Analysis of Heat Pump and Hot Water Tank System Using Python Modelling

Computational Methods and Modelling 3

MECE09033 (2024-2025)

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Introduction

This report presents the development, implementation, and analysis of a computational model simulating the performance of an air-to-water heat pump and hot water tank system for residential heating applications. By modelling system responses to external temperature variations and building heat demands, this project aims to contribute to energy-efficient thermal management solutions adaptable to various building types. The simulation incorporates an on/off control mechanism for the heat pump to ensure efficient operation. A key feature of the model is its user-friendly interface, which allows for adjustments to system parameters such as building insulation levels, temperature set points, and tank capacities. This flexibility extends the model's applicability beyond residential buildings, enabling its use for office buildings and other structures with varied heating requirements.

Graphical User Interface (GUI)

The GUI for this project was developed using Python's `tkinter` library to provide an interactive and user-friendly way to engage with the heat pump simulation model. The design focuses on enabling users to adjust parameters, explore different building configurations, analyse seasonal impacts, and visualise results dynamically, all within a single cohesive interface.

The GUI layout is structured into distinct sections, each serving a specific purpose:

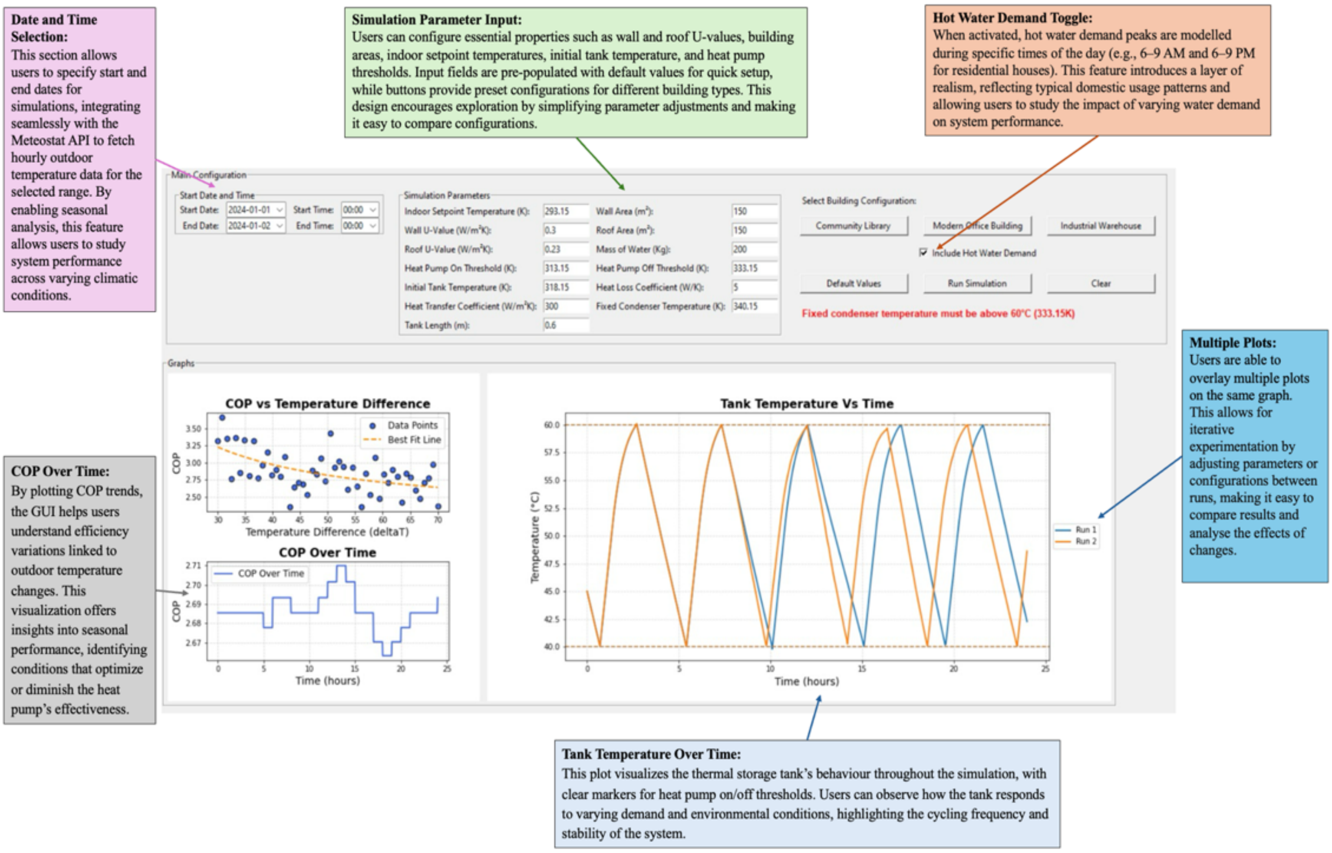

Figure 1: GUI Features

The GUI's user interaction design prioritizes flexibility and iterative testing. A reset button clears all data and plots, allowing users to reconfigure and rerun simulations without restarting the application. This feature enhances usability, enabling quick iterations and exploration of different scenarios.

The GUI includes robust error handling mechanisms to ensure a seamless user experience. Input validation prevents issues such as non-numerical values or parameters outside the acceptable range. For example, if the condenser temperature is set below the operational minimum or the selected time frame deviates from 24 hours, the application displays clear error messages and halts the simulation. These proactive feedback mechanisms guide users toward valid inputs, ensuring accurate and reliable results while minimising disruptions.

