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Smart control of PV heated hot water tank based on forecasts

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Abstract

The purpose of this experiment is the development of a control system for heating foils inside a hot water storage tank, designed to meet the Domestic Heating Water (DHW) demands of a common household. With optimization of energy use as the main priority, the system favors electricity from a set of photovoltaic panels located on the building's roof, and complements solar shortages with the selection of the cheapest grid electricity hours available. Implemented in Python, the model combines weather and electricity price forecasts to dynamically determine the more cost-effective energy source. This approach enhances efficiency, reduces reliance on the grid, and lowers household energy expenses.

Keywords: Smart Control Systems, Domestic Thermal Energy Storage, Photovoltaic Heating, Python for Modeling.

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1 Introduction

The integration of photovoltaic (PV) systems into residential applications is being seen as an important area of research because the need for sustainable energy solutions is increasing. Domestic hot water systems have emerged as a promising target because they account for an important share of household energy consumption [1]. Customary water heating methods often rely on fossil fuels and they contribute heavily to greenhouse gas emissions and rising energy costs. Switching to PV-powered alternatives can reduce both emissions and our dependency on non-renewable energy sources while offering a sustainable solution [2].

Solar water heating systems actively combine solar collectors and thermal energy storage (TES) along with advanced control strategies to balance energy generation, storage, and consumption, and they play a key role in achieving these important goals [3]. One central challenge is that solar energy production does not match hot water demand. TES systems paired with smart control algorithms can store excess energy during peak solar generation periods and release it during high demand periods [4].

Important progress has been made in optimizing solar water heating systems by concentrating on component design and capacity optimization and control strategies [5]. The design and sizing of system components, which include solar collectors and storage tanks as well as auxiliary heaters, play an important role in guaranteeing optimal performance and efficiency [6].

Studies highlight how adjusting system capacity with energy demand guarantees effective use of solar energy and minimizes losses. The use of stratified storage tanks is shown to improve energy retention because they maintain temperature layering and allow for consistent hot water delivery with minimal energy waste [7].

More and more people use advanced control strategies to improve system efficiency. Customary rule-based control methods that rely on fixed functional rules are being replaced by more dynamic approaches like model predictive control and these new methods offer greater flexibility and adaptability. MPC predicts energy demand and solar availability using models and real-time data and optimizes its operations. It has been shown by studies that energy costs can be importantly reduced by MPC with reductions of up to 58 % when compared to customary control methods and this shows the effectiveness of MPC in saving energy. User comfort is improved by MPC because desired temperature levels are maintained and energy needs are changed to dynamically [8].

Many researchers focus on conventional configurations and they include systems with external electric heating foils or solar-assisted heat pumps. These approaches often do not fully use the potential of PV-TES integration and do not include real-time variables like weather forecasts and electricity price fluctuations [5]. This gap is addressed by concentrating on a PV-grid-connected system with internal electrical heating elements. This configuration simplifies the system architecture while providing a unique opportunity to explore the benefits of integrating TES with intelligent control algorithms in a grid-connected environment.

By integrating weather forecasts and electricity price data, the proposed control strategy leverages time-of-use tariffs to minimize costs while maximizing renewable energy utilization [9]. This dynamic approach is particularly relevant as more energy markets adopt variable pricing structures, making cost-effective solutions increasingly important [5].

The state of the art in this field shows a growing focus on integrating PV systems with TES to improve the efficiency of renewable energy usage. Recent advancements include the development of stochastic MPC (SMPC) approaches, which address uncertainties in solar irradiance and energy demand forecasts, ensuring robust system performance even under variable conditions. Hybrid systems that combine thermal and electrical storage are also gaining attention, offering enhanced energy management capabilities across multiple household demands. However, these systems often face challenges related to computational complexity, highlighting the need for streamlined and practical solutions such as the one explored in this study [10].

Another trend in the field is the increasing use of Python for modeling and simulating solar water heating systems. Pythons flexibility, combined with its extensive library ecosystem, makes it an ideal tool for developing custom control algorithms and conducting detailed simulations [11]. Its open-source nature fosters collaboration and innovation, enabling researchers to build scalable and adaptable solutions. For example, Python-based MPC systems have been used successfully to optimize PV self-consumption, demonstrating their ability to adapt to varying energy demands. Implementing the control algorithm in Python aligns this study with these advancements, offering a modern and versatile approach to system modelling [12].

