Strategy 4, which consisted of a 250 L DHW tank, 550 L buffer tank and 7 kW heat pump. The analysis is done using a price signal of 75% of daily spread without heat pump force running, to investigate the correlation between appropriate component sizes. Finally, the best component sizes are chosen and required force running is performed in the next section which is dedicated to results.

10.1 Different sizes of DHW tank

In the first stage, DHW tank size was investigated. However, the size of the heat pump and buffer tank remained the same, with 7 kW and 550 L, respectively. Results for operative temperature, DHW temperature, energy consumption and electricity prices for different tank sizes are presented in Table 35. All details mentioned in this table are presented in Annex O.1 – O.8.

Table 35. Summary of different DHW tank sizes investigation with 7kW heat pump

Component Sizes							
Heat Pump Size (kW)				7			
Buffer tank size (L)				550			
DHW tank size (L)	400	500	600	700	800	900	1000
Annual Simulation Results (2021)							
HP Energy Produced (kW)	16074	16121	16145	16171	16205	16235	16217
HP El. Consumption (kW)	4637	4640	4647	4647	4661	4658	4648
Price (DKK)	2932	2905	2923	2941	2929	2908	2898
Hours of DHW temp<40°C (h)	60	14	4	4	3	1	5
Hours of Operative temp<20°C (h)	198	222	221	221	222	237	241

According to Table 35, the number of hours in which the DHW temperature is lower than 40°C and operative temperature in the building is lower than 20°C with 600 L and 700 L are the same. Furthermore, the final price and energy consumption of 600 L is lower than 700 L. It concludes that there is no economic benefit in tank sizes more than 600 L.

10.2 Different sizes of the Buffer tank

After finding the optimum size for the DHW tank, the same procedure of changing the size of the buffer tank was done. In this investigation, the DHW tank was considered as 600 L according to the previous investigation. The heat pump size remained at the same size 7 kW. Details of these investigations are mentioned in Table 36 and details can be found in Annex O.9 – O.13.

Table 36. Summary of different buffer tank sizes investigation with 7kW heat pump

Component Sizes					
Heat Pump Size (kW)			7		
DHW tank size (L)			600		
Buffer tank size (L)	550	600	700	800	1000

Annual Simulation Results (2021)					
HP Energy Produced (kW)	16145	16176	16157	16154	16162
HP El. Consumption (kW)	4647	4649	4632	4627	4609
Price (DKK)	2923	2921	2908	2904	2891
Hours of DHW temp<40°C (h)	5	17	6	16	10
Hours of Operative temp<20°C (h)	221	215	246	248	252

According to Table 36, changing the buffer tank size from 550 L to 600 L increased the hours for DHW lower than 40°C by 240% (12 hours). Furthermore, the number of hours lower than 20°C for operative temperature slightly decreased for the 600 L tank. However, further increasing the tank size to 700 L and more resulted in an increased number of hours below the comfortable temperatures. Therefore, as it can be concluded from that table, increasing the buffer tank size and keeping the same heat pump size (7 kW) is not capable of reducing the number of hours lower than 20°C for operative temperature. Therefore, it is concluded that the size of the heat pump needs to be increased to keep running costs low and maintain comfortable temperatures.

10.3 Increased size of Heat pump

Therefore, in the next stage investigation was focused on the heat pump size. The DHW tank remained the same (600 L) and the pump size was increased from 7 kW to 9 kW. The buffer tank was investigated from 550 L to 1000 L. According to Table 37, an increased heat pump size with a 550 L buffer tank consumed 5 kW less energy than a 600 L buffer tank. Moreover, the price for 550 L and 600 L tanks was the same. It can be concluded that the heat pump works more in low-price periods. Furthermore, during the coldest weather temperature (December and January), it works more efficiently. For larger buffer tanks (from 700 L to 1000 L) the increase in energy produced, electricity consumption, as well as price, was observed. It also showed an increase of hours below 40°C for DHW. Therefore, it was concluded that a 550 L buffer tank with an increased size of HP to 9 kW was the best scenario. The details of this investigation are presented in Annex O.14 – O.19.

Table 37. Summary of different buffer tank sizes investigation with 9kW heat pump

Component Sizes						
Heat Pump Size (kW)	9					
DHW tank size (L)	600					
Buffer tank size (L)	550	600	700	800	900	1000
Annual Simulation Results (2021)						
HP Energy Produced (kW)	16965	16985	17151	16979	17034	17034
HP El. Consumption (kW)	4337	4342	4386	4336	4347	4349
Price (DKK)	2798	2798	2800	2800	2802	2801
Hours of DHW temp<40°C (h)	3	4	8	8	8	6
Hours of Operative temp<20°C (h)	0	0	0	0	0	0

Table 38 presents the summary of the component sizing. As can be observed, the best results were achieved for combination C, where the size of the heat pump was increased from 7 kW to 9 kW, the DHW tank was increased to 600 L from 250 L and the buffer tank remained the same (550 L). In comparison, combination A consists of components that were currently used in the single-family house. As it can be observed, by increasing the size of some of the components the number of hours below

40°C for DHW between combinations A and C was drastically decreased by 124 hours. Furthermore, the number of hours for operative temperature below 20°C was reduced by 100%, the electricity consumption was decreased by approximately 7%, and the price was reduced by 130 DKK in 2021. Moreover, the energy produced raised by approximately 6% per year.

Table 38. Summary of Component sizing

Component Sizes			
Combination	A	B	C
Heat Pump Size (kW)	7	7	9
DHW tank size (L)	250	600	600
Buffer tank size (L)	550	550	550
Annual Simulation Results (2021)			
HP Energy Produced (kW)	15992	16145	16965
HP El. Consumption (kW)	4631	4647	4337
Price (DKK)	2928	2923	2798
Hours of DHW temp<40°C (h)	129	5	3
Hours of Operative temp<20°C (h)	188	221	0

10.4 Results

This section will investigate two following cases, Strategy 4, and Strategy 4 with Resized Components (RC). The force running of the heat pump was performed to reduce the number of hours below 40°C for DHW to zero to allow the model with new components (Strategy 4 + RC) to be comparable with Strategy 4. The main characteristics of simulation models and their outcomes are presented in Table 39. The following content of this section will present the results of heat pump operation, load shifting, savings as well as indoor comfort and DHW temperatures. The details of the push forced switching profile is presented in Annex O.20.

