Boosting Heating Prosumers' welfare gains: Integrating solar thermal energy with photovoltaics and heat pumps

Youssef El Makhrout[1]
[1]Institute for Research in Management and Economics, University of Savoie Mont Blanc, Annecy, France.

Abstract. This paper develops a theoretical model to analyze thermal comfort and electricity consumption at the household level, incorporating solar thermal systems, heat pumps, solar PV, thermal storage, battery storage, and grid use. We evaluate multiple adoption scenarios available to households, quantifying the economic surplus generated by each configuration. Results show that, before considering installation costs and related subsidies, the most profitable scenario is when the household adopts solar thermal with solar PV, a heat pump, battery storage, and thermal storage, as it yields the highest profitability. However, once installation costs and subsidies are incorporated, the most profitable scenario becomes the combination of solar thermal, thermal storage, and solar PV. The analysis highlights the crucial role of targeted renewable subsidies, particularly for heat pumps and solar thermal technologies, in promoting their adoption and enhancing cost-effectiveness. A redistribution of these subsidies is necessary to avoid the deadweight loss effect, which will then enable policymakers to increase subsidies for solar PV and battery storage.

Keywords: Heating prosumers; Electricity consumption; Renewable Energy; Renewable subsidies; Economic surplus; Thermal comfort; Solar thermal; Solar PV; Heat pumps; Battery; Thermal storage.

This is a preliminary draft. Please do not cite or distribute without the permission of the author.

1 Introduction

In France, the decarbonization of the residential sector is one of the main priorities of the country's climate and energy policy. The residential sector is responsible for almost 20% of the total country's greenhouse gas emissions, mainly as a result of energy consumption for space heating and domestic hot water production (ADEME, 2021; IEA, 2022). The national low-carbon strategy and new building regulations (RE2020) calls for a reduction in fossil fuel use, with accelerated development of renewable heating technologies (Ministère de la transition écologique, 2021). Households need energy for a variety of purposes, including cooking, heating, air conditioning, lighting and transportation. Different energy sources are used, such as coal, straw, liquefied petroleum gas (LPG), natural gas and electricity (Li et al., 2024). Heating represents 66% of energy consumption in the residential sector, making it the primary household energy expense item (ADEME, 2019).

Electricity in final energy consumption was represented 18% in 2015, and 20% in 2023. In 2024 and 2025, global electricity demand is predicted to grow faster than at any time since the post-Covid rebound (IEA, 2024). To meet the double challenge of climate change and rising energy demand, it is essential to switch to sustainable energy systems.

Renewable energy from the sun has the greatest potential and produces clean energy that does not damage the environment while it's in operation (Aboelwafa et al., 2018). There are two main categories of solar energy conversion technologies: solar photovoltaic energy systems and solar thermal energy systems. Solar photovoltaic (PV) is unique as it allows households to produce and self-consume electricity, even at small capacity levels, with minimal maintenance costs (Luthander et al., 2015). On the other hand, solar thermal heating plays an important role in providing thermal comfort, as it is one of the most renewable devices that responds to heating needs at the household level. The conversion efficiency of solar thermal systems is generally much higher than that of solar electric systems (Qingyang et al., 2021). However, heat pumps are widely regarded as one of the most promising technologies for providing space heating and cooling and domestic hot water production from renewable energy sources in residential buildings (Hadorn, 2015). They are distinguished by higher efficiency and lower emissions than fossil-fuel boilers. This technology appears to be crucial to the EU's transition to decarbonization (European Commission, 2023).

Heat pumps could be more productive if coupled with a solar thermal which supplies higher-temperature heat to the heat pump's evaporator (Palomba et al., 2022). But, the solar resource is always unavailable at night, on average 12 h a day. So, it is essential to take into account of the intermittency of renewable energy sources to ensure a reliable and continuous energy supply. This underlines the indispensable role of flexibility options (Dato et al., 2020; Durmaz et al., 2022). Thermal storage and batteries are needed in order to provide flexibility in managing variations.

Many factors influence the implementation of renewable energy technologies in buildings and housing. Different situations for single-family or collective property ownership produce different challenges (Heiskanen and Matschoss, 2017). The cost remains one of the main reasons for not adopting these technologies (Ali et al., 2022). However, solar thermal panels show a specification with their low costs compared to the solar PV system. It is considered as the least expensive solar technology available for commercial and industrial applications. It is also the most environmentally friendly solar technology available (Yadav and Gattani, 2022). This advantage is taken into consideration in the computation, as solar thermal is used first to provide heating and is complemented by a heat pump.

Various studies related to renewable energy devices focus mainly on the technical and engineering methodologies without any economic and behavioral analysis of their adoption. However, one exception is the study developed by Durmaz et al. (2022), with a unique focus on solar PV.

In this paper, we develop a four-period theoretical model that helps households optimize their electricity consumption and improve thermal comfort by evaluating the economic benefits of combining solar thermal, solar PV, heat pump, thermal storage, and battery systems. Solar thermal provides direct heating, while the heat pump complements it when solar heat is insufficient. Thermal storage ensures that excess solar heat can be preserved and used later, reducing reliance on electricity for heating. At the same time, solar PV combined with battery storage increases self-consumption of electricity and smooths demand peaks. Together, these technologies create a highly flexible and resilient household energy system, capable of improving thermal comfort and optimizing electricity consumption in the face of intermittent renewable supply. The analysis stresses the need for policy instruments that support not only electricity generation but also integrated systems combining solar thermal, solar PV, heat pumps, and thermal storage. However, a redesign of this

support is needed. By extending technical research with an economic and policy perspective, our study reveals new pathways for accelerating the deployment of sustainable decentralized energy systems. Our model can be applied to a wide range of climate zones, making it useful for policy-makers who want to stimulate the adoption of renewable energy systems for heating and electricity generation.