Modelling Approach

This computational model integrates various components to simulate the performance of an air-to-water heat pump and hot water tank system. The design emphasizes modularity, enabling individual components to interact seamlessly while remaining adaptable for future refinements.

The heat pump's efficiency, represented by the COP, is modelled as a dynamic function of the temperature difference between the condenser (fixed at 60°C) and the ambient air. Manufacturer provides data correlating to the outdoor temperature and COP. With these data points we can model them to fit the following equation:

$$\text{COP} = A + \frac{B}{\Delta T}, \text{ where } \Delta T = (T_{\text{cond}} - T_{\text{amb}})$$

For this model, T_{cond} is set to 60°C. Together with T_{amb} and COP, the parameters A and B were determined using a curve-fitting module. The resulting values are $A = 2.19 \pm 0.14$ and $B = 30.9 \pm 6.4\,\text{K}$, providing an accurate representation of the heat pump's efficiency across varying conditions.

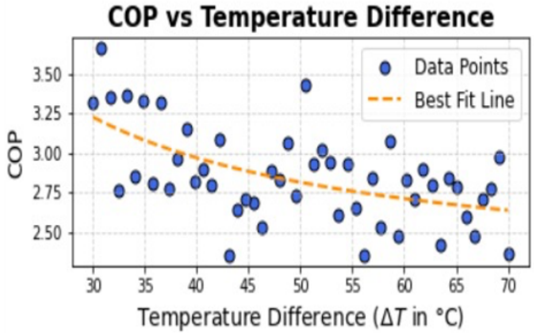

Figure 2: COP vs Temperature Difference (High Variance in B due to large spread of data)

The building heat load calculation was rooted in thermodynamic principles:

$$Q_{\text{load}} = A_w U_w (T_{\text{amb}} - T_{\text{setpoint}}) + A_r U_r (T_{\text{amb}} - T_{\text{setpoint}})$$

where A_w and U_w represent wall area and U-value, and A_r and U_r represent roof area and U-value. By incorporating real-time weather data, this calculation ensures that heat demand dynamically influences system performance. The interplay between insulation quality, surface area, and temperature difference underscores the critical role of building characteristics in energy demand. This direct interaction with the tank and heat pump outputs reflects how external conditions drive system dynamics.

The equation for heat transfer is given by:

$$Q_{\text{transfer}} = U_{\text{condenser}} \times A_{\text{condenser}} (T_{\text{condenser}} - T_{\text{tank}})$$

This equation assumes unlimited heat addition, which is unrealistic. To address this issue, the heat pump's input power (W_{in}) is set to 2 kW [1] limiting the maximum Q_{transfer} entering the heat pump. The value is calculated as follows:

$$Q_{\text{transfer, max}} = W_{\text{in}} \times \text{COP}$$

This ensures the system operates within practical limits while reflecting real-world constraints.

