Domestic hot water heating with direct electricity from PV panels and the grid

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Abstract

A solar domestic hot water tank with direct electrical heating is investigated experimentally. The investigations are carried out from January to June 2024 under Danish weather conditions. The tank has five electrical heating foils on the outside vertical tank surface. The tank is well insulated, and thermal bridges are avoided by having all the pipe connections at the bottom. The different electrical foils are supplied with electricity from PV panels or the grid. A semi-smart controller allows the tank to be heated with electricity from the grid at night to establish the energy needed to cover the demand the following day. The investigations show that the domestic hot water system can supply all the energy needed for domestic hot water at a levelized cost of heat of 0.28 €/kWh. The levelized cost of heat can be directly compared to the electricity price users pay for purchasing electricity from the grid.

Keywords: PV heated tank, control strategy, levelized cost of energy

1. Introduction

Fossil fuels dominate the heating sector. Apart from the use of traditional biomass, only 11% of the global heating needs were met by modern renewables in 2021, Solar-Heat-Worldwide-2023.pdf (iea-shc.org). Countries worldwide have committed to reducing their CO_2 emissions by significantly increasing their share of renewable energy by 2030. Worldwide, the operation of buildings accounts for about 40 % of the primary energy consumption and approximately 25 % of the greenhouse gas emissions. In Europe, buildings are responsible for 40 % of the energy consumption and 36 % of CO_2 emissions, of which water heating accounts for around 16 % of the energy consumption and 14% of CO_2 emissions, IEA-EnergyEnd-usesandEfficiencyIndicatorsdatabase-HighlightsNovember2023.xlsb (live.com).

The energy consumption for heating and cooling of buildings can be significantly reduced by building envelope improvements in existing buildings and clever design of new buildings. Still, such measures do not affect the energy demand for hot water. Therefore, decentralized solutions with individual storage tanks and solar energy collectors will be needed in the city of the future, interacting with existing grid infrastructures in the best possible way.

In recent years, photovoltaic technologies have taken over the dominant position of solar thermal water heaters in installed renewable capacity globally, Renewables 2023 (windows.net). Direct electric heating with PV panels is a robust technology because there is no circulation pump, and the requirements for maintenance are minimal. Reduced installation costs are expected because of the system's lower complexity than traditional solar thermal water heaters. Further, smart and adaptive control systems can interface with the household's energy consumption for water heating, lighting, household machinery, and possible electrical vehicles, optimize the use of the produced energy, and maximize the efficiency and profitability of the system.

The system types utilizing PV panels for heating are referred to as PV2heat or Power2heat systems and are already widely used, especially in combination with heat pumps. However, system solutions utilizing PV electricity directly are also on the market. For example, in Germany, the company NEXOL Photovoltaic AG (https://www.nexol-ag.net) offers retrofit solutions with one or two heating elements and controller for existing hot water tanks if the tank has one or two available 1.5-inch E-sleeves located at suitable heights in the tank.

In this project, electrically heating foils mounted on the outside surface of the tank supplied with electricity from PV panels or the grid are investigated experimentally. This approach is well-suited for new or retrofit systems that do not have available E-sleeves.

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2. Aim and scope

The research aims to develop a cost-effective PV-heated domestic hot water system with a standard hot water tank, a smart control system, and a good interplay with the electrical grid. The suitability of the system will be elucidated. Hot water tanks can significantly reduce the non-renewable energy consumption of buildings by using energy more efficiently. Further, hot water tanks can help to balance the grid, as they provide a storage capacity for a surplus of electricity.

3. Method

The solar domestic hot water system comprising an electrical heated hot water tank, PV panels, and inverter is installed in a test facility at the Technical University of Denmark (Lat. 55.79°, Lon. -12.52°).

The PV panels and the inverter are referred to as the PV system in this paper.

The domestic hot water tank is a standard hot water tank, type 42002, with a volume of 196 liters from METRO THERM, the PV panels are type MG230, Racell BLACK Diamond from RACELL, the inverter is type PIKO MP plus 2.5-1 kW from Kostal solar electric, and the electrical heated foils (EHF) are type HSSD/C from SAN Electro Heat A/S.

The temperatures inside the tank are measured at five different levels. The temperature sensors, copper/constantan, type TT, are arranged in a glass tube inserted into the tank through the bottom (Figure 1 and Figure 2).

Fig. 1: Glass tube with temperature sensors (T1-T5) for temperature measurements inside the tank

The tank is equipped with five electrically heated foils of a maximum of 1000 W each. The electrical heating foils cover the complete vertical tank surface. The tank is well insulated with 100 mm of mineral wool on the side and 200 mm on the top. The bottom is insulated with molded flamingo. Thermal bridges are avoided by having all the pipe connections in the bottom of the tank (Figure 2).

Six photovoltaic panels with a total gross area of 8.928 m^2 are installed on the test facility's 45° tilted south-facing roof (Figure 3).

