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Performance analysis and optimization of a solar assisted heat pump concept

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Abstract. Solar-assisted heat pumps have become a popular choice for efficient and environmentally-friendly heating and hot water production. This article introduces a unique concept of integrating a solar thermal facade into buildings to provide the cold source for a heat pump, which is a novel approach compared to other available solutions. While accurate sizing is crucial for efficient system operation, evaluating the potential benefits of better control strategies is also important because these strategies can bring significant benefits to the system. However, at present, there is a shortage of tools that can facilitate accurate sizing and effective evaluation of various control strategies for such systems. This article explores the benefits and challenges associated with this innovative technology, highlighting the need for developing models with a good representation of the system behavior and accurate performance estimation. A parametric study will be conducting on the principal components sizing for various climates in France. The aim is to gain a comprehensive understanding of the installation's potential performance, with the optimization of sizing and control strategies to be performed at a later stage.

1. Introduction

Given the challenges posed by climate change and the urgent need to reduce carbon emissions through the use of renewable energy sources and electrification, buildings must play a crucial role in this transition. It's worth highlighting that heating accounts for a significant portion of total energy consumption [1], emphasizing the need to focus on this aspect in the transition.

Solar thermal systems are effective in meeting a portion of thermal needs, but they often suffer from energy supply and demand mismatches on both a daily and seasonal basis, requiring backup heat systems. In contrast, heat pumps can provide a reliable heat supply at any time since they are connected to the electrical grid. While they are identified as energy-efficient and eco-friendly devices, they tend to perform poorly in low external temperatures. Geothermal solutions can improve their performance, but they are often expensive and not suitable for every location [2]. Therefore, combining both solutions,

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solar thermal system and heat pump, what is known as a solar-assisted heat pump (SAHP) has been demonstrated to be a promising solution for overcoming the individual challenges of both technologies.

Despite the increasing popularity of SAHPs significant technical and economic challenges still restrict their widespread adoption. One significant barrier to their development is the cost and integration of the solar thermal collector into the building [3].

This challenge has prompted the development of an innovative concept: a low-cost unglazed panels structure integrated into the building façade, that collects solar energy in a tank to serve as a cold source for the heat pump while this resource is available.

However, the performance of such complex systems is challenging to estimate and highly influenced by meteorological conditions. Proper sizing is crucial to optimize the efficiency of the system. Furthermore, traditional reactive control approaches are not ideal for efficiently managing variable energy sources and thermal storage control. In contrast, advanced control strategies, such as Model Predictive Control (MPC), have demonstrated a great potential [4]. This control approach offers the ability to predict future energy demands, allowing for proactive optimization of the system.

The lack of dedicated tools for optimizing sizing and testing different control strategies, is a significant hurdle for the efficient development of SAHP systems [5].

Therefore, this paper proposes a methodology to develop dedicated tools that can help to enhance the performance of such system. The proposed methodology will first focus on modeling the installation and calibrating its main component: the solar thermal facade. Then, a parametric study will be conducted to better understand the potential performance of the system. This study will explore different facade surface areas and storage capacities under various climate conditions in France, using a specific case study building.