Table 39. Comparison between Strategy 4 before and after component resizing

Component Sizes		
Heat Pump Size (kW)	7	9
DHW tank size (L)	250	600
Buffer tank size (L)	550	550
Heat Pump Operation		
Heat Pump Force Running	Yes	Yes
Working Hours (h)	2538	2182
Switch-on Times	1079	565
Annual Simulation Results (2021)		
HP Energy Produced (kW)	16593	16981
HP El. Consumption (kW)	4784	4341
Price (DKK)	3106	2799
Hours of DHW temp<40°C (h)	0	0
Hours of Operative temp<20°C (h)	0	0

10.4.1 Operative and DHW temperature

According to Figure 65, the increased size of the heat pump and buffer tank lowered the difference between the minimum and maximum operative temperature in the building. Results showed that the average operative temperature increased in all months in 2021. Furthermore, during the coldest weather temperature (December and January), it works more efficiently. Hourly data used for this comparison is mentioned in Annex P.1.

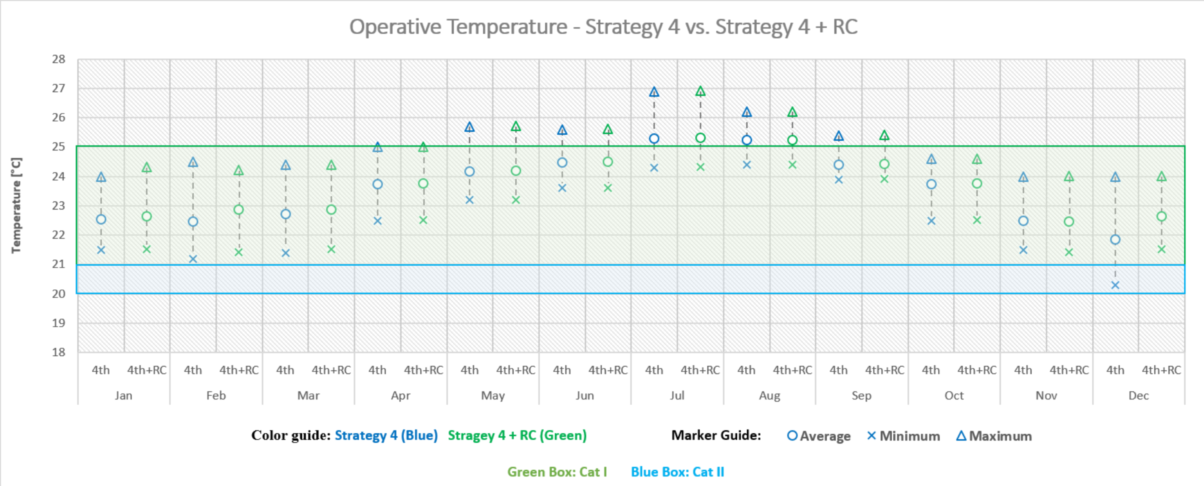


Figure 65. Impact of resizing components - Operative temperature comparison - strategy 4 vs. strategy 4 + RC

Regarding DHW temperatures, increased component sizes have kept the requirements for DHW while an increase in average DHW temperature can be seen in Figure 66 and details can be found in Annex P.2.

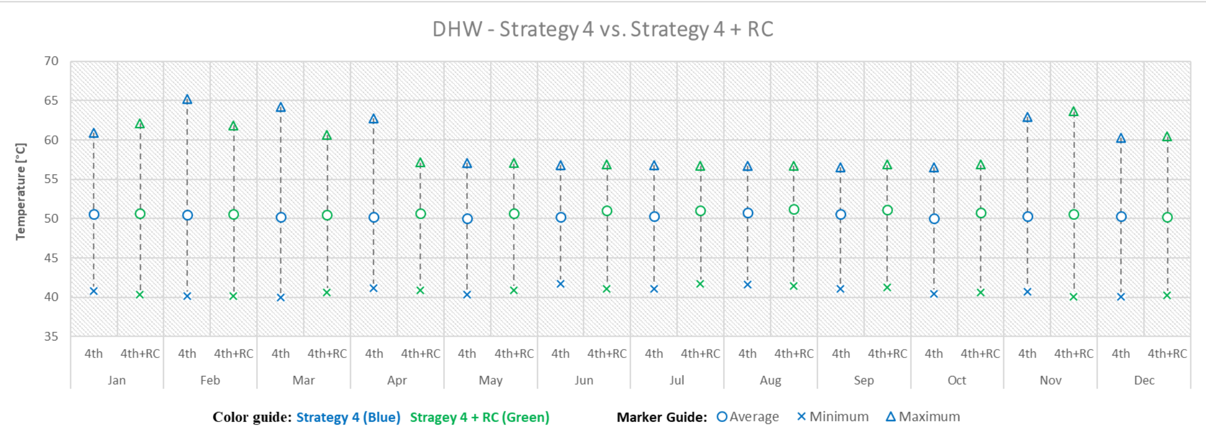


Figure 66. Impact of resizing components - DHW comparison - strategy 4 vs. strategy 4 + RC

10.4.2 Heat Pump Energy Consumption

Figure 67 shows that a heat pump with a higher capacity (9 kW) consumes less electricity. Furthermore, due to using an increased size heat pump, working time decreased by 356 hours and the number of heat pump switch-on was reduced by 47% from 1079 to 565 times. Details regarding this comparison can be found in Annex P.3.