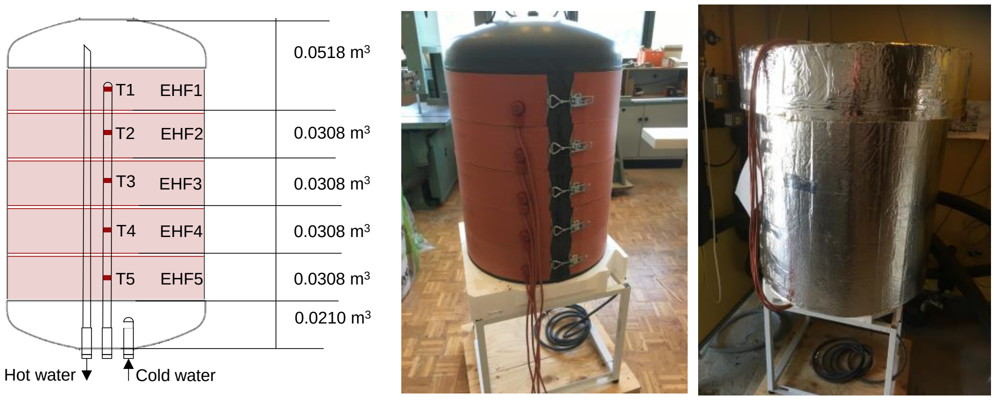

Fig. 2: Tank design

Fig. 3: PV panels on the roof of the test facility (left) and the inverter (right)

The five electrical heating foils are supplied with electricity from PV panels or the grid. The tank is heated sequentially from the top to a usable temperature. Since only one foil operates at a time, thermal stratification is established in an excellent way in the hot water tank. The electricity produced by the PV panels can also be used to cover the electricity consumption in the building and/or be sold to the grid.

Ideally, the use of electricity from the grid is optimized by forecasts of consumption, electricity prices, and PV production based on weather forecasts, and electricity from the grid would only be used in low-cost electricity periods where the PV panels could not cover the demand. However, consumption, weather, and electricity price forecasts are not included in the control of the investigated system.

4. Operation conditions and evaluation method

The control strategy is designed in LabVIEW, Bitter et al. (2006), and it provides that the tank is heated sequentially from the top with electricity from PV panels or the grid. Only if the electrical energy produced by the PV system exceeds 1000 W, which is the maximum power of each electrical heating foil, are two neighboring heating foils activated simultaneously. In this case, the first heating foil used 1000 W, and the second foil used the rest.

During nighttime, from midnight until 6 am, the tank is heated by electrical energy from the grid to establish the energy to cover the daytime heating demand, if not already present. The tank is heated until the temperature of the three upper layers (T1, T2, T3) exceed 55 °C. The energy amount established is sufficient to cover the domestic hot water demand without considering the solar energy supplied to the tank during the daytime. Incoming solar heat from the day can reduce the energy supplied to the tank from the grid the following night.

During the daytime, all electrical power produced by the PV system is supplied to the tank, and no electrical energy from the grid is exchanged with the grid. The tank is heated layer by layer from the top until the temperature in each layer reaches 90 °C.

The solar radiation measurements are obtained from the DTU climate station (https://weatherdata.construct.dtu.dk) located on the roof of a 3-story building next to the test facility. The test facility is a 1-story building surrounded by other buildings and trees. Consequently, the PV panels may be shaded in periods where there are no shades affecting the climate station. This is mainly a problem in the morning and the evening. Therefore, such periods are excluded when determining the efficiency of the PV system.

The daily hot water consumption is 100 liters heated from 10 °C to 50 °C. Hot water is tapped from the top of the tank through a PEX pipe inserted through the bottom of the tank. Tapping takes place at 7 am, noon, and 7 pm in three equal portions with a volume flow rate of about 2.5 l/min.

Measured data are obtained with a time resolution of 1-minute. Data of the used measurement equipment is shown in Table 1.

Tab. 1: Measurement equipment

Equipment	Type	Location	Accuracy
Flow sensor	Clorius Combimeter 1.5 EPD	DHW loop	± 2-3 %

Temperature sensor	Copper/constantan, type TT	DHW loop, Tank	± 0.5 K
Pyranometer	Kipp & Zonen CMP11	DTU Climate station	± 1.4 %
Pyrheliometer	Kipp & Zonen CHP1	DTU Climate station	± 1 %
Ambient temperature	Vaisala weather transmitter WXT520	DTU Climate station	± 0.3 K

The electrical energy amounts from the grid and the PV system (Q_{grid} and Q_{PV}) are measured directly with an energy meter, while the tapped energy (Q_{tap}) is calculated from the measured hot and cold water temperatures and the volume flow rate. The energy change in the tank (Q_{change}) is calculated from the measured temperatures (T1, T2, T3, T4, T5) and the respective volume each temperature sensor represents, see Figure 2. The energy balance is used to determine the heat loss of the tank (Q_{loss}):

$$Q_{grid} + Q_{PV} - Q_{tap} - Q_{loss} + Q_{change} = 0 \quad \text{(eq. 1)}$$

$$Q_{loss} = Q_{grid} + Q_{PV} - Q_{tap} + Q_{change} \quad \text{(eq. 2)}$$

$$Q_{change} = Q_{tank.start} - Q_{tank.end} \quad \text{(eq. 3)}$$

The total solar radiation on the PV panels (Q_t) is determined with measurements from the DTU climate station (https://weatherdata.construct.dtu.dk). The measured solar irradiance data are direct normal irradiance (DNI), global irradiance (G), and horizontal diffuse irradiance (G_d). The total irradiance on the PV panels (G_t) is determined in the following way, assuming an isotropic distribution of the diffuse irradiance (Liu and Jordan, 1963) and a reflectance coefficient (ρ) of 0.2:

$$G_{bt} = DNI \cdot \cos \Theta, i \quad \text{(eq. 4)}$$

$$G_{dt} = G_d \cdot \left(\frac{1+\cos\beta}{2}\right) + G \cdot \rho \cdot \left(\frac{1-\cos\beta}{2}\right) \quad \text{(eq. 5)}$$

$$G_t = G_{bt} + G_{dt} \quad \text{(eq. 6)}$$

$$Q_t = G_t \cdot A_{PV} \quad \text{(eq. 7)}$$

The efficiency of the PV system (η_{PV}) is determined in the following way:

$$\eta_{PV} = \frac{Q_{PV}}{Q_t} \quad \text{(eq. 8)}$$

5. Results

The measurements were obtained from January to June 2024, and Table 2 shows the availability of measurements.