2. Methodology

2.1. System description and case study overview

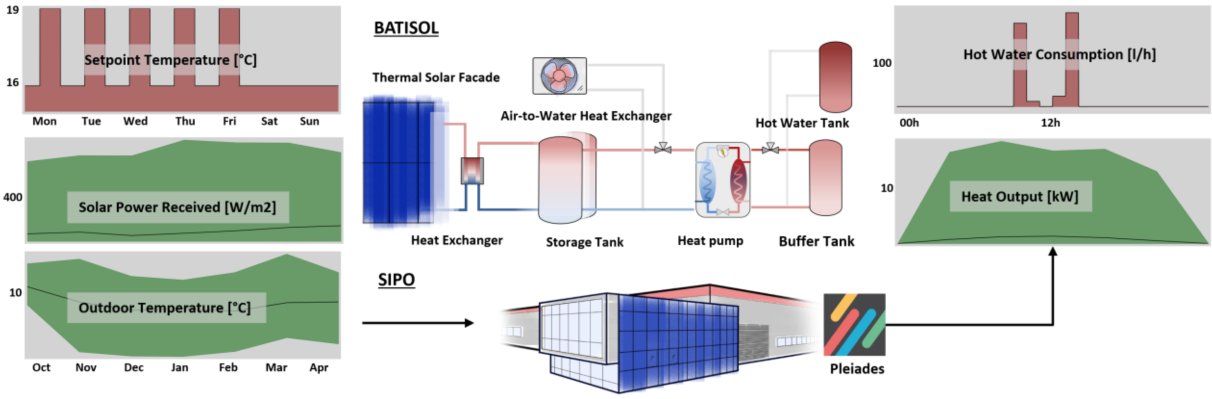

Figure 1. Case study overview.

The installation described in this study, named BATISOL (Figure 1), is a self-supporting metal structure clad composed of vertical metal panels that serve a dual function as both the building facade element and thermal collector. The solar heat energy is collected through a water and glycol mixture loop on the backside of the panels. The energy is then stored in a tank to overcome the intermittency of the solar resource. The stored energy is used as the cold source for a water-to-water heat pump, providing a reliable source of heat for both space heating and domestic hot water needs in the buildings. When there is no more available solar energy in the tanks to keep the heat pump functioning, an air-to-water heat exchanger using ambient air takes over.

This case study aims to estimate the potential of the installation on a partially occupied 425 m^2 office building, named SIPO. To focus on the system itself, the thermal needs of the building, meteorological conditions, and hot water consumption are regarded as boundary conditions. Hourly thermal loads for the building are estimated thanks to a dynamic thermal simulation software for different meteorological conditions, with temperature settings of 19°C and 16°C for occupied and unoccupied periods, respectively.

2.2. Modeling

The Modelica language was chosen to simulate a physical model of the installation. Modelica has gained increasing interest in recent years, and numerous libraries and tools are now publicly available, demonstrating the dynamism of the developer community. This open equation-based language offers flexibility and facilitates the reuse of submodels from dedicated libraries [6].

Due to the importance and complexity of the solar facade thermal system in the SAHP installation, a specific detailed mathematical model was developed for this component. This model takes into account the specific physical behaviors and characteristics of the solar facade, allowing for a more accurate representation of its contribution to the overall system performance. Relevant models for subsystems such as heat pumps, tanks, and pumps were utilized directly from models available in the Buildings library [7] or extended from them.

Simulation and implementation of parameters in Modelica is automated using a Python environment, which makes it easier to implement numerous numerical methods required for studying, optimizing, and validating the model. Python is also useful for data processing from the simulations, visualization, and analysis. Additionally, it can be used to implement and integrate more complete control strategies into the simulation.

2.3. Calibration and validation procedure

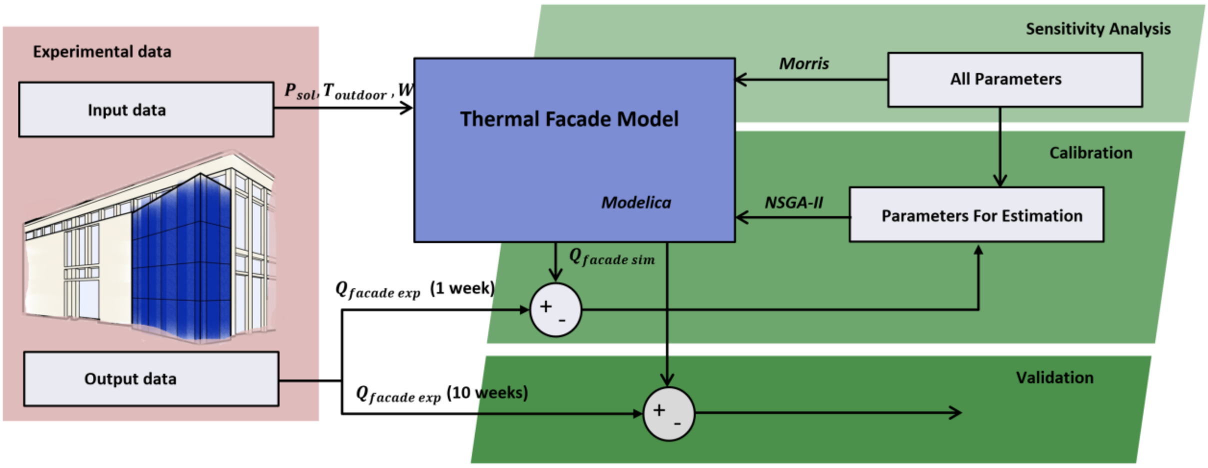

Figure 2. Calibration and validation procedure diagram

Accurately estimating the performance of the system relies heavily on the precision of the solar thermal façade model, which provides the outlet water temperature estimation over meteorological conditions. Although model parameters were initially estimated based on physical knowledge, a calibration procedure is used to improve accuracy.