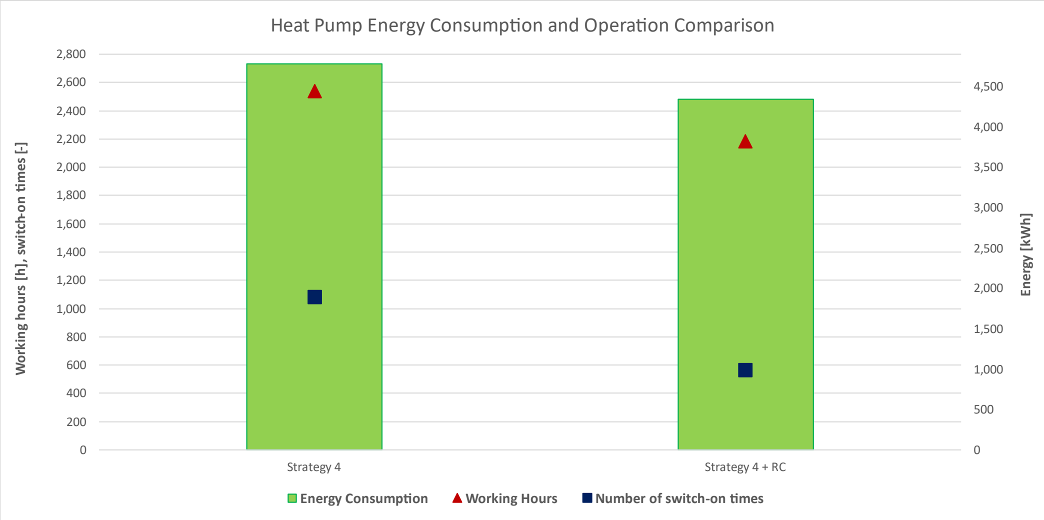


Figure 67. Impact of resizing components - Heat pump energy consumption and operation comparison

In Figure 68, one can see a detailed investigation of switch-on times. Increased sizes of components contributed to fewer amount of switch-on times throughout the year for both DHW and space heating. Moreover, one can see a direct impact of increased DHW tank volume and heat pump power on the switching time during summer - on average, the number decreased by roughly 50%. During the heating season, switch-on times related to space heating decreased more than DHW. The details for this comparison are presented in Annexes K.5, N.4, and P.4.

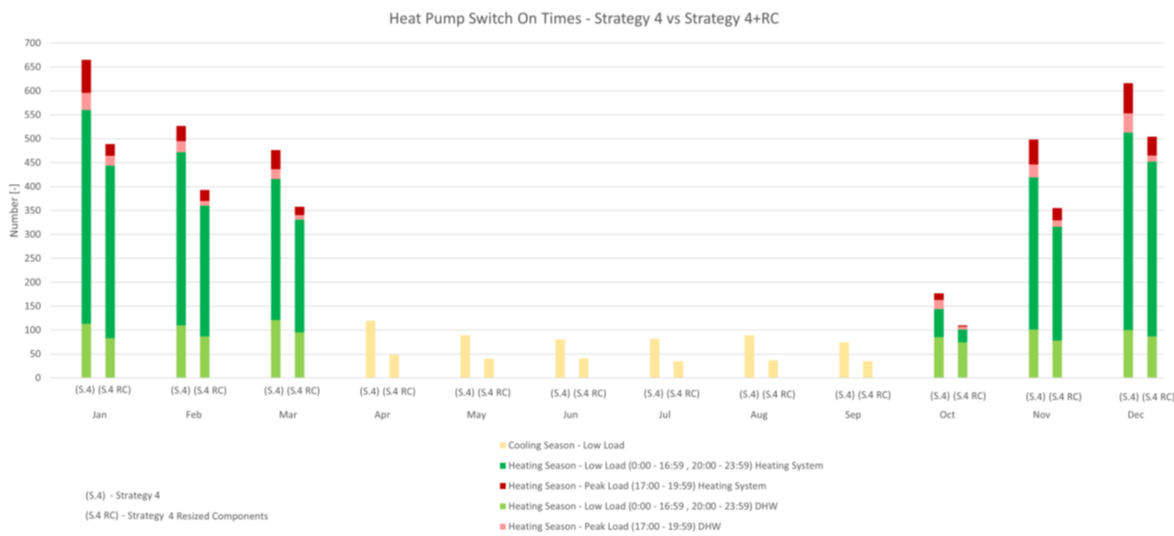


Figure 68. Impact of resizing components - Heat pump switch-on times for DHW and heating systems split into load periods for strategy 4, strategy 4 + RC

10.4.3 Load Shifting Comparison

The load shifting is depicted in Figure 69. It is given a normalized percentage difference to investigate the impact of implementing increased component sizes in Strategy 4+RC. In Figure 69, one can see a load shifting as a result of implementing an increased volume of DHW tank and Heat Pump power (Strategy 4 - Strategy 4+RC), it can be seen that an additional 3.8% of the load occurring during the Peak Period in Strategy 4 has been distributed over Low Load Period in Strategy 4+RC. All details used to generate Figure 69 are presented in Annexes N.2, K.2, and P.5.

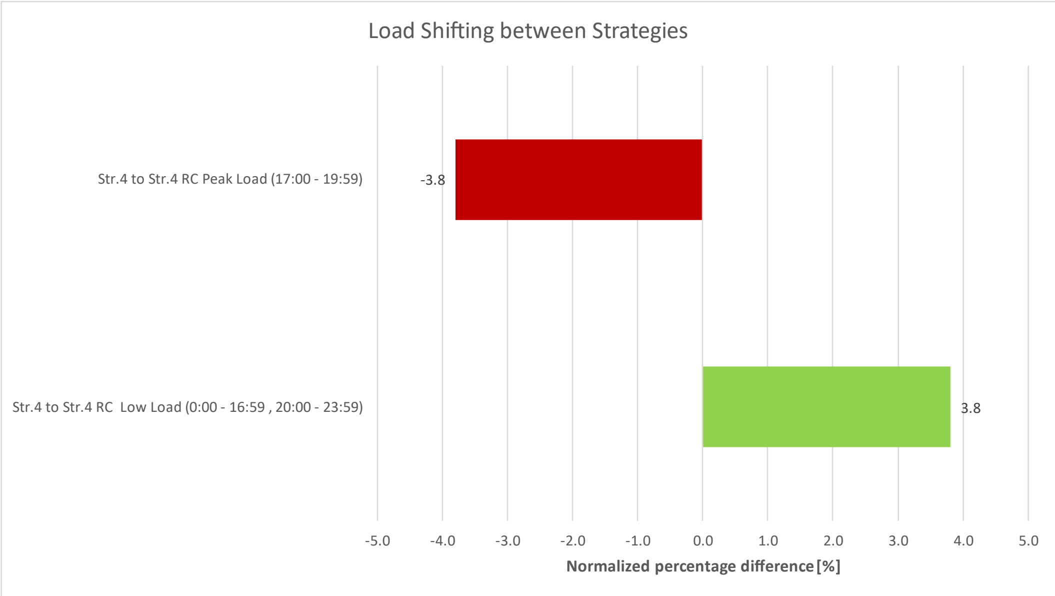


Figure 69. Impact of resizing components - Load shifting comparison for (strategy 4 vs. strategy 4 + RC)

11. Reference case comparison

In this chapter, a comparison between the final solution and the reference case (Strategy 2) is made.