The hot water tank dynamics were modelled using an ODE that balances heat inputs and outputs:

$$\frac{dT_{\text{tank}}}{dt} = \frac{Q_{\text{transfer}} + Q_{\text{load}} - Q_{\text{loss}}}{M_{\text{water}} \times C_{\text{water}}}$$

where Q_{transfer} is the heat supplied by the pump, Q_{load} is the building's heat demand, and Q_{loss} which accounts for thermal dissipation:

$$Q_{\text{loss}} = U_{\text{tank}} \times A_{\text{tank}} \times (T_{\text{tank}} - T_{\text{amb}})$$

Including Q_{loss} ensures inevitable heat losses are modelled realistically, adding fidelity to the simulation.

The ODE transitions smoothly between steady-state and transient conditions, effectively capturing the system's practical behaviour during changes in heating demand and pump cycling.

To solve the ODE, the `scipy.integrate.solve_ivp` function with the Runge-Kutta (RK45) method was employed. This method's adaptive step-sizing balances computational efficiency with the accuracy required during rapid transitions, such as heat pump activation or deactivation. By dynamically adjusting step sizes, the solver ensures responsiveness to system changes while minimising computational overhead during steady-state conditions.

The on/off control mechanism for the heat pump was designed to optimise energy efficiency while reducing wear and tear. The pump activates when the tank temperature drops below 40°C and deactivates when it exceeds 60°C, maintaining a practical operating range. This control logic balances maintaining thermal comfort with minimising frequent cycling, which could lead to inefficiencies or mechanical stress.

The interaction between this control mechanism and tank dynamics demonstrates the system's interdependencies, ensuring that operational decisions reflect real-world constraints.

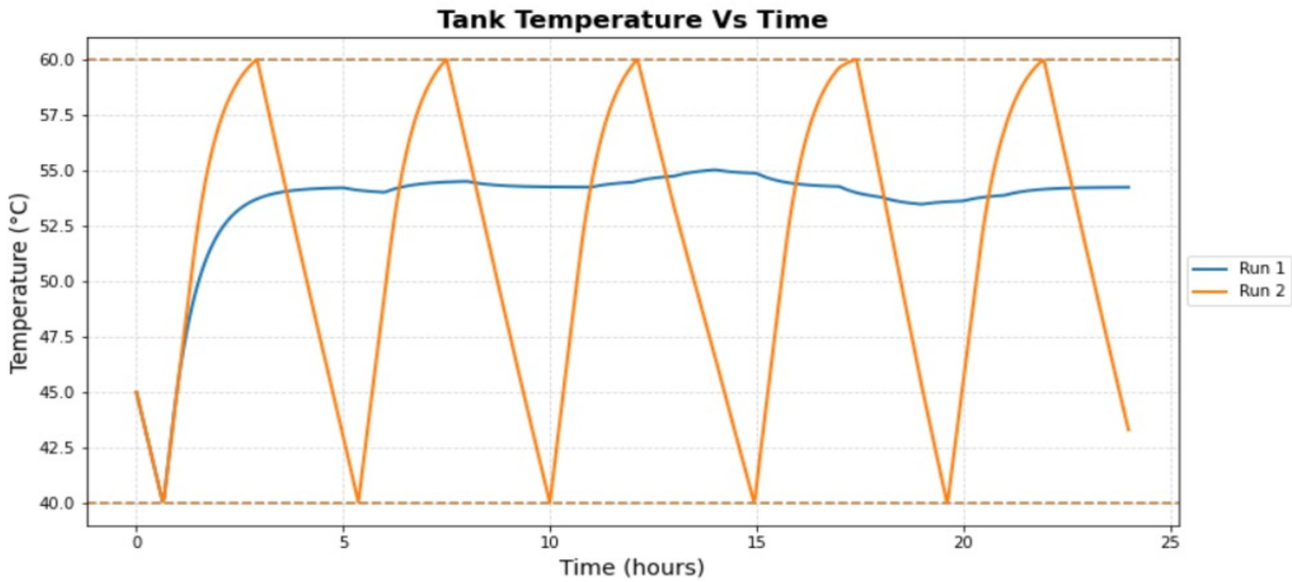

Figure 3: Tank Temperature vs Time (Fixed Condenser)