The overall calibration procedure is described in the Figure 2 : a full-scale system was developed, instrumented, and operated under real conditions for an entire winter season. After collecting and processing data, a total of 10 independent complete weeks were obtained.

Firstly, the most significant week, in terms of diverse conditions and energy production, is identified and selected as the training period for calibration, while the remaining weeks were utilized for validation.

Secondly, due to the large number of parameters in the model and the long calculation times, a sensitivity analysis method was employed to identify the most influential parameters and facilitate the optimization procedure. The Morris method was chosen because of its lower computational cost [8]. It measures the influence of parameter variations using μ*, indicating the central tendency of the output with respect to the input factors, and σ, which quantifies the spread of the output values and indicates how much the output is influenced by the input factors.

Thirdly, the NSGA-II algorithm is utilized for the optimization procedure, as it enables the handling of the complexity and non-linearity of the model and helps avoid the risk of local minima. The values of the parameters are estimated by minimizing the mean squared error between the n predicted energy values ($Q_{i,\ sim}$) from the model and the corresponding experimentally observed energy values ($Q_{i,\ exp}$):

$$MSE = \frac{1}{n}\sum_{i=0}^{n} \left(Q_{i,\ sim} - Q_{i,\ exp}\right)^2 \tag{1}$$

Finally, the validation error, which represents the mean percentage error between the total energy produced by the simulation and the experimental results for each of the data weeks, weighted by the corresponding experimentally produced energy values, is calculated:

$$Error_{Validation} = \frac{\sum_{i=0}^{n} |E_{i,\ exp} - E_{i,\ sim}|}{\sum_{i=0}^{n} |E_{i,\ exp}|} \tag{2}$$

2.4. Parametric study

Using the developed and calibrated Modelica, simulations are conducted to estimate the system performance for the specific building previously described. This study considers the city of La Rochelle, Nancy, and Nice to cover the main climates conditions in France.

Once the simulation results are obtained, two main indicators are used to evaluate the performances. The Seasonal Coefficient of Performance (*SCOP*), indicates the energy efficiency of the system over the winter period taking into account auxiliary system consumption (pumps). The *energy savings* indicator is calculated by estimating the difference between the electrical energy consumption of the concept system and a classical air-to-water heat pump system. The reference consumption is estimated by simulation.

A third indicator, the *payback period* is also estimated by calculating the time required for the energy savings to offset the surplus cost of installation, considering an average electricity cost of 0.21 euros per kWh.

3. Results and investigations

3.1. Calibration and validation of the solar thermal façade

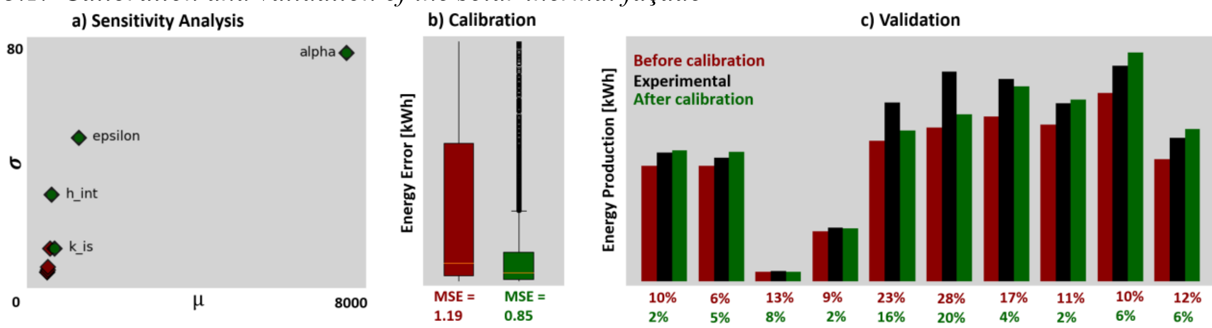

Figure 3. Calibration results summary.