11.1 DHW and Operative Temperature

According to Figure 70, running the price-dependent strategies (4th and 4th + RC) caused to increase in average operative temperature in the heating season. The most significant difference between the reference case and price-dependent strategies is the temperature band. The lower temperature band in the reference case is due to a different type of control. Floating control increases the average operative temperature throughout the heating season due to larger fluctuation, and increased upper setpoint. All data used to draw Figure 70 is presented in Annex P.1.

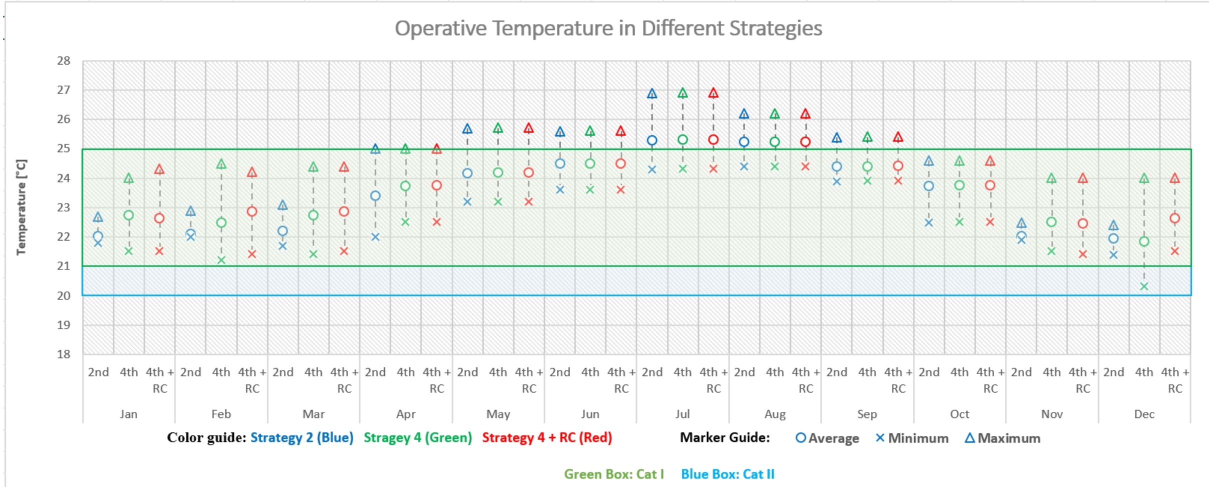


Figure 70. Operative temperature comparison in different strategies

As it is depicted in Figure 71, average and minimum DHW temperatures are almost the same for the reference case and price-dependent strategies. Using a larger heat pump capacity and DHW tank volume provides a smaller DHW temperature band compared to Strategy 2. The possibility of producing a larger amount of energy in a short period of time and storing it for a longer time, results in a smaller average temperature during the heating season, compared to a 7 kW heat pump in Strategy 2. Details of hourly data used to generate Figure 71 can be found in Annex P.2.

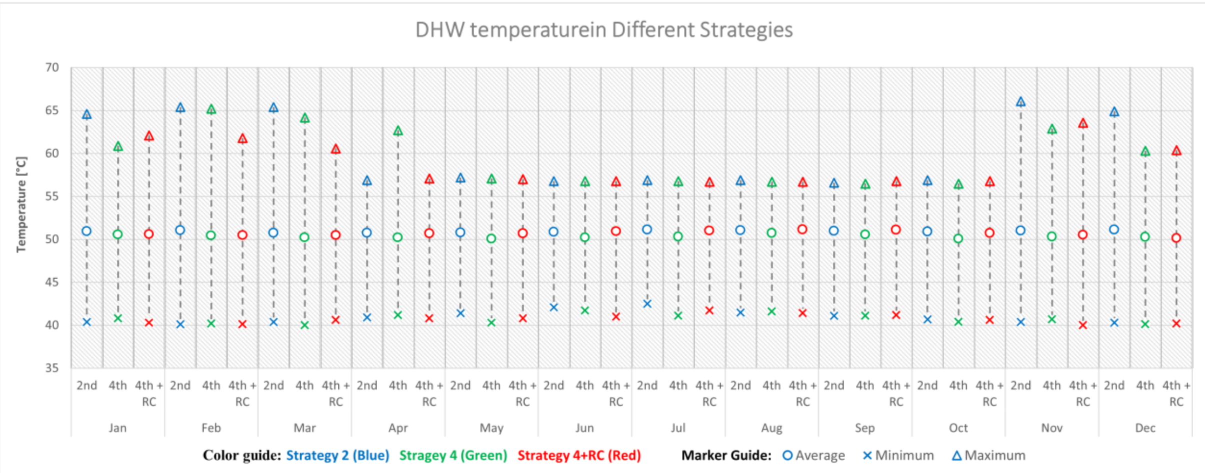


Figure 71. DHW temperature comparison in different strategies

11.2 Heat Pump Energy Consumption

Figure 72 shows that a heat pump with a higher capacity (9 kW) consumes 8% less electricity comparing the reference strategy. Furthermore, due to using an increased size of heat pump and electricity signal prices, working time decreased by approximately 12% and the number of heat pump switch-on reduced by around 61% which led to less wear in the heat pump parts. The detailed values used for this comparison are presented in Annex P.3.

