EVALUATION OF A PV+THERMOELECTRIC HEAT STORAGE SYSTEM FOR SUPPLYING DOMESTIC HOT WATER

Summary

Domestic hot water (DHW) accounts for approximately 25% of residential energy consumption in Chile (Comisión Nacional de Energía, 2018). Most DHW systems rely on the conversion of electrical or chemical energy into heat, which entails energy losses, safety considerations (e.g., for gas burners), or dependence on centralized infrastructure. This work presents the simulation and evaluation of a PV+Thermoelectric heat storage system based on a Peltier device powered by a PV panel. The system is designed to operate flexibly under different climate conditions.

Simulations show that full thermal charging ($> 99\%$ SOC) is achieved within 6 to 10 hours under favorable conditions (> 600 W/m², > 18 °C). Under these conditions, the system consistently reaches over 60 °C at the top node, enabling effective hot water delivery.

The thermal behavior of the tank is modeled using a one-dimensional nodal approach based on the advection-diffusion equation and calibrated with experimental data. The system is expected to improve energy efficiency and enable decentralized DHW production in urban areas throughout Chile, especially for low-income families.

Keywords: Thermal energy storage, Thermoelectric, Advection-diffusion equation, PV, Domestic hot water (DHW)

Prefix: Blind Review

1. Introduction

Domestic hot water (DHW) represents around 25 % of household energy use in Chile (CNE, 2018). Conventional DHW systems are powered by gas or electricity, which lead to significant energy losses, safety risks and reliance on a centralized infrastructure. These challenges underscore the need for alternative DHW technologies that offer greater safety, ease of installation, and adaptability to local energy conditions.

Chile has some of the highest levels of solar radiation worldwide, with daily averages over 6 kWh/m^2 in the northern regions (Ministerio de Energía de Chile, 2019), which has supported the growing adoption of solar thermal systems in residential applications. However, these technologies depend strongly on sunlight availability and need structural changes that are not always possible in urban buildings.

At the same time, ambient temperatures in cities are rising due to global warming and urban growth, this increases the urban heat island effect. In Santiago, studies report temperature differences of up to 9 °C between urban and rural zones (Centro de Cambio Global UC, 2020). This surplus heat, especially in densely built areas, remains largely untapped for domestic energy use. Its availability presents an opportunity for low-infrastructure, localized water heating solutions that are better adapted to urban conditions.

This study focuses on the simulation and techno-economic evaluation of PV+Thermoelectric heat storage system based on a 40 L tank (NEX-P40). The system collects solar and local heat to reach water temperatures between 20 °C and 50 °C, with a nominal coefficient of performance (COP) of 2.0. It operates with a small 270Wp PV panel, avoiding the need for large solar collectors or complex installations. The system is fully electric, does not use combustion, and works without connection to the gas grid. This allows for safer operation, lower greenhouse gas emissions, and greater energy independence at the household level. The evaluation focuses on charging efficiency and the potential reduction in annual CO_2 emissions compared to conventional systems.

2. Methodology

The thermal behavior of the system is simulated using a one-dimensional nodal model applied along the tank height, supported by scale analysis (Bejan, 2013). During the charging phase, heat transfer is described by an advection-diffusion balance that accounts for conduction, natural convection, and thermal losses. Internal fluid movement is driven by natural convection, modeled using the Advanced Flow Distribution (AFD) method (Riebel, 2024).

For the discharging stage, a quasi-one-dimensional model adapted from Nizami et al. (2013) is implemented to represent thermal stratification and turbulent mixing. The Richardson number (Ri) is used to assess mixing intensity, and the effects of turbulent eddies are considered in the estimation of energy transfer between layers.

The model includes experimentally derived correction factors to adjust internal flow estimation under realistic operating conditions. Calibration is carried out using experimental data by minimizing the dynamic time warping (DTW) distance between measured and simulated temperature profiles. A genetic algorithm is applied to optimize key model parameters.

System performance is evaluated in thermal, environmental, and economic dimensions. Thermal indicators include storage efficiency and state of charge (SOC). The environmental assessment estimates annual CO_2 savings compared to fossil-based or high-power electric systems. The economic evaluation focuses on the annual thermal energy delivered by the system and its solar fraction, as a measure of reliance on renewable energy over conventional DHW technologies.

3. Experimental setup, Results and Conclusions

The proposed system is designed to enable decentralized DHW generation by capturing local heat through a photovoltaic-powered Peltier heat pump. A full prototype was implemented and tested using a 40 L NEX-P40 tank and a 270 Wp PV panel.