This research not only builds on existing knowledge but also introduces practical and economic innovations. By addressing key challenges in system optimization, dynamic control, and renewable energy integration, the study contributes to the ongoing effort to make solar water heating systems more efficient and accessible. The insights gained have the potential to advance the state of the art in PV-powered hot water systems, providing a scalable and sustainable solution for residential energy needs [1].

The integration of PV systems with intelligent control strategies represents a critical step toward achieving energy sustainability. By dynamically optimizing energy usage and leveraging TES, these systems can overcome the intermittency of solar power, ensuring consistent hot water availability while reducing costs and environmental impacts. This research's focus on real-time control and innovative system configurations enhances the practicality of PV-TES systems, making them adaptable to the evolving demands of modern energy markets. These contributions are particularly significant as renewable energy adoption accelerates, emphasizing the need for robust and user-focused solutions that effectively bridge the gap between energy production and consumption. [13]

2 Methods

2.1 Code explanation

The objective of this study is to design a smart control system for optimizing the energy usage of a photovoltaic (PV)-heated domestic hot water system. The system uses both solar and grid energy to meet the energy demands of a hot water tank. The methodology involves the calculation of power required to heat the water, determination of the available solar energy, and decision-making processes regarding when to use grid electricity or solar energy.

2.1.1 Data Inputs and Initialization

The system relies on several data inputs, including solar power forecasts, grid power prices, and layers' temperature data. The time and temperature dependencies are crucial for optimizing the energy consumption of the system. The solar power forecast is obtained through the `pvlib` library, which is a Python package designed for the modeling of photovoltaic (PV) systems. The following steps describe the core calculations:

- **Solar Power Forecasting:** The solar power available at each time step (i.e. every hour) in the next 24 hours is forecasted using averaged data from previous years from `pvlib`, which incorporates geographical location, solar radiation, and the position of the sun. The `pvlib` functions and other implemented equations calculate the expected irradiance and convert it into a usable power value for each time step. This step ensures that the available solar power is correctly factored into the energy balance. This data, in possible future applications of this control system, could be taken from reliable weather forecasting sources for the location set.
- **Grid Power Prices:** The grid power price for each hour in the next 24 hours is used to minimize the cost of heating, ensuring that grid energy is used only when solar power is insufficient and the price is the cheapest. The grid power prices are sorted and filtered for use in the upcoming heating cycles. The price data in the future version of this control system can be potentially switched to real forecast prices, instead of using past years' data as it is done now.
- **Temperature Measurement:** The starting temperature measurements for the layers in the tank are for now set to realistic fixed values. In the future, these data will be constantly updated with the temperature sensors located in every layer of the tank.

2.1.2 Heating Cycle and Energy Balance

The energy balance is calculated at each time step, where the system determines whether it should heat the water using solar power or grid electricity. The following describes the primary steps involved:

- **Energy Tapping:** The initial energy required for the tapping cycle is computed based on the current temperature in the tank and the desired temperature increase. This is expressed as:

$$E_{\text{tap}} = C_{\text{layer}} \cdot \Delta T \tag{2.1}$$

where C_{layer} is the specific heat capacity of the water in each layer, and ΔT is the temperature difference between the current and target temperatures. This step calculates the total energy required for the system to reach the desired temperature.

- **Grid Power and Solar Power Calculation:**

The `pvlib.location.Location` class was used to define the system's geographical location (latitude, longitude, and timezone). The solar position, including zenith and azimuth angles, was calculated using the `get_solarposition` function. Using this data, irradiance on the tilted plane of the PV panels was determined via `pvlib.irradiance.get_total_irradiance`, which combines:

  - Direct normal irradiance (DNI),
  - Diffuse horizontal irradiance (DHI),
  - Global horizontal irradiance (GHI).

$$I_{\text{POA},t} = DNI_{\text{tilt}} + DHI_{\text{tilt}} + E_r, \tag{2.2}$$

where:

  - $DNI_{\text{tilt}} = DNI \cdot \cos(\theta)$, the direct beam irradiance adjusted for the tilt angle.
  - DHI_{tilt}, the diffuse irradiance on the tilted surface.
  - $E_r = GHI \cdot \rho_g \cdot R_r$, the ground-reflected irradiance, calculated as:

$$R_r = \frac{1 - \cos(\beta)}{2}, \tag{2.3}$$

where β is the panel tilt angle and ρ_g is the ground reflectance (albedo, assumed to be 0.2).