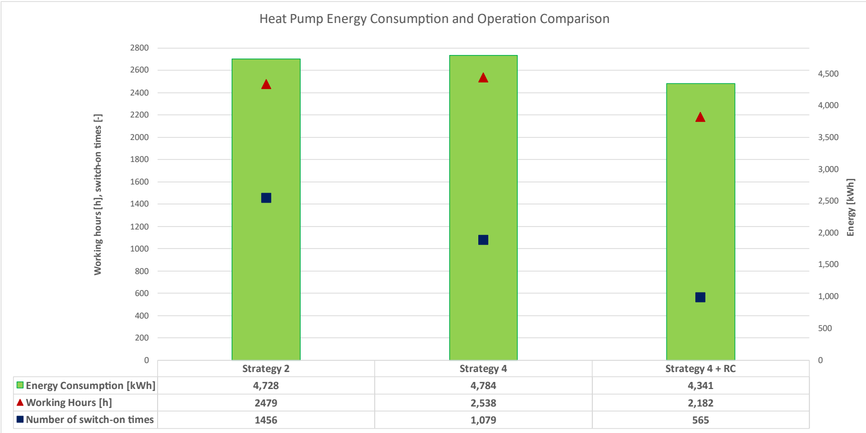


Figure 72. Heat pump energy consumption and operation comparison for Strategy 2, 4, and 4 + RC

Figure 73 represents switch-on times split into operations after implementing increased components. Once, bars representing switch-on times split into operation are compared it can be concluded that the switch-on occurrence of the heat pump during the Peak Load period is minimised by 3.5 times on average. This is an indication of decreasing the total cost of running a heat pump throughout the year. Summarising once compared, Strategy 2 and Strategy 4+RC it can be stated that designing a proper DHW tank size as well as the power of the heat pump is crucial in reducing the number of switch-on times, therefore energy savings derived from load shifting. Hourly data used in Figure 73 is mentioned in Annexes H.5, K.5, N.5, and P.4.

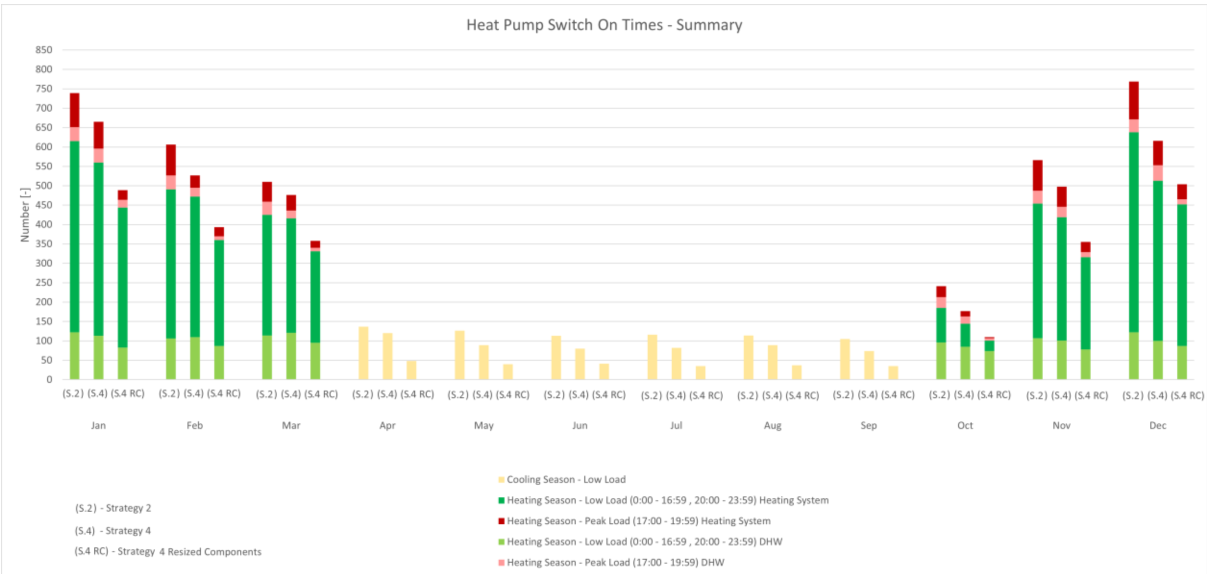


Figure 73. Heat pump switch-on times for DHW and heating systems split into load periods for reference case (Strategy 2) strategy 4, and strategy 4 + RC

Figure 74 depicts the average coefficient of performance (COP) of the heat pump throughout the year 2021 for Strategies 2, 4, and 4 + RC. Based on this figure, it can be concluded that during the heating season, the larger heat pump (9 kW) in Strategy 4 + RC works more efficiently compared to Strategies 2 and 4 which use a 7 kW heat pump. Due to an increased capacity of the heat pump in Strategy 4 + RC, fewer fluctuations in average COP occurred throughout the year while a drop in COP happened once moving from the cooling season to the heating season in Strategies 2 and 4. The values used for this comparison can be found in Annex P.6.

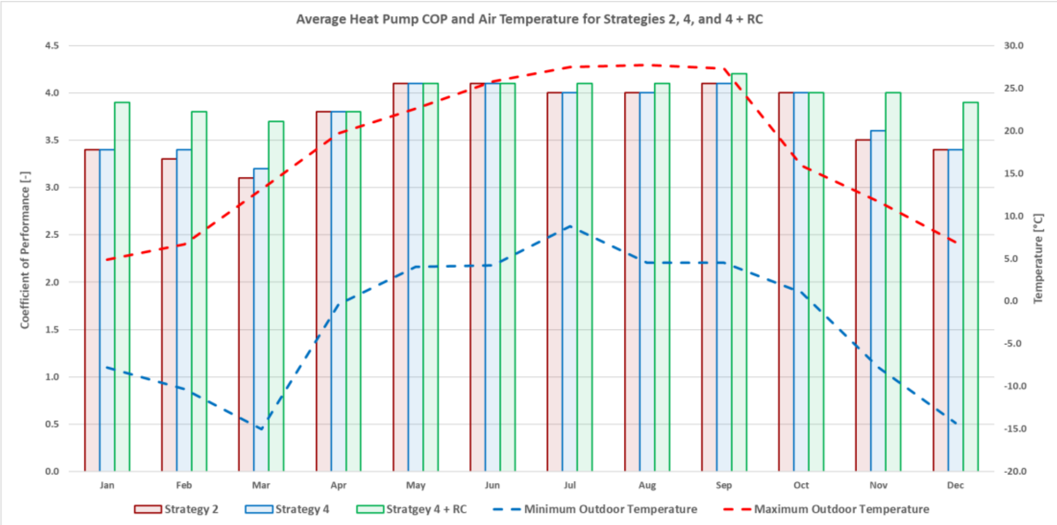


Figure 74. Average Heat Pump COP and Air Temperature for Strategies 2, 4, and 4 + RC

11.3 Load Shifting

Summarising once compared, Strategy 2 and Strategy 4+RC have a difference of 6.2% in loads occurring during the Peak Load period that have been moved to the Low Load period. This finding indicates that designing a proper DHW tank size as well as increasing the power of the heat pump is crucial in improving load shifting further. This comparison is presented in Figure 75 and detailed information can be found in Annexes H.2, N.2, K.2, and P.5.