Tab. 2: Periods with available measurements

Month	January	February	March	April	May	June
Measurement days	1-31	1-18	1-31	1-30	1-31	1-28

5.1 Weather conditions

Figure 4 shows the monthly beam and diffuse solar radiation on the PV panels as well as the monthly average ambient temperature. About 50% of the energy comes from the beam radiation, except for January and May, where the beam radiation accounts for about 65%.

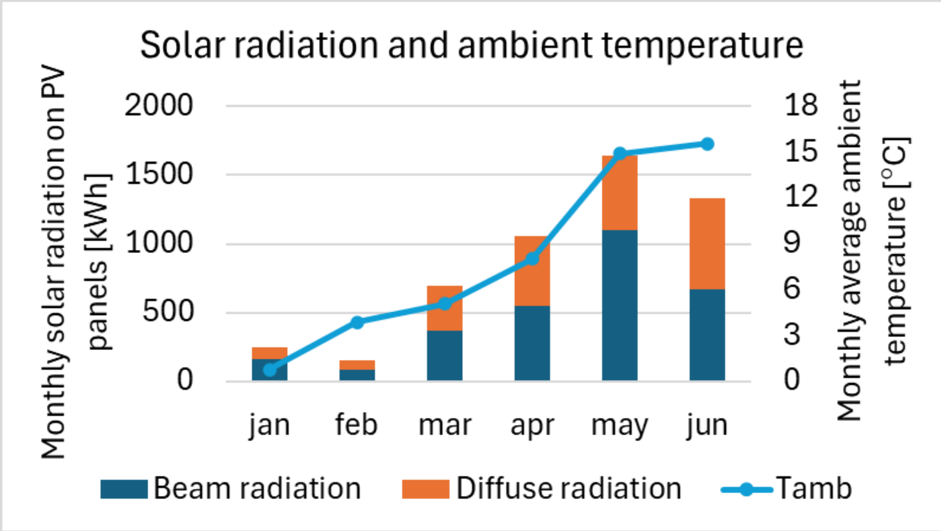

Fig. 4: Solar radiation and ambient temperature

5.2 Domestic hot water consumption

Figure 5 shows the energy tapped from the tank. There are only small variations in the daily tapped energy.

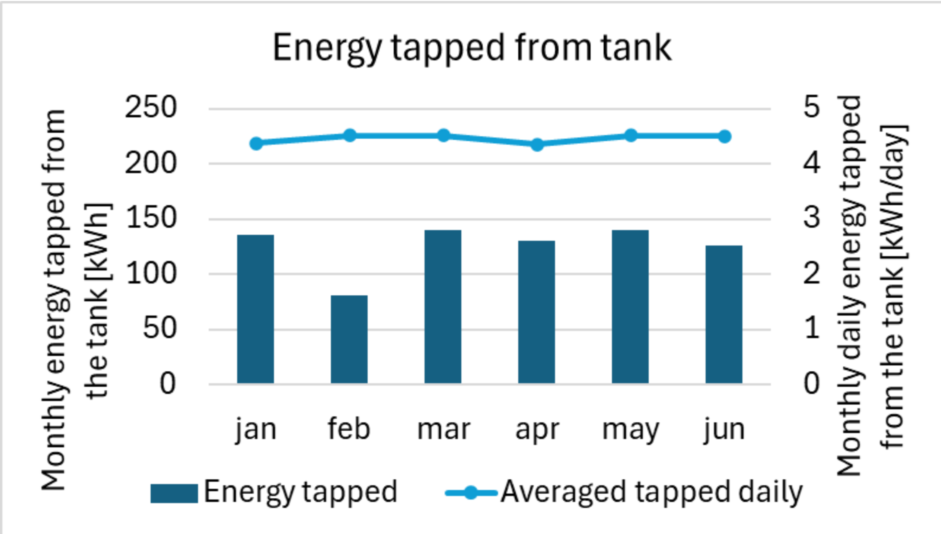

Fig. 5: Energy tapped from the tank

5.3 Tank temperatures and heat losses

Figure 6 shows the weighted average tank temperature and the heat loss from the tank. The tank temperature is the lowest in January and February when the contribution from the PV system is limited. As the tank temperature increases, the heat loss increases. In June, the tank heat loss is higher than in May, even though the average tank temperature is higher in May.

The test facility where the tank is located is a light building highly affected by weather conditions such as ambient temperature, solar radiation, wind speed, and wind direction. During the daytime, the temperature in the test facility is higher, especially when the sun is shining, and during nighttime, the temperature is lower.

When the tank is heated at night with electricity from the grid, the electrical power supplied to the electrical heating foils is always 1000 W. Consequently, the temperature of the tank wall is the highest while the temperature in the test facility is the lowest.

When the tank is heated during the day by electricity from the PV system, all the electricity is supplied to the heating foils. The electrical power rarely exceeds 1000 W. In case the power exceeds 1000 W, the excess power is supplied to the next electrical heating foil. Consequently, the temperature of the tank wall is lower most of the time compared to the nighttime conditions, while the temperature in the test facility is highest.