Then, the system power output $P_{\text{PV},t}$ is given by:

$$P_{\text{PV},t} = \eta_{\text{PV}} \cdot A_{\text{PV}} \cdot I_{\text{POA},t}, \tag{2.4}$$

where:

  - η_{PV}: Efficiency of the PV module, assumed to be 15%.
  - A_{PV}: Area of the PV panels, set to 9 m^2.

  – $I_{\text{POA},t}$: Total plane-of-array irradiance.

  The system next calculates the power required to heat the water for each layer. If the available solar power is insufficient to meet the required power, grid power is used. The energy input from the grid is calculated by:

$$P_{\text{grid}} = \min\left(P_{\text{total}}, \text{GridMaxPower}\right) \tag{2.5}$$

  where P_{total} is the total energy required to reach the target temperature, and GridMaxPower is the maximum power the resistance coils can provide for each layer. If solar energy is available, the system will first prioritize using the PV system over the grid.

- **Temperature Update:** As the water is heated using either grid or solar power, the temperature of the water layers is updated. This is done by calculating the change in temperature for each layer using:

$$\Delta T = \frac{P \cdot \Delta t}{C_{\text{layer}}} \tag{2.6}$$

  where P is the heating power applied to the specific layer in the specific hour considered and Δt is the time interval for heating (one hour). The new temperature is then updated accordingly.

The heating power applied to the specific layer during the hour under consideration is denoted by P, while Δt represents the heating duration (one hour). The temperature is then updated accordingly based on these parameters.

2.1.3 Energy Optimization Loop

The core of the system is a loop that continuously checks the energy balance and decides whether to use grid or solar power, based on the upcoming energy demand and available resources. This loop runs for each hour and adjusts the heating process accordingly. The decision-making process involves several steps:

- **Select Cheapest Grid Hour:** In each iteration, the system selects the cheapest grid hours available before the next draw-off. The grid power prices are sorted, and the system selects the first available hour with the lowest price.
- **Check for Solar Availability:** The system checks whether solar power is available and sufficient for heating. If so, it updates the power values accordingly, and solar energy is used first. The decision is based on comparing the energy required with the solar power available.
- **Update Heating Cycles:** Once the system has determined the available resources (solar or grid), the appropriate heating cycle is selected, and the temperature of each layer is updated. If the grid is selected as the preferred energy source, the layer is heated

to the required temperature. Otherwise, all available solar energy is used efficiently, distributing it across all layers until the temperature reaches the 90 degrees of Celsius limit. This is repeated for each hour until the desired temperature is reached.

2.1.4 Control Algorithm Flow

The method employs an iterative control algorithm that continuously adjusts the heating process by checking the remaining power required and the availability of solar and grid energy. This process involves:

- Updating the energy requirements at each step.
- Checking the available solar and grid energy for each hour.
- Allocating energy based on availability, with a priority given to solar power when possible.
- Adjusting the heating process based on the power used and the current temperatures in the tank.

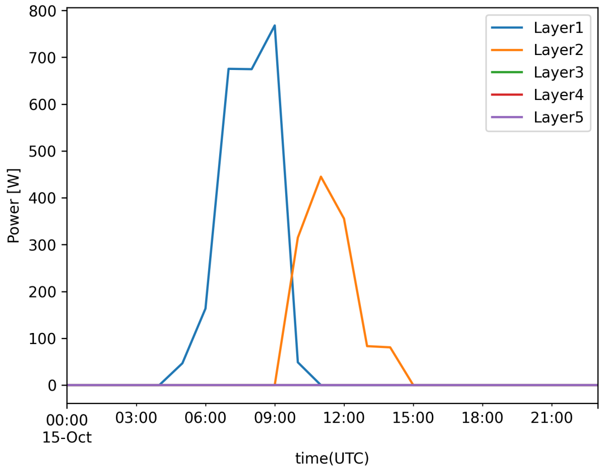
2.1.5 Simulation and Data Handling

The simulation was conducted over a 24-hour period with hourly time steps. The workflow includes:

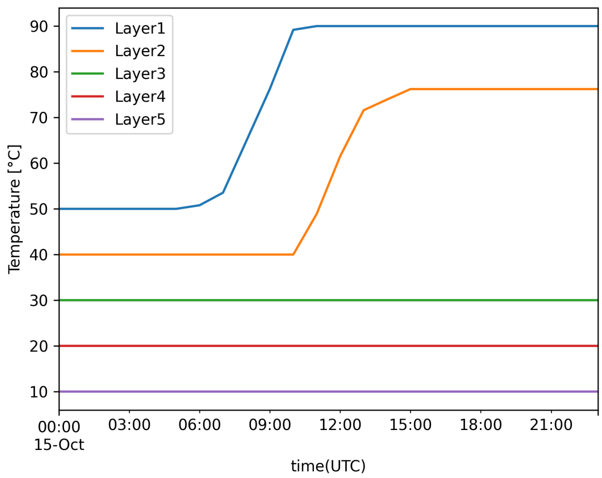
1. Solar Energy Calculation: For each hour, the solar energy generated by the PV system is calculated using `pvlib`.
2. Tapping Event Check: At predefined times, water tapping events are simulated, and the top layer is updated.
3. Energy Calculation: Allocating energy based on availability, with a priority given to solar power when possible.
4. Parameters Update: Updating the heat content, temperature and heat demand in each layer.

3 Results and Discussion

The following section of the report includes a description of the results achieved by running the code with different dates: case **a)**, the hottest day of 2016 (in terms of irradiation), June 1st; case **b)**, the coldest day of 2016, December 27th; and case **c)**, an arbitrary day that reflects a mid-point in terms of irradiation, October 15th.



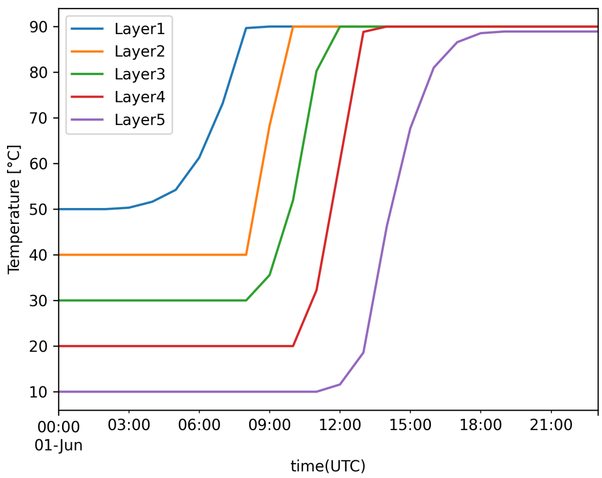
(a) Heat power for case **c)**



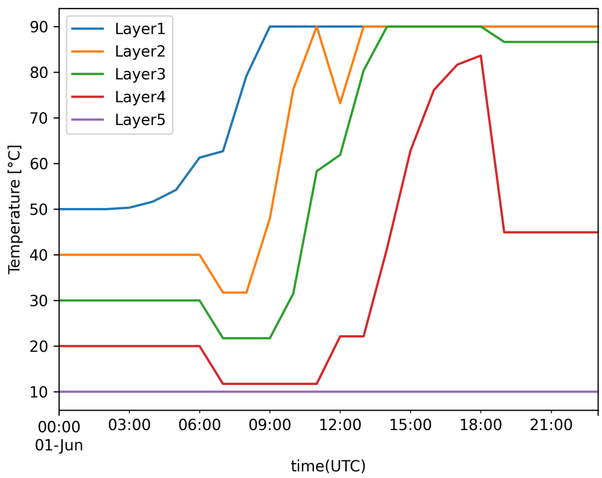
(b) Layer temperature evolution for case **c)**

Figure 1: Heat power and layer temperature evolution for case **c)**

A first look into the solar heating dynamics of the program is shown in Figure 1. The data pictured corresponds to case **c)**, and the influence of sun power for layers one and two is clearly reflected in the temperature inside of the tank.