The results of the Morris analysis performed on the physical parameters of the solar thermal facade are shown in Figure 3. Out of the eleven parameters, only four were chosen for the calibration process, and optimization through the selected week allowed the reduction of the Mean Squared Error (MSE) from 1.19 to 0.85. The validation results also improved with better estimation through the newly optimized parameter values, and the error indicator decreased from 15% to 8%. Therefore, the calibration process has successfully increased the precision of the model.

Based on the precision of the experimental data collected, the calibrated model is deemed acceptable for a first performance estimation. However, some errors still exist, and future investigations will explore whether it is possible to obtain better accuracy by varying the optimization method or selecting a different training period.

3.2. Parametric study

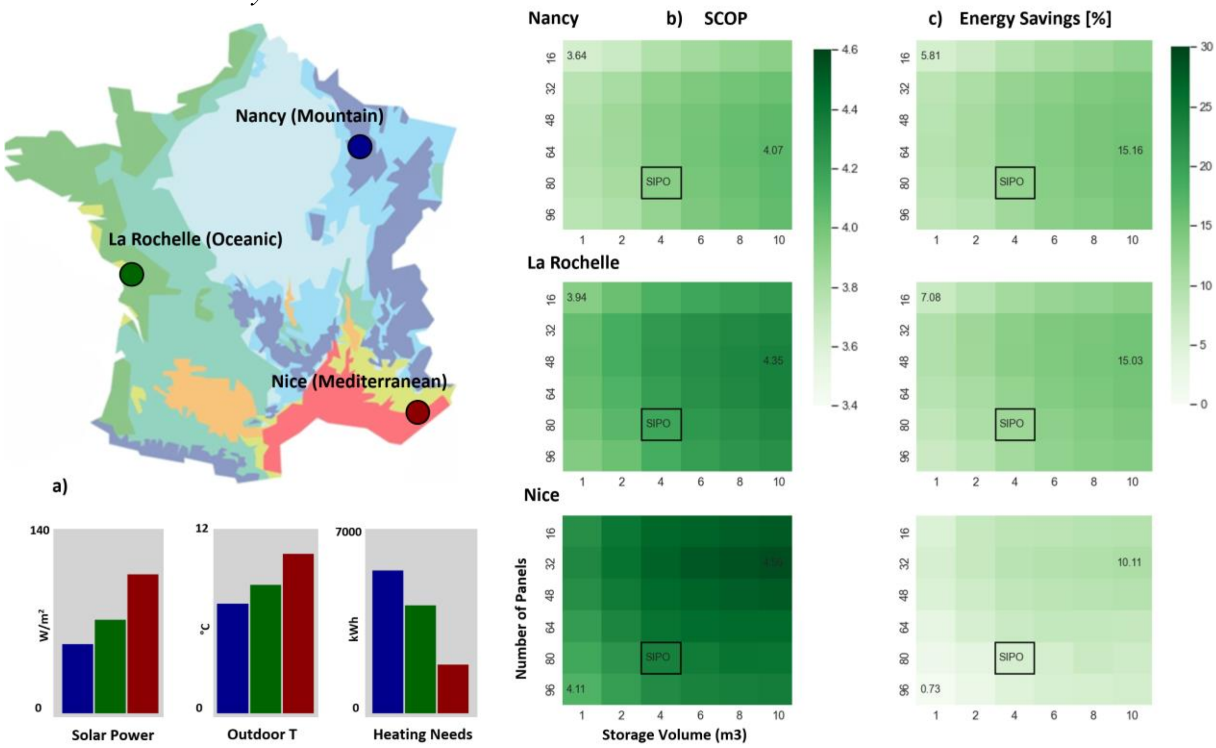

Figure 4. Performance Estimation for Various Sizing and Weather Conditions.