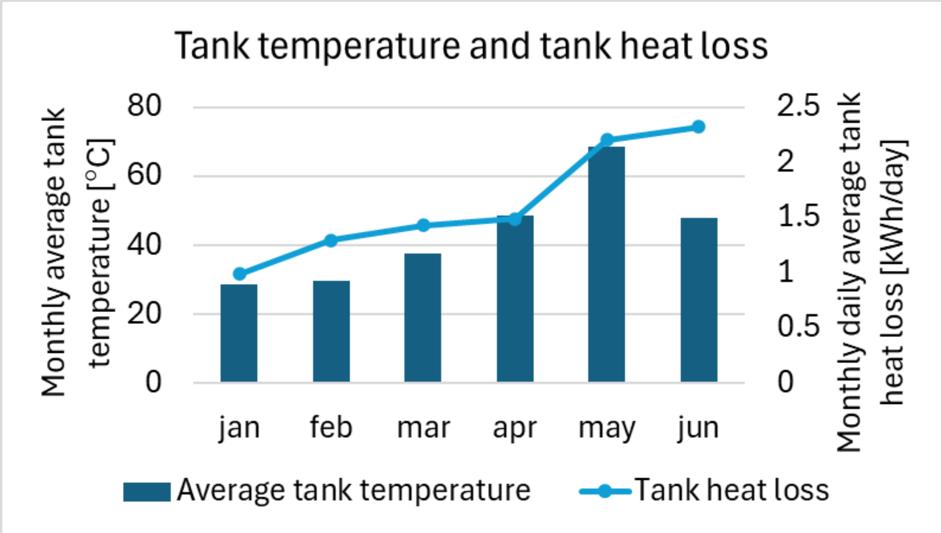

Fig. 6: Tank temperatures and tank heat loss

Figure 7 shows the temperature variations in the test facility from January to June 2024.

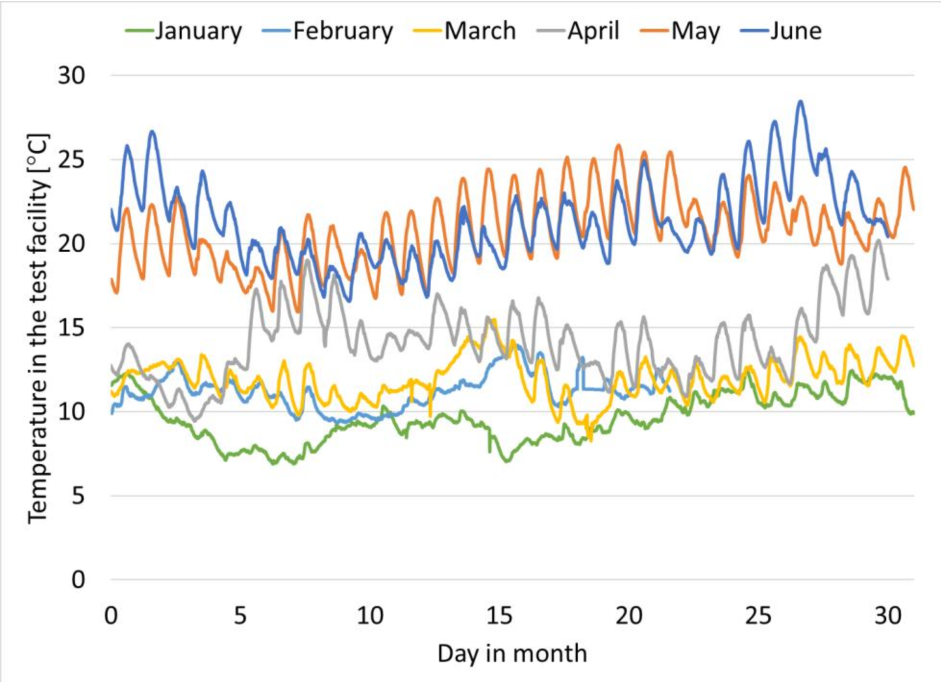

Fig. 7: Temperatures in the test facility

The temperature difference between the tank wall and the water in the tank at the same level is less than 10 K when the electric heating foil is operated with the full power of 1000 W and lower when the power is lower. The tank wall temperature is only measured at the upper heating element, EHF1. Figure 8 shows the tank temperatures during a night period with 1000 W heating through the electric heating foils and the tank wall temperature at the level of the upper heating foil. The tank wall temperature difference between the tank wall and the water at the upper level is high at the beginning of the heating period. This is explained by the water velocity along the inside of the tank wall being downward in periods without heating and upward in periods with heating. At the beginning of the heating period, while the water velocity switches direction, the heat transfer is lowest. This process takes about 10 minutes. The heat transfer from the hot tank wall to the water increases as the upward water velocity develops and reaches its maximum when the water velocity profile is fully developed after about 30 minutes.