In run 1, the system operates with a fixed condenser temperature of 60°C. However, it reaches a steady state where, preventing the tank temperature reaching the desired 60°C threshold. This limitation highlights the system's inability to meet heating demands under these conditions. To address this, the condenser temperature was increased to 70°C in Run 2, enabling the heat pump to supply sufficient energy to overcome the heat load and allowing the tank temperature to reach the 60°C target.

Visualisation of system behaviour through COP trends, tank temperature profiles, and heat pump status over time provides critical insights into the model's performance. These outputs, combined with metrics such as average COP, total energy consumption, and heat loss, allow for meaningful evaluation of system efficiency and potential areas for optimisation.

Engineering and Results Analysis

To optimize the heat pump system, three key parameters were analysed to determine the most suitable water storage tank size: energy consumption, tank heat loss and pump cycling frequency. The preferred tank configuration minimises energy usage and heat loss while maintaining a pump cycling rate of approximately 4–5 cycles per day. Staying within this range reduces wear on the pump, thereby extending its lifespan and lowering maintenance costs for occupants. Exceeding this limit would accelerate mechanical wear, increasing operational expenses over time.

The simulation was tested on three building types:

Table 1: Building Configurations

Building Type	**Insulation**	**Wall Area**[m^2]	**Roof Area**	**Indoor Set Temp**	**Operating Hours**
		[m^2]	[m^2]	[°C]	(Hot water demand)
Library	Moderate	150	150	20	8AM - 6PM
Warehouse	Poor	250	180	20	24 Hrs
Office	Good	250	170	20	6AM - 9PM

Building-specific parameters, such as wall and roof U-values and floor areas, were based on UK standards to simulate realistic heat transfer dynamics.

The most significant factor influencing standing heat loss in the tank is its surface area, which is determined by two variables: length and radius. Assuming the tank is a perfect cylinder, optimising its length plays a crucial role in minimising surface area while preserving the required volume. By carefully adjusting the tank's dimensions, standing heat losses can be significantly reduced without compromising its capacity. This optimisation ensures the tank has sufficient volume to effectively manage the desired number of pump cycles per day, achieving a balance between thermal efficiency and operational stability. The cylindrical design's focus on minimising surface area also aligns with the overall objective of reducing energy consumption and heat loss, ultimately lowering operational costs.

Library Tank Dimension Justification

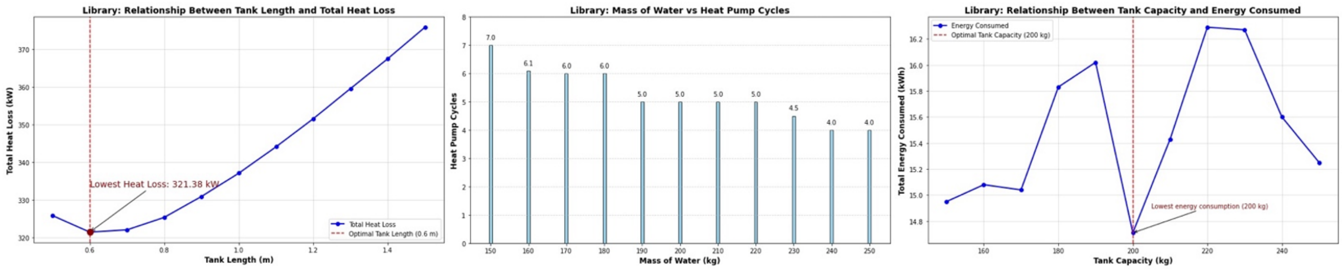

Figure 4: Library Optimisation

The library's moderate insulation and predictable operational hours mean its heat load is relatively low and stable. A 200 kg tank provides sufficient thermal storage to limit pump cycles to the desired range. The cycles vs. mass of water graph confirms that this configuration achieves a balance between limiting pump cycling and preventing excessive standing losses. Larger tanks would unnecessarily increase standing losses, reducing overall efficiency.