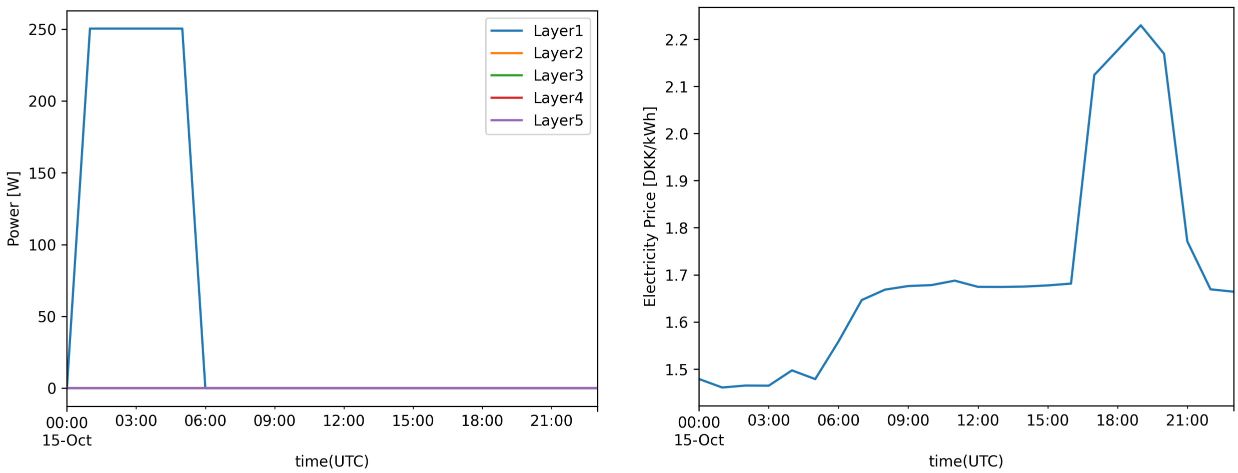
(a) Layer temperature evolution, solar input



(b) Layer temperature evolution with draw-offs

Figure 2: Layer temperature evolution comparison (solar input vs. draw-offs), case **a)**

Moving onto the implementation of the tank water draw-offs, case **a)** presents the effect of the drop in temperature for all layers, with water from layer one leaving the tank and the subsequent temperature readjustment for the remaining layers (depicted above in Figure 2)



(a) Grid power needs, case **c)**

(b) Electricity prices evolution, case **c)**

Figure 3: Grid power needs and electricity prices evolution, case **c)**

The grid implementation, on the other hand, presents some issues. The program correctly reads the cheapest electricity hours to heat the tank, but fails to apply the correct amount of power necessary for the first draw off, as shown by Figure 3. Instead, the program heats constantly at 250 W from 1 to 6 AM, when it should heat once at 1 AM and just before tapping, following Table 1.

Time (UTC)	Layer1	Layer2	Layer3	Layer4	Layer5
2016-10-15 00:00:00	50.000000	40.000000	30.000000	20.000000	10.000000
2016-10-15 01:00:00	54.215000	40.000000	30.000000	20.000000	10.000000
2016-10-15 02:00:00	54.215000	40.000000	30.000000	20.000000	10.000000
2016-10-15 03:00:00	54.215000	40.000000	30.000000	20.000000	10.000000
2016-10-15 04:00:00	54.215000	40.000000	30.000000	20.000000	10.000000
2016-10-15 05:00:00	54.215000	40.000000	30.000000	20.000000	10.000000
2016-10-15 06:00:00	55.001000	40.000000	30.000000	20.000000	10.000000
2016-10-15 07:00:00	49.338000	30.567000	20.567000	10.567000	10.000000

Table 1: Temperature evolution by layer and hour, case **c)**

This issue can translate in insufficient water temperature for draw-offs (below 55 °C), with Figure 4a showing an accurate water exit temperature for the third tapping ($\simeq$ 70 °C) and Figure 4b giving an inadequate output of $\simeq$ 27°C.