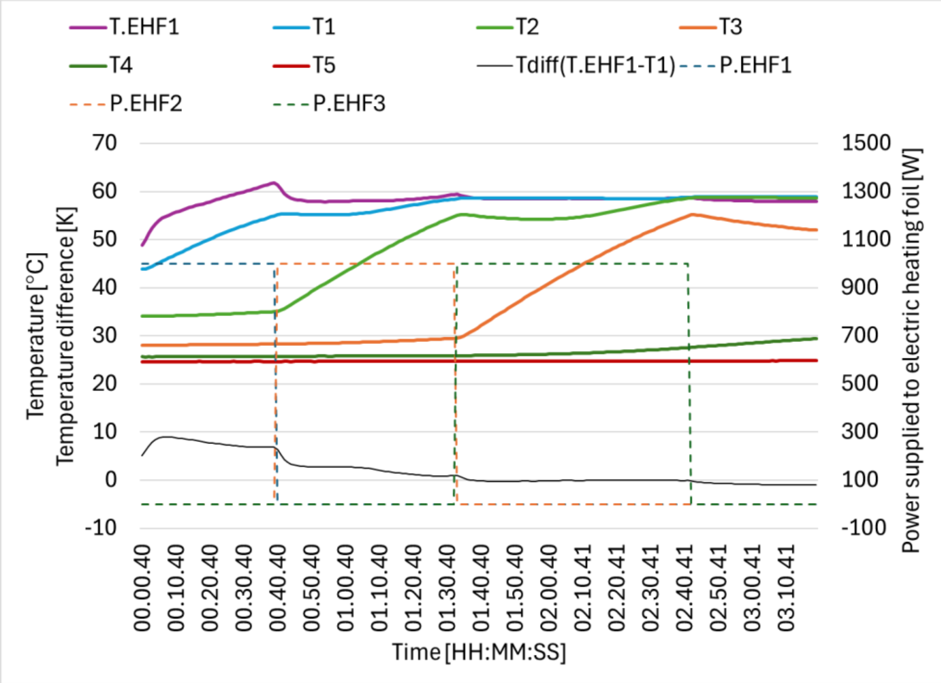

Fig. 8: Temperatures in the tank during heating at night on June 24, 2024

5.4 Electrical energy supply

Figure 9 shows the monthly energy supply to the tank from the grid and the PV panels, as well as the average efficiency of the PV system. The monthly average PV system efficiency increases slightly from 12.7% in January to 13.6 % in June. March stands out with the highest efficiency of 14 %. The reason for the highest efficiency in March is that the ambient temperature is still low while the solar radiation is high.

The hourly PV system efficiency as a function of the total solar radiation on the PV panels is displayed in Figure 10. There are some outliers in January, February, and March. These are due to snow laying on the PV panels or the pyranometer of the climate station. The outliners in May are due to obstacles casting shading on the PV panels while not on the climate station. The PV system efficiency has a maximum when the solar radiation is about 2 – 4 kWh/h. For low solar radiation, the share of diffuse radiation is high, resulting in low efficiency. For high solar radiation, the PV cell temperature is relatively high, resulting in low efficiency.

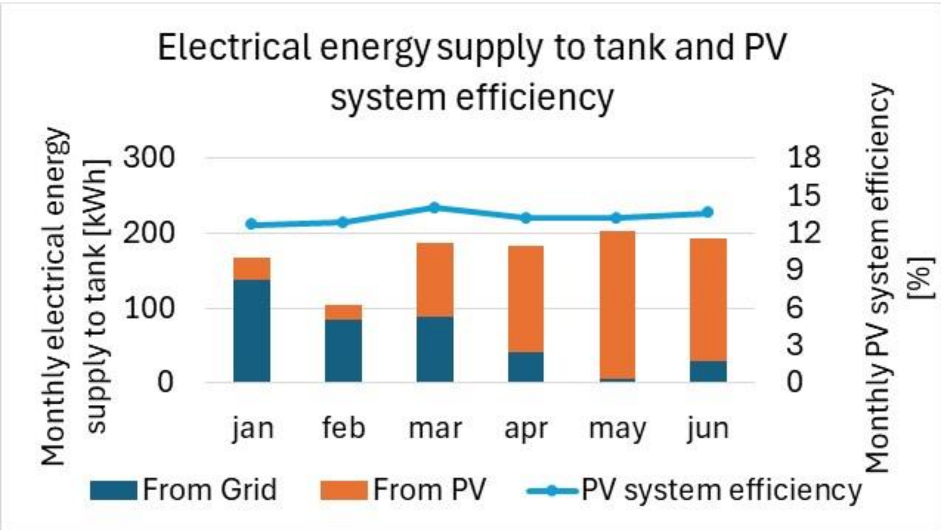

Fig. 9: Electrical energy supplied to the tank and PV system efficiency

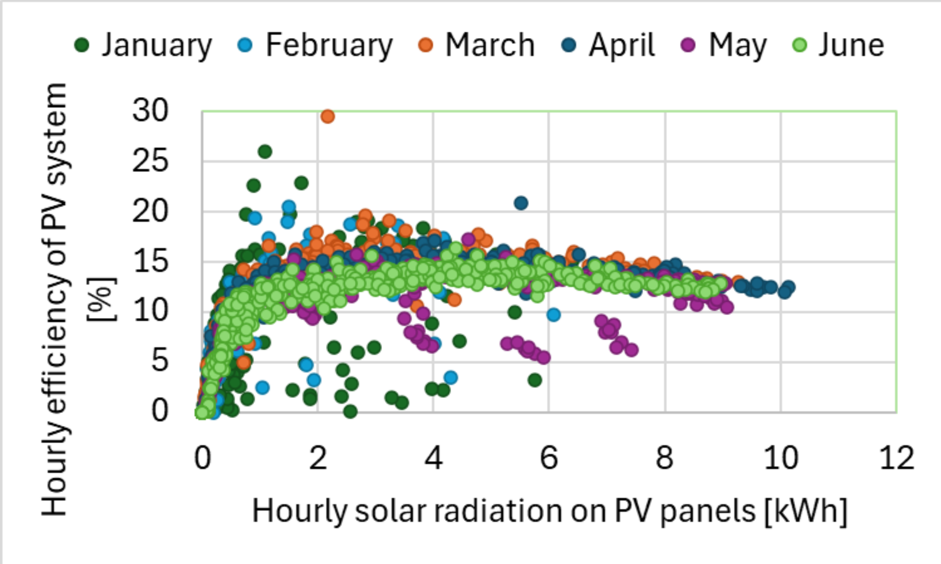

Fig. 10: PV system efficiency versus solar radiation on PV panels (8.928 m^2)

Figure 11 shows the monthly energy supply to the tank during nighttime, where the energy comes from the grid, and Figure 12 shows the monthly energy supply to the tank during daytime, where the energy comes from the PV panels.