Warehouse Tank Dimension Justification

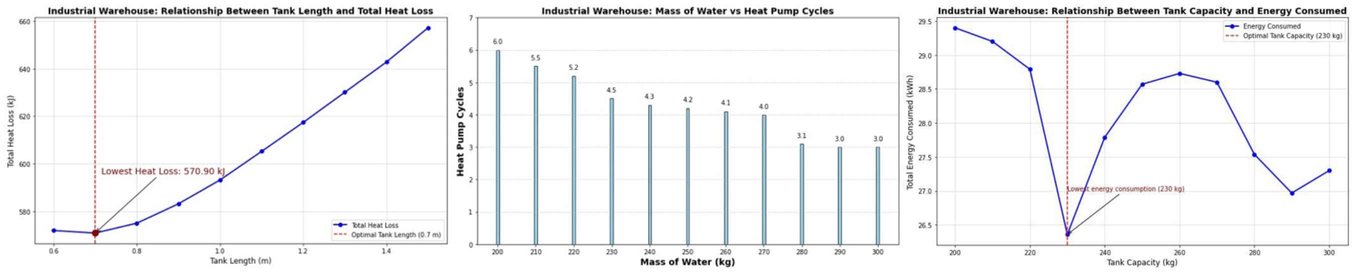

Figure 5: Warehouse Optimisation

The warehouse's poor insulation and large surface area result in substantial heat loss, necessitating a larger tank to effectively buffer the thermal load. A 240 kg tank was selected as it minimizes temperature fluctuations, stabilizes the heat pump's operation, and maintains the optimal cycling. A smaller tank would lead to more frequent cycling, causing increased wear on the pump and reducing its operational lifespan. On the other hand, an excessively large tank would raise standing losses due to its greater surface area, diminishing overall energy efficiency. The 240 kg tank strikes an optimal balance between reducing cycling and minimising heat loss, as supported by the graphs, which demonstrates its ability to achieve both goals efficiently.

Office Tank Dimension Justification

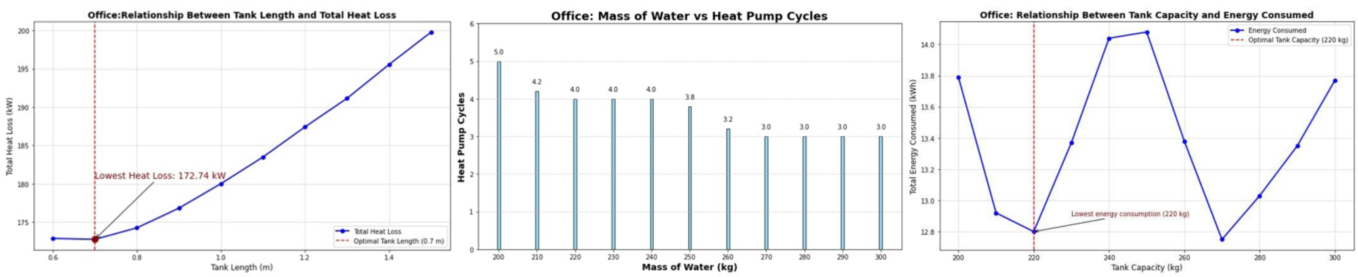

Figure 6: Office Optimisation

The office building's superior insulation and predictable thermal demands contribute to relatively low heat loss. Although a 270kg tank achieves slightly lower total energy consumption, its increased surface area results in higher standing losses, effectively negating the marginal energy savings. A 220kg tank provides an optimal balance between thermal storage and operational efficiency. The cycles vs mass of water graph reinforces this choice, demonstrating that a 220kg tank maintains pump cycles within the target range, ensuring stable operation while avoiding unnecessary energy losses. This configuration also aligns well with the building's operational schedule, offering sufficient thermal storage during peak demand periods and minimising standing losses during off-hours.