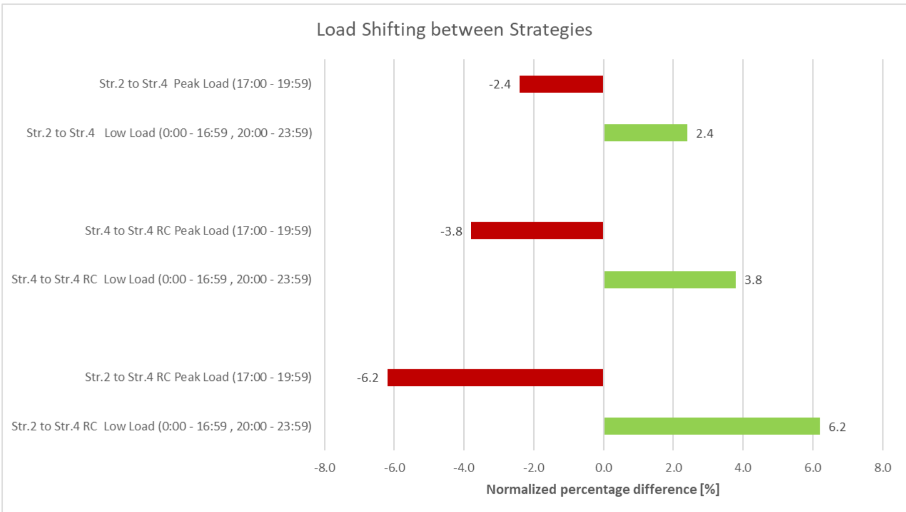


Figure 75. Load shifting comparison for reference case (2nd) and price-dependant strategies (4th and 4th + RC)

11.4 Savings and total economy including taxes

This subsection will investigate the impact of electricity taxation accordingly to Danish law. In Table 40 one can see the composition of total electricity price and values that were used in further calculations of total electricity price.

Table 40. Applied costs to spot electricity price

Electricity Price Composition	Source	Values
Raw electricity price	Nord Pool	Price per hour per day
Network tariff	Radiuselnet	Division for 2 seasons for low and peak loads
Network subscription	Radiuselnet	21 DKK per month [33]
Transmission costs	Energinet	4,9 øre per kWh [31]
Electricity tax	Elforsyningens	90 øre per kWh [34]
VAT	State	20% of the price

As presented in Table 41, for each element of the electricity price adequate calculations were performed. The spot electricity price obtained from Nord Pool by the hour, the network tariff, subscription, and taxes were added. The heat pump electricity consumption per hour was taken from the simulation results for Strategy 4 + RC with increased capacity of the components as well as for Strategy 2 and Strategy 4. The full calculations are presented in Annex Q. Due to different network tariffs, two prices per kWh were used. With that being said, the calculations were divided into individual months to include the proper network tariff prices and times associated with it.

Table 41. Calculation of total electricity price with tax

Elements of total el. price (in order)	Calculation method	Unit
Raw el. price	Raw el. price * Heat pump el. Consumption	DKK/kWh
Network tariff	23,63 or 63,07 * Heat pump el. Consumption	DKK/kWh
Transmission costs	0,90 * Heat pump el. Consumption	DKK/kWh
Electricity tax	0,049 * Heat pump el. Consumption	DKK/kWh
Network subscription	$\frac{26}{Number\ of\ hours\ in\ month}$	DKK
Total Price without VAT	Raw el. price + network tariff + transmission costs + el. tax + network subscription	DKK
Total price with VAT	$\frac{\text{Total price without VAT} + * 100}{80}$	DKK

Table 42 presents the annual electricity cost to run a heat pump before and after taxation as well as savings for Strategy 2, Strategy 4 and Strategy 4+ RC. All figures mentioned in Table 42 with taxation can be seen in Annexes Q.2, Q.4, and Q.6. As one can see, implementing the electricity price signal in Strategy 4 reduced the yearly electricity cost by 333 DKK. Moreover, increasing the size of the components further decreased the annual costs by an additional 360 DKK. With that being said, the savings between Strategy 2 and Strategy 4+RC resulted in a total of 693 DKK per year. It can be stated that the proper size of the DHW tank as well as the increased power of the heat pump is a crucial factor in maximizing savings derived from load shifting throughout the year. However, this comparison was made for Strategies using raw electricity prices. Therefore, adding the taxes to the spot electricity price resulted in 11865 DKK annual electricity costs for Strategy 2, which in comparison to Strategy 4 with increased capacity of the components was higher and resulted in 1502 DKK in savings.

Table 42. Savings as a result of taxation

	Strategy 2	Strategy 4	Strategy 4 + RC	Strategy 2 (+tax)	Strategy 4 (+tax)	Strategy 4 + RC (+tax)
Economy [DKK]	3466	3106	2799	11865	11512	10363
Savings [DKK]	-	333	693	-	353	1502

Furthermore, in Figure 76, one can see the influence of the average monthly price spread on the rate of change in savings between Strategy 2 and Strategy 4+ RC. For each day, the maximum and minimum electricity price was determined. From all the daily maximum and minimum values, the average values were obtained, which are presented in Figure 76 on the left side. One can see a relation between the price spread and the rate of change in savings. The larger the spread, the higher the rate of change in monetary savings. It can be also concluded that larger prices are not influenced strongly by taxes because, in the end, taxes have a smaller monetary share of the whole price. The small price is influenced strongly by taxation because taxes have a larger share than raw electricity prices. In other words, adding approximately 95 øre to each kWh that is being consumed while raw electricity price is large – contributes to a large fraction of the total monetary price. Whereas, in a scenario where the raw electricity price is large the fraction of the total monetary price is small.