The PV system and the grid use the upper electric heating foils (EHF1, EHF2, EHF3), and the two lowest foils (EHF4, EHF5) are only used by the PV system.

The number of hours the individual heating foils are utilized can be seen in Figure 13. The upper electric heated foil (EHF1) is utilized about 60 % of the total operation time, while the next two foils (EHF2, EHF3) are utilized about 15 % of the time. The two lowest-located foils (EHF4, EHF5) are only utilized about 4% of the time. Utilization of the individual electrically heated foils is a direct consequence of the control strategy and the climate under which the system operates.

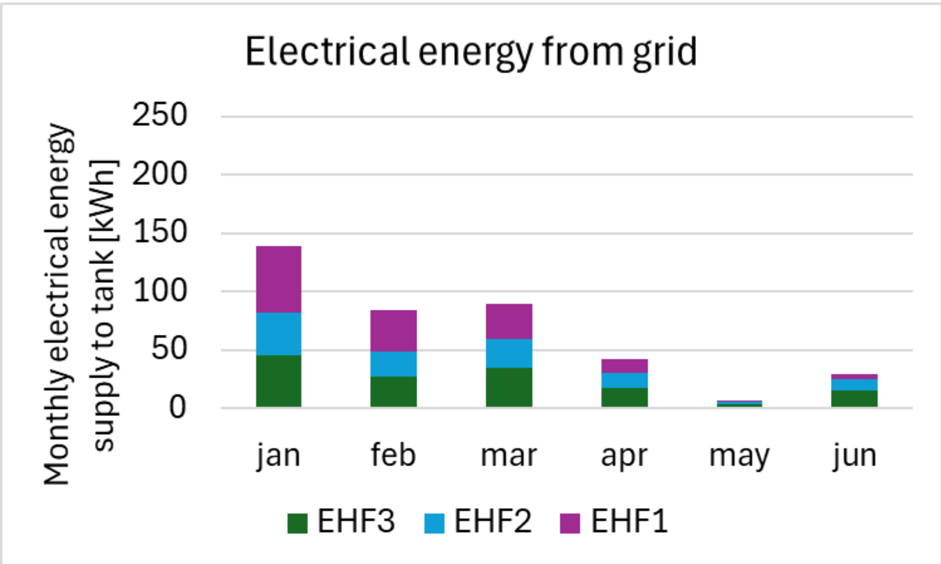

Fig. 11: Electrical energy from the grid

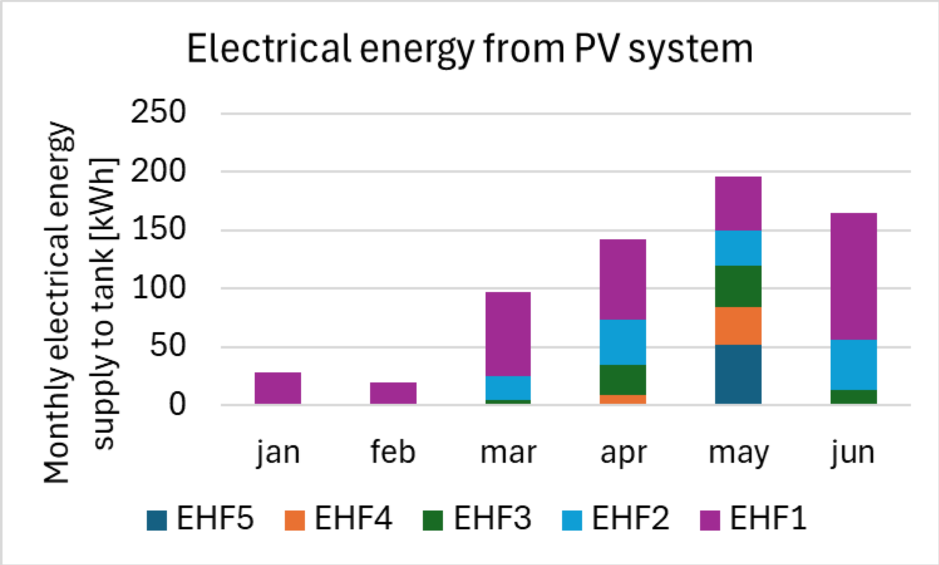

Fig. 12: Electrical energy from the PV system

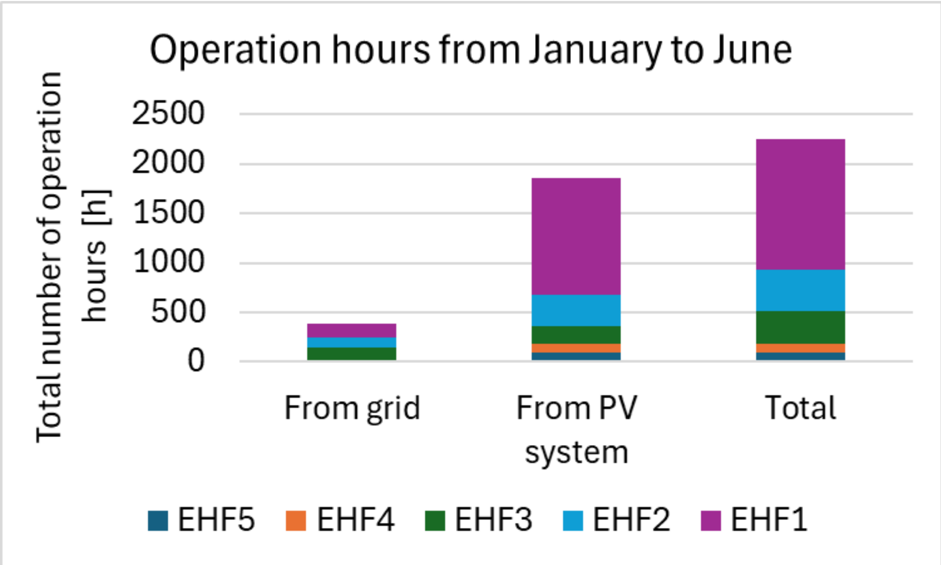

Fig. 13: Operation hours

5.5 Economy

The cost of the investigated system is compared to the cost of a conventional heating system comprising a domestic hot water tank heated by an electrical heating element with electric energy from the grid and a controller always keeping the usable temperature in the tank. Only the extra costs for the investigated domestic hot water system over the cost for the conventional domestic hot water system are included in Table 3. The prices include VAT. The lifetime of the system is estimated to be 20 years, during which only the anode used to protect the tank from corrosion needs replacement approximately every five years. The owner can easily replace a flexible anode through the top of the tank. If the tank is well maintained, an exchange of the PV modules and the electric heating foils will result in another 20-year system lifetime at a low cost. However, in this paper, only a lifetime of 20 years is considered.

Tab. 3: System costs

PV panels and inverter	2,800 €
Electrical heating foils	1,900 €
Domestic hot water tank	270 €

Control system	270 €
Installation	1500 €
Total system costs, incl. installation	6,740 €

The levelized cost of heat can estimate the cost of providing domestic hot water with the investigated system type, LCoH (Louvet et al., 2019):

$$LCoH = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t(1-TR) - DEP_t \cdot TR}{(1-r)^t} - \frac{RV}{(1-r)^T}}{\sum_{t=1}^{T} \frac{E_t}{(1-r)^t}} \quad \text{(eq. 9)}$$