Table 2: Optimised Tank Dimensions

Building Type	Length [m]	Radius [m]	Mass of Water [kg]	Volume [m^3]	Surface Area [m^2]	# of Cycles [-]
Library	0.6	0.33	200	0.20	1.93	5
Warehouse	0.7	0.24	230	0.23	2.16	4.5
Office	0.7	0.22	220	0.22	2.07	4

Method Improvement Suggestions

To enhance the model's realism and explore the impact of variable usage patterns, a hot water demand increase was introduced during two peak periods: 6 AM to 8 AM and 5 PM to 7 PM [2]. These times simulate typical daily hot water use, like morning and evening showers or cooking. The hot water demand is modelled using a function called `human_usage_pattern`, which defines the probability bias for hot water usage. This bias reflects higher usage during the morning (6 AM to 9 AM) and evening (6 PM to 9 PM). The demand is scaled by a factor of 1.4 for mornings, 1.75 for evenings, and reduced to 0.5 between 9am to 6pm. A separate function, `generate_hot_water_demand`, generates a random base demand using a Gaussian distribution and applies the human usage bias to create a time-dependent profile.

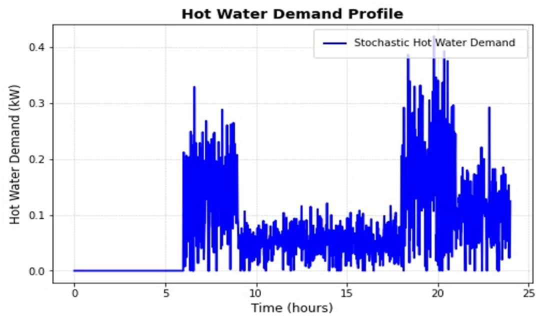

Figure 7: Hot water demand profile

The `Q_load_combined` function integrates the stochastic hot water demand with the building's heat load, ensuring that total load calculations reflect variable usage patterns. Based on user input, the `Q_load` function is adjusted to conditionally include the hot water demand. The time biases set in the code align with daily usage patterns, indicated by UK government data that hot water accounts for approximately 19% of a building's energy consumption [2].

Total Energy [kWh]	Hot Water Demand [kWh]	% of Energy [%]
16.28	3.31	20.33

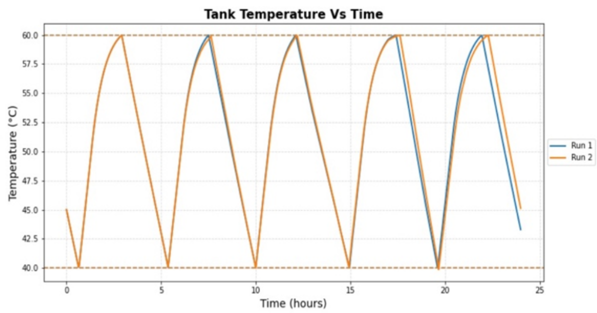

Figure 8: Tank Temperature vs Time Including Hot Water Demand (Run 2) and Excluding Hot Water Demand (Run 1)

When simulating the heat load using standard building values, the energy consumed for hot water accounted for 20.33% of the total energy, closely aligning with the theoretical value of 19%. This 2% deviation highlights the model's accuracy and reliability.

Conclusion

This project has shown the development of a python model simulating a heat pump and hot water tank system and the analysis of its effectiveness. Various factors were tested, and it was shown that insulation quality, building size and tank size all have a significant impact on the effectiveness of the system. The model can be used to find the most efficient parameters for any type of building, as shown in the engineering analysis section for three types of buildings. This analysis also shows the significance of effective building insulation in the efficiency of a heat pump system. The model could be improved by doing analysis on additional building types and by further analysing the effects of factors such as building occupancy. The system could also be developed by adapting the model to include a cooling system to make the model applicable year round.

References

[1] "Home Appliances Ratings." Electrical Safety First, http://www.electricalsafetyfirst.org.uk/guidance/safety-around-the-home/home-appliances-ratings/. Accessed 21 Nov. 2024.

[2] "Domestic Hot-Water Use in the UK." Department for Energy Security & Net Zero, 15 Mar. 2024.