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MARGINAL BENEFITS OF THERMAL ENERGY STORAGE IN RESIDENTIAL PV - HEAT PUMP SYSTERMS: A PARAMETRIC STUDY

Summary

This work investigates the relationship between thermal energy storage capacity and heating self-sufficiency in residential PV–heat pump systems. While previous studies have shown a strongly nonlinear increase in self-sufficiency with storage size, the structural origin and economic implications of this behavior remain insufficiently understood. A parametric study is conducted using both a simplified energy-balance model and a detailed dynamic Modelica model to identify the storage capacity range in which marginal technical and economic benefits decline sharply. The results are expected to clarify the marginal benefits of increasing storage capacity while addressing the influence of PV sizing and modelling fidelity.

Keywords: Photovoltaic integration, Heating self-sufficiency, Dynamic simulation

Field of application for the findings: Sizing of thermal energy storage in residential PV–heat pump systems

1. Introduction

The decarbonization of the building sector requires heating systems that minimize dependence on external fossil energy by offering flexibility to utilize inherently intermittent renewable energy sources. Thermal energy storage (TES) is regarded as a key enabler for sector coupling between electricity and heat, however, quantifying its effects in a consistent and transferable manner remains a methodological challenge.

A recent study by Lüchinger et al. (2024) introduced an elementary, technology-agnostic method to characterize residential buildings equipped with heat pump (HP), photovoltaics (PV) and TES by their thermal self-sufficiency (TSS). Using an hourly energy-balance model with predefined priority rules and idealized storage behavior, the authors derived upper and lower bounds of TSS as a function of storage capacity. The results revealed a strongly nonlinear relationship: small storage capacities yield substantial increases in TSS, whereas achieving higher levels (e.g., from 60% to 80%) requires a disproportionate increase in storage size. The study identified the need to better understand the characteristic shape of the TSS curve and the associated cost–benefit implications.

In parallel, a more detailed investigation by Delgado-Díaz et al. (2025) developed and experimentally validated a dynamic system model of a residential PV–HP–TES configuration, including hydraulic constraints, temperature-dependent heat pump performance, stratified storage behavior and explicit control logic. This work employed multi-objective optimization to maximize thermal self-sufficiency while minimizing levelized cost of heat (LCOH) and global warming potential. The results demonstrated realistic upper bounds of thermal self-sufficiency in the range of approximately 80–85% for the investigated configurations and highlighted the importance of control strategies and storage design for system performance.

Despite these advances, gaps remain in the understanding of the relationship between storage capacity and heating self-sufficiency. Previous results indicate a strongly nonlinear increase in self-sufficiency with storage size, suggesting the existence of a characteristic transition beyond which additional storage capacity yields only limited incremental benefit. The physical and systemic mechanisms underlying this behavior—such as the shift from short-term cycling to predominantly seasonal storage operation have not yet been systematically analyzed. Furthermore, the dependence of this transition on key design parameters, in particular PV capacity and system configuration, has not been quantified in a consistent framework.

The present work addresses these questions through a parametric study of residential PV–HP–TES systems, with a focus on understanding the marginal technical and economic benefit of increasing storage capacity. Using both a simplified energy-balance model and detailed dynamic simulations, the study aims to:

(i) confirm the existence of a well-defined storage capacity range in which marginal gains in self-sufficiency decline sharply

(ii) quantify the associated marginal changes in the levelized cost of heat

(iii) assess the dependence of this critical capacity range on system parameters such as PV sizing

(iv) evaluate whether simple energy balance-based models are sufficient to capture this structural behavior or whether dynamic effects and control constraints fundamentally alter results

2. Methodology

The study is based on a comparative parametric analysis using two modelling approaches with different levels of abstraction: A simplified energy-balance model enables high-resolution exploration of the parameter space, while a detailed dynamic model of a residential heating system captures the influence of heat transfer limitations, control logic and hydraulic constraints.

The two models are used to simulate the same Swiss single-family house equipped with roof-mounted PV, air-water heat pump, hydronic floor heating and a water-based (sensible) TES. The annual energy demand for space heating (SH) amounts to 12’000 kWh, while the demand for domestic hot water (DHW) is equivalent to 3’560 kWh. The heat pump is controlled to utilize excess PV generation (i.e., after subtracting all other residential loads) by charging the TES until a maximum temperature of 55°C is reached. Selected scenarios additionally consider direct electric heating for further charging.

The simplified model is similar to that presented by Lüchinger et al., except storage capacities for space heating and domestic hot water (DHW) are separated and an upper limit is set on the heat pump’s electrical power. This model works by enforcing the energy balance between the heat pump, SH- and DHW demands, and the two respective storage units. The TES is characterized merely by its capacity and a single state-of-charge variable.

The detailed model implemented in Modelica is partially based on component models in the Buildings library. The system model comprises the following main components:

- PV modules, efficiency adjusted based on estimated module temperature
- building simplified as a single thermal zone, 5R2C model accounting for heat losses and solar gains
- floor heating with 7 identical parallel circuits, 1D discretization along the flow path
- heat pump, mathematical model with fitted polynomials on evaporation and condensation temperatures
- SH buffer storage tank operated in 2 zones, 1D discretization along the vertical axis
- DHW storage tank with internal heat exchanger, both storage- and heat exchanger volumes discretized

As opposed to the simplified model, fluid flow and heat transfer is explicitly modelled within and between these components. This model captures several physical and operational effects not represented by the energy balance approach, including thermal inertia, charging- and discharging constraints due to imperfect stratification, and control-induced dynamics.

A systematic parameter variation is to be performed, primarily varying the storage volume (capacity) from hourly to seasonal scale, and the installed PV power. Further parameters may be included if they are deemed particularly influential based on early results. Simulations covering at least one year will be conducted using both models (the simplified model will be able to provide more data points) and key indicators will be derived and evaluated according to the study’s aims. These indicators include the heat pump’s seasonal performance factor, heating- as well as overall energy self-sufficiency and the levelized cost of heat.

3. Results and discussion

Using the energy-balance model, a qualitatively identical relationship of storage capacity and heating self-sufficiency as presented by Lüchinger et al. has already been established. This was to be expected, since the models are built very similarly. The detailed model is currently being tested, results are not available at this time. Once simulations are completed, the derived indicators will be used to address points (i)-(iv) stated in the introduction.

4. References

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