The application is for residential use. No subsidies or operation and maintenance costs are included for the expected lifetime of the system of 20 years. Therefore, equation 9 can be simplified:

$$LCoH = \frac{I_0}{\sum_{t=1}^{T} Q_t} \quad \text{(eq. 10)}$$

$$E_t = Q_{conv}^{ref} - Q_{grid} \quad \text{(eq. 11)}$$

The energy demand of a conventional heating system (Q_{conv}^{ref}) is estimated in the following way:

$$Q_{conv}^{ref} = Q_{tap} + Q_{loss}^{ref} \quad \text{(eq. 12)}$$

The tapped energy (Q_{tap}) is estimated as the average energy amount tapped each month from the investigated system times the number of days in the month. The tapped energy (Q_{tap}) and the energy supplied by the grid (Q_{grid}) are then multiplied by two to account for the whole year. The heat loss of the conventional heating system (Q_{loss}^{ref}) is estimated to be 1 kWh/day during the whole year.

LCoH is calculated to be 0.28 €/kWh and can be directly compared to the electricity price from the grid.

The electricity price from the grid is made up of the raw electricity production price, electricity tax, transmission network tariff, system tariff, and costs to the grid company. Figure 14 shows the monthly average electricity prices hour by hour during the days of the months of January to June 2024. The electricity prices are lowest at night when the load on the grid is low, but they are also low during the daytime in the spring and summer months due to an increasing number of installed large-scale PV systems that feed electricity into the grid. In the evening, when the load on the grid is highest, the electricity prices are also the highest.

Whether the investigated system as presented here is economically attractive compared to a conventional system depends on how the conventional system with an electrically heated domestic hot water tank draws electricity from the grid and how the electricity prices will vary in the future.

A smart control that draws electricity from the grid based on forecasts of electricity prices, solar radiation, and consumption patterns could optimize electricity use further. Furthermore, the system cost could be lower if the system was sold as a complete plug-and-play unit. Both actions would result in a reduction in LCoH.

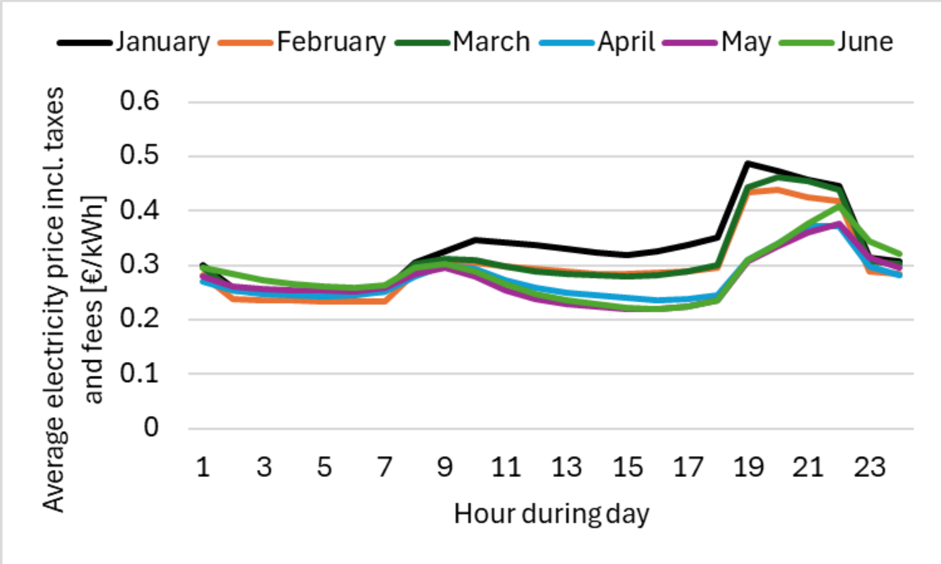

Fig. 14: Electricity prices, incl. electricity tax, transmission network tariff, system tariff, and costs to the grid company