This statement can be seen while comparing data from January and December. At the beginning of the year, the rate of change increased by 3.8 times, whereas at the end by 1.8 times, despite the spread difference. The data used to generate Figure 76 are presented in Annex Q.7.

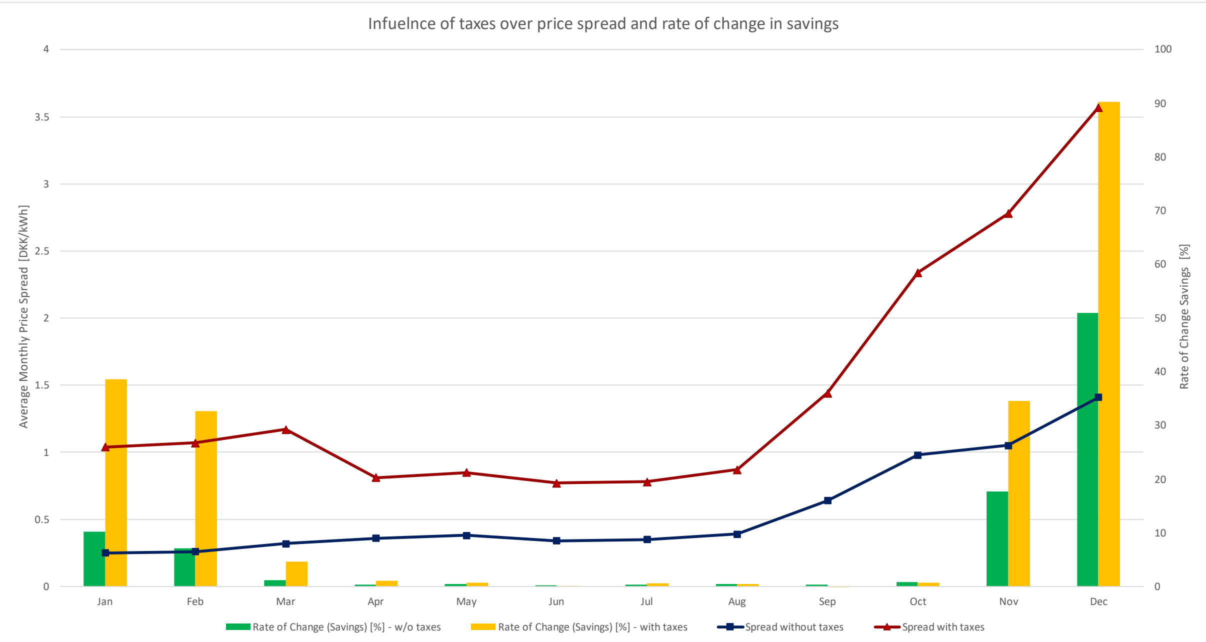


Figure 76. Strategy 2 to Strategy 4+RC rate of change and influence of taxes over it

12. Discussion

Results from this master thesis, built on existing evidence, supported the theory, that using the thermal inertia capacity of the building materials coupled together with a thermal energy storage tank and heat pump leads to increased energy flexibility to shift the loads [21] [8] [17] [22]. This report investigated demand-side management strategies, with the incorporation of an air-to-water heat pump as well as thermal energy storage, to enable load shaping using the BaB concept. Generally, it is assumed that load shifting can contribute to the stability of the grid by shifting the heating demand from peak hours to off-peak periods.

Results in this study indicated the importance of coupling the operation of a heat pump and two thermal storage tanks together with the electricity price signal, which contributed to maintaining acceptable indoor comfort as well as tap withdrawal temperatures at reduced annual electricity costs. Implementing control based on price signals in combination with the BaB concept is a great way of keeping heat pump exploitation costs low. A floating setpoint control and high thermal inertia of the building resulted in accelerating load shifting, which is supported by previous researches [19] [24].

An important factor in controlling annual costs is the 24-hour price spread, therefore a strategy based on daily price spread shows great flexibility in shifting loads. When comparing 13 different switching profiles, a favourable price signal is based on 75% of a daily spread performed as best with keeping close to IEQ category I. In cases with undersized heat pumps and thermal energy storage, a need for force running is required to keep up with comfort categories. Therefore, in situations like this, special care should be taken. On the contrary with the increased heat source as well as thermal energy storage sizes, increased energy flexibility does not require as much force running the system.

One of the key outcomes in this study supports the theory that increasing thermal energy storage volume increases the ability to shift more load from peak hours to off-peak hours. Moreover, coupling it with a larger booster – in this case increasing the power of the heat pump results in increasing load shifting further, therefore monetary savings [21] [17]. The results indicated that the larger the heat pump the faster the reaction. Therefore, in the BaB concept, the heat sink is charged more quicker, and there is a reduced chance of force running the heat pump during expensive price periods. Furthermore, it is assumed that increasing the thermal energy storage contributes to extending the withdrawal time, which resulted in less frequent charging, therefore switch-on times.

Sources of errors may arise due to delimitation which can influence the overall results, therefore deviations are to be expected. The control of the system was limited, due to software limitations. Hourly electricity pricing profiles cannot influence any software input. It is impossible to have a dynamic setpoint based on price signals, using Polysun. For instance, there is no possibility to increase the setpoint in a domestic hot water tank from 55°C to 65°C when prices are considered low. It is assumed that there are savings to be made by introducing such additional control.

Furthermore, some previous researches [12] [13] [14] have focused on load shifting in houses with Photovoltaic panels. This research was focused on load shifting possibilities without PV panels and battery on-site as well as without interference with occupants' daily schedules. It is assumed that coupling a heat pump with PV panels as well as an on-site battery, would have a positive influence on the results and electrical load shifting throughout the year – especially during the cooling season.