The study involved a parametric evaluation of the system by varying the number of panels from 16 to 96 and the storage volume from 1 to 10 m^3. To assess the performance, three different indicators previously defined were estimated for various sizing options and input conditions. Figure 4 a displays the input conditions for the winter period for the city considered in the study, including solar power received by the solar thermal facade per square meter "Solar Power", the mean ambient temperature "Outdoor T", and the total energy required to maintain the setpoints temperature within the buildings "Heating Needs". This information is key to comprehend the context in which the system performance was evaluated. Figure 4 b shows the SCOP value and Figure 4 c the energy saving value for each sizing option. Both extremum and reference values for the SIPO building are included.

The results indicate that the SCOP performance is proportionally increased with the solar radiation and the outdoor temperature received, which is expected. However, the overall consumption of the auxiliary system reduces the benefits of the energy savings, making it sometimes challenging for the system to surpass the reference system, especially in good weather conditions (Nice).

The payback period for the system is very high (several decades to centuries). The results highlight the need to reduce costs, especially for the solar facade. The correlation between heat needs and payback period being high and testing the system on different buildings with varying heat needs may be relevant.

In terms of sizing, it is more appropriate to have more storage than surface area of thermal solar façade in locations with important solar radiation, such as Nice. Meteorological conditions in Nancy leads to the better performances in term of energy savings.

The study highlights the significance to have an accurate sizing based on specific climate conditions and emphasizes the need to further investigate the system for other buildings applications.

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4. Conclusion and outlook

This work aims to develop a methodology for developing and calibrating a solar-assisted heat pump model to estimate its potential. The study parameters emphasize the requirement for further research to enhance their cost-effectiveness and applicability to different building types. Based on the unique building application studied, the economic viability of the SAHP system is not insured.

By accurately describing the control rules in the simulation, the potential for optimization can be better understood. Furthermore, automation with Python will enable the development of tools for optimizing sizing and testing various control strategies, including Model Predictive Control. This approach will eventually facilitate the development of energy-efficient and cost-effective solutions for SAHP systems.

Acknowledgments

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References

[1] Cao, Xiaodong, Xilei Dai, and Junjie Liu. 'Building Energy-Consumption Status Worldwide and the State-of-the-Art Technologies for Zero-Energy Buildings during the Past Decade'. Energy and Buildings 128 (September 2016): 198–213. https://doi.org/10.1016/j.enbuild.2016.06.089.

[2] Ma, Zhenjun, Lei Xia, Xuemei Gong, Georgios Kokogiannakis, Shugang Wang, and Xinlei Zhou. 'Recent Advances and Development in Optimal Design and Control of Ground Source Heat Pump Systems'. Renewable and Sustainable Energy Reviews 131 (October 2020): 110001. https://doi.org/10.1016/j.rser.2020.110001.

[3] D'Antoni, Matteo, and Onorio Saro. 'Massive Solar-Thermal Collectors: A Critical Literature Review'. Renewable and Sustainable Energy Reviews 16, no. 6 (August 2012): 3666–79. https://doi.org/10.1016/j.rser.2012.02.076.

[4] Péan, Thibault Q., Jaume Salom, and Ramon Costa-Castelló. 'Review of Control Strategies for Improving the Energy Flexibility Provided by Heat Pump Systems in Buildings'. Journal of Process Control 74 (February 2019): 35–49. https://doi.org/10.1016/j.jprocont.2018.03.006

[5] Fan, Yi, Xudong Zhao, Zhonghe Han, Jing Li, Ali Badiei, Yousef Golizadeh Akhlaghi, and Zhijian Liu. 'Scientific and Technological Progress and Future Perspectives of the Solar Assisted Heat Pump (SAHP) System'. *Energy* 229 (August 2021): 120719. https://doi.org/10.1016/j.energy.2021.120719.

[6] Wetter, Michael, Christoph Haugstetter, Silver Lane, and East Hartford. 'MODELICA versus TRNSYS – A Comparison between an Equation-Based and a Procedural Modeling Language for Building Energy Simulation', 2006, 8.

[7] Wetter, Michael. 'Modelica Buildings Library and Best Practices for Modeling of Thermofluid Flow Systems', 2020, 30.

[8] Goffart, Jeanne, and Monika Woloszyn. 'RBD-FAST: une méthode d'analyse de sensibilité rapide et rigoureuse pour la garantie de performance énergétique', 2018, 9.