6. Perspectivation

The investigations showed that a PV-based domestic hot water system with electrical heating foils placed on the surface of the tank walls and with backup from the electric grid could work and cover the total hot water consumption. The system can both be economically attractive for consumers and provide a good interplay with the energy system. It is therefore suggested to start research to elucidate the suitability of similar PV-based heating systems with backup from the electric grid, which can cover the total yearly heat demand of buildings. Among other things, the following questions should be answered for different buildings:

- What is the best design and size of the system from an economical point of view?
- Under which conditions is it favorable to include a heat pump or an electric battery in the system?
- How much can a smart control system optimizing purchases and sales of electricity to/from the electric grid improve the system?
- Are the optimal system solutions more suitable than other solutions, such as heat pump systems, solar heating systems, etc., from an economical point of view?

7. Conclusions

A 196-liter domestic hot water system heated by electricity from 8.928 m^2 PV panels and the grid is experimentally investigated. The tank is heated by five electric heating foils mounted on the vertical tank surface under the tank insulation. The system is tested under Danish weather conditions from January to June 2024.

The investigation shows that the domestic hot water system can supply all the energy needed at a levelized cost of heat of 0.28 €/kWh. The levelized cost of heat can be directly compared to the electricity price users pay for purchasing electricity from the grid, which varies during the day and the year.

The investigation also showed that the temperature of the tank wall is less than 10 K compared to the temperature inside the tank when the power supplied to the electric heating foil is the maximum of 1000 W. The heat transfer between the electric heating foil and the tank water is lowest in the first 10 minutes of a heating period, where the water velocity along the inside tank wall changes direction from downward to upward and reaches its maximum after about 30 minutes when the upward water velocity is fully developed.

8. Acknowledgments

This research project was funded by the Bjarne Saxhof Foundation through the project “Energy supply systems for buildings based on PV panels” and by the Danish Energy Agency through the project “EUDP 2022-I3 IEA SHC Smart Solar Hot Water for 2030”, EUDP program grant no: 134223-495988.

9. Nomenclature

Quantity	Symbol	Unit
Energy from the grid	Q_{grid}	kWh
Energy from the PV system	Q_{PV}	kWh
Energy tapped from the domestic hot water tank	Q_{tap}	kWh
Energy loss of domestic hot water tank	Q_{loss}	kWh
Energy change in the domestic hot water tank	Q_{change}	kWh
Energy content in the domestic hot water tank at the start	$Q_{tank.start}$	kWh
Energy content in the domestic hot water tank at the end	$Q_{tank.end}$	kWh
Energy demand of the conventional heating system	Q_{conv}^{ref}	kWh
Energy loss from the conventional heating system	Q_{loss}^{ref}	kWh
Total energy on the PV panels	Q_t	kWh
Global irradiance	G	W m^{-2}
Diffuse irradiance on horizontal	G_d	W m^{-2}
Beam irradiance on the PV panels	G_{bt}	W m^{-2}
Diffuse irradiance on the PV panels	G_{dt}	W m^{-2}
Direct normal irradiance	DNI	W m^{-2}
Incidence angle on PV panels	Θ, i	°
Tilt of PV panels	β	°
Reflectance coefficient	ρ	-
Efficiency of PV system	η_{PV}	-
Area of PV panels	A_{PV}	m^2
Initial investment	I_0	€
Subsidies and incentives	S_0	€
Operation and maintenance costs	C_t	€ y^{-1}
Corporate tax rate	TR	%
Asset depreciation	DEP_t	€ y^{-1}
Residual value	RV	€
Saved final energy	E_t	J y^{-1}
Discount rate	r	%
Period of analysis or temperature	T,t	Years or °C

10. References

Bitter, R., Mohiuddin, T., Nawrocki, M., 2006. *LabVIEW: Advanced programming techniques*. Crc Press.

Climate station at DTU, https://weatherdata.construct.dtu.dk

IEA Energy End-uses and Efficiency Indicators database (November 2023 edition), Highlights, IEA-EnergyEnd-usesandEfficiencyIndicatorsdatabase-HighlightsNovember2023.xlsb (live.com)

Liu, B.Y.H., Jordan, R.C., 1963. The Long-Term Average Performance of Flat-Plate Solar Energy Collectors. Solar Energy, Vol. 7, No. 2, 1963 53-74.

Louvet, Y., Fischer, S., Furbo, S., Giovannetti, F., Helbig, S., Köhl, M., Mugnier, D., Philippen, D., Veynandt, F., Vejen, K., 2019. Economic comparison of reference solar thermal systems for households in five European countries. Solar Energy, 193 (2019) 85-94. https://doi.org/10.1016/j.solener.2019.09.019

NEXOL Photovoltaic AG, https://www.nexol-ag.net

Renewables, 2023, Renewables 2023 (windows.net)

Solar Heat Worldwide, 2023 Edition, Solar-Heat-Worldwide-20231.pdf (iea-shc.org)