A further implication of the results is limited by the simplification of the simulation model due to the software limitations. With that being said, the tap withdrawal, as well as occupancy schedules, were processed to fit software input requirements, which impact the DHW withdrawal temperature, times of withdrawal as well as times when the building is occupied. The fact that this research was based on a retrospective approach - weather data (DRY reference year 2013) and spot electricity prices from Nord Pool for the year 2021 causes conflicts in the realistic reflection of results. One of the few factors that influence electricity prices are solar PV production and wind production, therefore weather influences the electricity price and can possibly cause a mismatch in the final result. As a result, these constraints have an impact on the operation of the heat pump as well as operative temperatures in the building and annual savings.

Summarising this master thesis indicates that using DSM strategies allows for shifting the load, which contributes to annual savings. Moreover, using two thermal energy storage tanks together with a heat pump improves the operative temperature in the house as well as maintains the temperatures for tap withdrawal. Furthermore, using electricity price signals together with the BaB concept contributes to higher annual savings. Lastly, the impact of components' capacities indicated its influence on DHW withdrawal, indoor comfort and economy.

13. Conclusion

The scope of this study was to investigate the load-shifting possibilities using an electricity price signal to optimize the cost of heating and DHW in a single-family house. House is situated in Egernsund south of Denmark and has a total area of 176,4 m^2. In this study, the subjects of analysis were air-to-water source heat pump coupled with a DHW tank, a space heating tank and an underfloor heating system.

Building case was used as a basis for establishing four strategies that allow investigating the impact of using electricity price signal as well as increased capacity of thermal energy storages and heat pump on the amount of load being shifted from Peak price periods to Low price periods and maintaining comfortable temperatures, having intentions to increase annual savings for running the heat pump. This study was taking a retrospective approach using already existing data, rather than future predictions. Weather data was based on the Danish reference year 2013, whereas raw electricity prices were based on Nord Pool 2021.

For the purpose of investigation, the building case was analysed from four perspectives – Strategy 1 through Strategy 4. The first strategy called the reference case used a 250 L DHW tank and a heating setpoint of 22°C. The second strategy, reference case with thermal energy storage used a 250 L DHW tank and 550 L space heating tank with the same heating setpoint as mentioned previously. Following, the third and fourth strategies adopt the BaB concept as well as incorporate an electricity price signal to operate the heat pump using a floating heating setpoint of 24 – 21.5°C. The difference between Strategy 3 and Strategy 4 is the component configuration – using 1 thermal energy storage and 2 thermal energy storages respectively.

The electricity price signal was based on raw electricity prices and various heat pump switch-on profiles were created according to the hourly electricity prices from Nord Pool. Comparing all strategies showed that using two separate tanks for DHW and space heating, provides a more even tap withdrawal temperature and indoor operative temperature with fewer fluctuations during the heating season. Therefore, strategies with a single tank have not been further investigated. Results showed that 2.4% of the electricity used by the heat pump during High Load in Strategy 2 moved to Low Load in Strategy 4.

Furthermore, the best-performing strategy was further analysed using sensitivity analysis to find component sizes that reduced costs while still maintaining comfortable temperatures. A dependency has been found that increasing the heat pump power as well as thermal energy storage has an influence on increased heat production by 2% and decreasing the number of switch-on times as well as working hours by approximately 47% and 14%, respectively. At the same time reducing operating costs for the studied case. Moreover, increasing the size of a DHW tank and heat pump power in Strategy 4 + RC resulted in an enhanced share of shifted loads. Shifting the load from the Peak period to the Low period resulted in 3.8% and 6.2%, comparing Strategy 4 with Strategy 4 + RC and Strategy 2 with Strategy 4 + RC, respectively. A summary of project strategies and development results is presented in Table 43.

Resizing of components improved the flexibility of the heating system according to heating demand in such a way that resulted in electricity costs decreasing by 12.6% after taxes compared to the reference case. Moreover, it resulted in 8% smaller electricity consumption, 12% shorter operation duration and 61% lesser switching number. Finally, the increased price spread due to taxation has a larger influence on low raw prices, rather than larger raw prices caused mainly by electricity tax and transmission costs.

Table 43. Summary of all strategies

		Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 4 + RC
Component Sizes	Heat Pump Size (kW)	7	7	7	7	9
	DHW tank size (L)	250	250	250	250	600
	Buffer tank size (L)	0	0	550	550	550
Heat Pump Operation	Heat Pump Force Running	No	No	Yes	Yes	Yes
	Working Hours (h)	2529	2479	2340	2538	2182
	Switch-on Times	1838	1456	1103	1079	565
Annual Simulation Results (2021)	Hours of DHW temp.<40°C (h)	0	0	0	0	0
	Hours of Operative temp.<21°C (h)	0	0	159	106	0
	Hours of Operative temp.<20°C (h)	0	0	0	0	0
	HP Energy Produced (kW)	15856	15983	15161	16593	16981
	HP El. Consumption (kW)	4681	4728	4419	4784	4341
	Price before tax (DKK)	3451	3466	2969	3106	2799
	Price after tax (DKK)	**-**	**11865**	**-**	**11512**	**10363**

14. Future works

Based on this master thesis research and obtained results the following further research can be performed incorporating the following:

Photovoltaic panels can be integrated into the heating system in such a way that produce electricity and run the heating system mostly in the cooling season (heat pump or electrical heater), to heat up the DHW tank to the maximum possible temperature. Considering the PV panels and on-site batteries in the heating system can lead to more savings due to the increased flexibility of the heating system by allowing it to run with non-grid electricity.

Using more advanced software to take into account all variable conditions in advance, i.e., number of occupants in the building, withdrawal intensity, predicted electricity price, forecasted weather conditions, and heating demand schedules for running the heating system will control it much more efficiently. So, the system will make a schedule to run the heat pump according to the predicted electricity prices and weather conditions to meet the heating demand with the lowest running costs and highest comfort conditions. Furthermore, an advanced control with a dynamic setpoint for a DHW tank as well as the buffer tank that is dictated by pricing spread would be beneficial to investigate.

Finally, a new algorithm can be introduced using machine learning techniques. It will allow to give occupants different options to run the heating system according to their needs or changes in routine. The algorithm would take historical data for electricity prices, and weather. That would result in constant adjustment of an algorithm to the following scenarios as the occupants wish:

- Economy mode, which considers the best running cost scenario,
- Comfort mode, which takes into account different categories of thermal comfort,
- Environment mode, which deals with the lowest CO_2 emission during the heating procedure.

15. References

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