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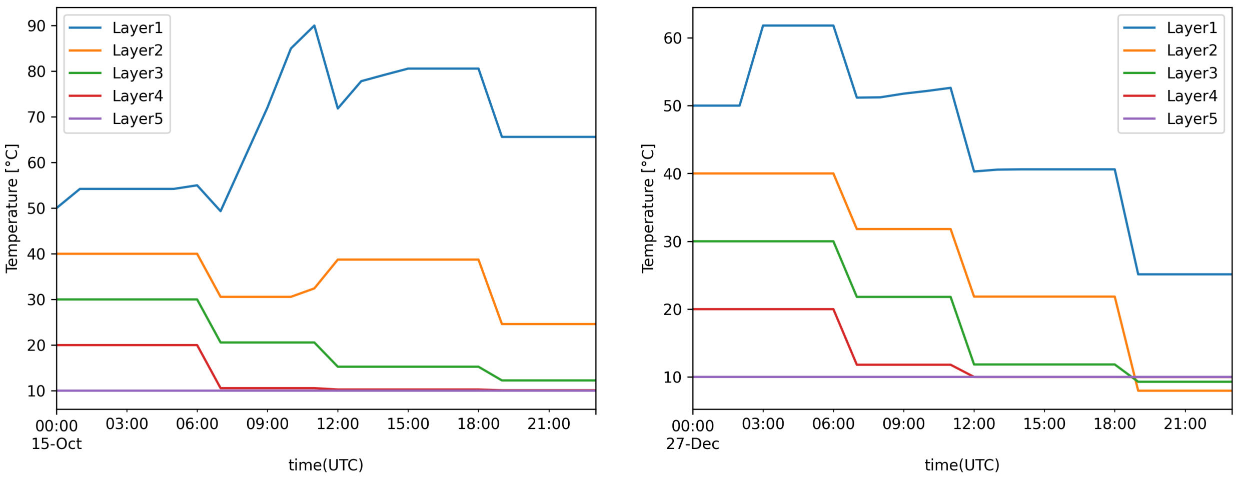

(a) Layer temperature evolution, case **c)**

(b) Layer temperature evolution, case **b)**

Figure 4: Comparison of layer temperature evolution, cases **b)** and case **c)**

Discussing further limitations, the system relied on historical data for solar irradiance (2005-2015) and electricity prices (2016) rather than real-time or forecasted values. The lack of synchronized data sets from the same year introduces potential inconsistencies in the results. Furthermore, leap years were excluded from all data sets, which could affect simulations for those specific days. Fixed initial temperatures were also assumed for each tank layer, as the system can not read real-time sensor data at this stage, likely affecting the accuracy of temperature updates during the simulation and the allocation of heating power.

Furthermore, heat losses to the environment and inter-layer mixing during cold water refills are not modeled. These omissions have the potential to overestimate system efficiency and underestimate the energy required to maintain the desired temperature.

Finally, the choice of the program's start time in relation to predefined tapping schedules can lead to discrepancies in energy allocation and heating cycles. Starting the program close to a tapping event without sufficient historical data may distort the system's initial response, although that is more of a design limitation that a mistake from the program.

With all of this in mind, the system features a number of limitations that might not make it a plug-in implementation from the get-go, but the use of realistic temperatures and electricity prices, the accurate use of sun power and the understanding of electricity and power inputs make it a fairly accurate system that can serve as a simulation tool and a guideline for future projects on the field.

4 Conclusion

This study developed and tested a smart control system for a PV-heated domestic hot water tank, focusing on optimizing energy usage, maximizing solar power usage and minimizing grid electricity utilization. The system effectively utilized solar energy during peak production periods and strategically selected grid electricity when the prices were the lowest. By utilizing low-cost electricity from the grid to anticipate the heat load during low solar availability, the control system and the TES itself demonstrated its potential for energy-efficient operation.

One of the strengths of this study lies in its modular design and flexibility, which create opportunities for future adaptability and scalability. The control algorithm, though simplified for this initial implementation, is structured to accommodate real-time data inputs, sensor integration, and dynamic system behaviour with minimal adjustments. This adaptability makes the system highly suitable for evolving technological advancements, such as improved forecasting tools, smarter sensors, and dynamic energy tariffs. Additionally, the use of Python, with its extensive library ecosystem, ensures that the system can be expanded to include advanced machine learning techniques or integrated into larger smart home energy management systems. This flexibility highlights the potential for the control system to play a key role in advancing energy-efficient domestic water heating in both residential and community-scale applications.