The test bench includes thermocouples, a flowmeter, a photovoltaic analog wattmeter, and ambient temperature and humidity sensors. All instruments are connected to a CR1000 datalogger for data acquisition. A solenoid valve, operated by an external controller, regulates the charging and discharging routines (Fig. 1).

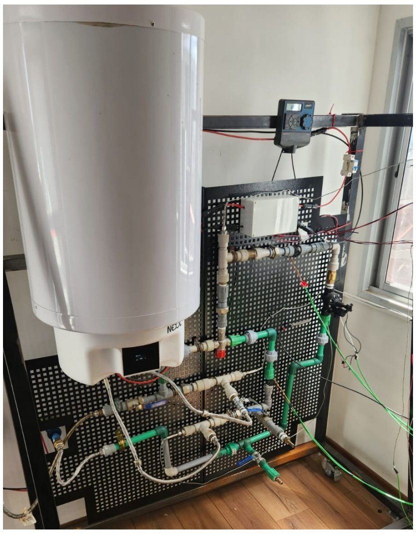

Fig. 1a: Experimental test bench for evaluating the NEX-P40 system.

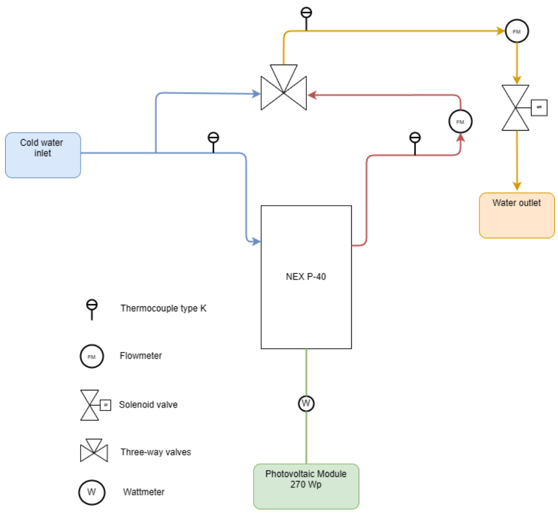

Fig. 1b: Schematic diagram of the experimental setup and instrumentation of the NEX-P40 system.

Fig. 1: Experimental configuration of the PV-powered thermoelectric storage system

To evaluate the system's performance under different weather conditions, a parametric simulation was conducted using 100 combinations of ambient temperature (10–30 °C) and peak solar irradiance (400–900 W/m²), assuming a bell-shaped daily profile for both inputs. All simulations achieved a final state of charge greater than

99%, confirming the thermal feasibility of the proposed system. Fig. 2a shows the time required to complete charging, while Fig. 2b shows the average tank temperature at end of charging process for each scenario.

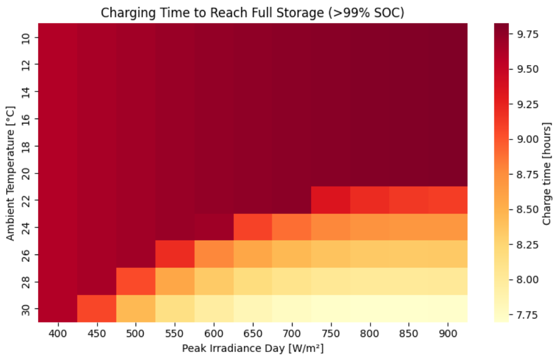

Fig. 2a: Charging time to reach full storage (>99% SOC)

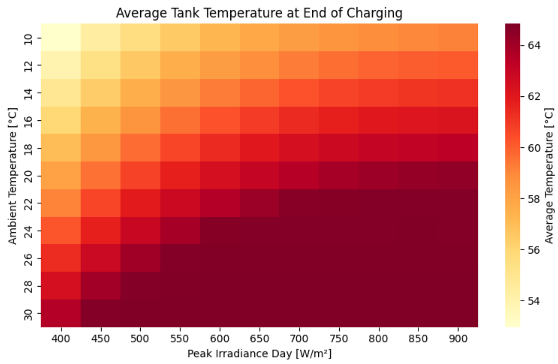

Fig. 2b: Average tank temperature at end of charging

Fig. 2: Simulated thermal charging performance as a function of ambient temperature and peak irradiance.

These results confirm that the system can be fully charged within typical daylight hours using only a 270 Wp PV panel. This validates its potential as a decentralized DHW solution for urban areas with limited infrastructure, requiring no gas connection, combustion systems, or complex hydraulic installations.

4. References

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