However, several limitations were identified. The system relied on historical rather than real-time data, and the lack of synchronized data sets for solar irradiance and electricity prices potentially affected the results. Additional simplifications, such as neglecting heat losses, thermal mixing effects, and real-time tank temperature measurements, further reduced the accuracy of the simulation. A limitation of the program is its sensitivity to the start time, which affects its adaptability. Specifically, if the start time is adjusted too close to a draw-off event, the program may attempt to store an excessive amount of heat within a limited timeframe. This behaviour conflicts with the thermodynamic constraints of the system, leading to unrealistic calculations and misleading outputs.

In conclusion, the smart control system shows promising potential for optimizing energy usage in PV-heated water tanks. Addressing limitations such as real-time data integration, improved synchronization of solar and electricity price data, and accounting for system losses will enhance its accuracy. With further development, the system could become a key solution for efficient and sustainable water heating.

References

[1] Elsabet Nielsen, Simon Furbo, and Jianhua Fan. *Domestic hot water heating with direct electricity from PV panels and the grid.*

[2] David Saldivia, Anna Bruce, and Baran Yildiz. *Domestic hot water systems as energy storage for excess PV. A thermal model and performance analysis.* 2023.

[3] Simon Furbo et al. “Smart solar tanks for small solar domestic hot water systems”. In: *Solar Energy.* Vol. 78. Feb. 2005, pp. 269–279. DOI: `10.1016/j.solener.2004.08.022`.

[4] Kjersti Berg, Vemund H. Lenes, and Karen B. Lindberg. “Optimal control of domestic hot water tanks in a housing cooperative - benefits for the grid”. In: *IEEE PES Innovative Smart Grid Technologies Conference Europe.* IEEE Computer Society, 2023. ISBN: 9798350396782. DOI: `10.1109/ISGTEUROPE56780.2023.10407406`.

[5] Joan Tarragona, CĂ¨sar FernĂĄndez, and Alvaro de Gracia. “Model predictive control applied to a heating system with PV panels and thermal energy storage”. In: *Energy* 197 (Apr. 2020). ISSN: 03605442. DOI: `10.1016/j.energy.2020.117229`.

[6] Emmanouil Psimopoulos et al. “Smart control strategy for PV and heat pump system utilizing thermal and electrical storage and forecast services”. In: *ISES Solar World Congress 2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings.* International Solar Energy Society, 2017, pp. 2240–2251. ISBN: 9783981465976. DOI: `10.18086/swc.2017.33.07`.

[7] Loris Amabile et al. “Optimizing the self-consumption of residential photovoltaic energy and quantification of the impact of production forecast uncertainties”. In: *Advances in Applied Energy* 2 (May 2021). ISSN: 26667924. DOI: `10.1016/j.adapen.2021.100020`.

[8] Fabrizio Sossan et al. “Scheduling of domestic water heater power demand for maximizing PV self-consumption using model predictive control”. In: *2013 4th IEEE/PES Innovative Smart Grid Technologies Europe, ISGT Europe 2013.* 2013. ISBN: 9781479929849. DOI: `10.1109/ISGTEurope.2013.6695317`.

[9] Zhihao Zhang et al. “A day-ahead operation regulation method for solar water heating based on model predictive control”. In: *Energy and Buildings* 301 (Dec. 2023). ISSN: 03787788. DOI: `10.1016/j.enbuild.2023.113715`.

[10] Xiaoqi Liu et al. “Model predictive control under forecast uncertainty for optimal operation of buildings with integrated solar systems”. In: *Solar Energy* 171 (Sept. 2018), pp. 953–970. ISSN: 0038092X. DOI: `10.1016/j.solener.2018.06.038`.

[11] Richard Lane and Paul Tuohy. *The design and simulation in Python of a model predictive control system to maximise use of local renewables in a heat network with thermal storage.* 2019.

[12] Andrew Lyden, Graeme Flett, and Paul G. Tuohy. “PyLESA: A Python modelling tool for planning-level Local, integrated, and smart Energy Systems Analysis”. In: *SoftwareX* 14 (June 2021). ISSN: 23527110. DOI: `10.1016/j.softx.2021.100699`.

[13] William Robert Wagar. *Simulation and Validation of a Single Tank Heat Pump Assisted Solar Domestic Water Heating System*. 2013.