Further sections of the paper are structured as follows. In section 2, related literature is presented. The development of solar thermal in France and related financial subsidies are reviewed in section 3. In section 4, we explain the theoretical model and we present our data and the model calibration in section 5. The results are presented and explained in section 6, before concluding the paper in section 7.

2 Literature Review

In recent decades, solar thermal systems have received particular attention from scientists due to their high efficiency and ability to provide low-cost domestic and industrial heating (Eze et al., 2024; Sharma et al., 2017). A comparison was made between solar thermal energy and photovoltaic (PV) energy, powering an air-source heat pump (ASHP). An open-source Python software tool based on mixed integer linear programming was developed and applied in East Germany. The results show low sensitivity to electricity price. The PV concept with an ASHP is better suited to densely populated areas compared to the thermal energy alone (Sporleder et al., 2024).

In the north of Italy, an energy system for a single-family home, equipped with photovoltaic and thermal hybrid solar collectors, two storage tanks and a heat pump was analyzed. A mathematical model was used to simulate the electrical and thermal performance of the hybrid solar collectors. The results show that the air-solar system is moderately less efficient than a ground-source heat

pump configuration (Emmi et al., 2016).

In addition, Wang et al. (2020) published an article that provided a comparative literature review, aimed to assess the performance of air-source heat pump (ASHP) systems assisted by solar thermal (ST), photovoltaic (PV) and hybrid photovoltaic/thermal (PV/T) energy. The results show that the PV-ASHP system offers the best technical economic performance. The ST-ASHP and PV/T-ASHP systems perform less well.

In that year, Obalanlege et al. (2020) studied a combined solar heating and electricity system using hybrid photovoltaic-thermal (PVT) heat pumps for residential applications. Based on thermodynamic analysis and a quasi-steady-state heat transfer model, the results show that increasing the water flow rate in the PVT panel improves the overall system efficiency from 61% to 64.5%. Additionally, the PVT panel's efficiency increases by 6.5% when the PVT tank capacity is scaled up from 1 L to 100 L.

An evaluation of PV-T with heat pumps in ten European cities has already been published using transient simulations and incorporating thermal energy storage. Weather conditions and energy demand are considered for $100m^2$ houses. Seville, Rome, Madrid and Bucharest were identified as optimal locations. In addition, PV-T systems can meet 60% of the combined heating demand and almost 100% of the cooling demand each year. The levelized cost of energy (LCOE) for PV-T systems is 30% to 40% lower than for PV systems alone (Ramos et al., 2017).

Leonzio (2017) has published a literature review paper on solar photovoltaic and photovoltaic/thermal systems integrated with absorption heat pumps[1] and thermal energy storage. The paper shows that researchers found that this integration can be an interesting alternative in cooling systems, re-

[1] Absorption heat pumps: are air-source heat pumps that use a heat source such as natural gas, propane, solar-heated water, or geothermal-heated water instead of electricity. See https://www.energy.gov/energysaver/absorption-heat-pumps-emerging-technology-large-homes

sponding to the requirements of energy saving and environmental protection. In addition, other research has added valuable insights. Calise et al. (2016) show that integrating thermal and electrical sources improves overall system performance and efficiency and reduces reliance on external electricity. This study uses dynamic TRNSYS simulations of a solar-assisted heat pump system with PV/T collectors in various climatic conditions. Moreover, Using Monte Carlo simulation, Cui et al. (2020) perform a long-term (25-year) life-cycle cost assessment of a PVT-assisted heat pump system supplying thermal and electrical energy to a residential building. The results obtained with different incentive schemes (feed-in tariff vs. smart export guarantee, for example) are compared and show that there is a strong influence of storage integration and incentive structures on economic performance and savings over the lifetime of the system.

Furthermore, studies such as Usman et al. (2022) analyze which factors can influence the choice of the optimal HVAC and renewable energy systems. For this purpose, a multi-criteria evaluation of domestic energy systems in four different climates is carried out, combining different configurations of HVAC and renewable energy systems. The results show that climate strongly influences the choice of optimal system, with a preference for ground-source heat pumps in colder regions and absorption chillers with flat-plate collectors in warmer regions.

However, despite the valuable insights provided by these studies, important gaps remain in the analysis of the economic potential of combining solar thermal, PV, and heat pump systems in residential contexts. Most existing literature tends to treat these technologies in isolation or through simplified binary comparisons (e.g., PV vs. solar thermal, or PV-ASHP[2] vs. ST-ASHP[3]). The role of integrated systems, especially those that combine multiple renewable sources with both

[2]photovoltaic-assisted air source heat pump: a hybrid system where a photovoltaic (PV) solar panel is combined with an air-source heat pump (ASHP) to provide space heating, cooling, and/or domestic hot water.

[3]Solar Thermal–Assisted Air-Source Heat Pump.

electrical and thermal storage, remains underexplored.

Concerning the economic analysis of household's electricity consumption, an exception is shown by Durmaz et al. (2022) as they investigate how investments in systems containing solar panels, battery storage and smart meters affect the welfare gain of a UK household. Results show that the adoption of a PV system is beneficial regardless of the existence of a storage device and the pricing system. However, smart meters are essential to make storage devices profitable. Engineering approaches focus on adding the net present value concept without accounting for the behavior of the household, who can decide to adapt its electricity or heating consumption. To the best of our knowledge, we evaluate for the first time the profitability of a solar thermal installation coupled with a solar photovoltaic and a heat pump for a French household by developing a household optimization model. Following the study published by Durmaz et al. (2022), we add solar thermal energy and heat pumps to the economic model to see how they can impact a household's economic surplus, hence the need for public policy support.

3 Solar thermal in France and related subsidies

In 2022, France had the second largest production of renewable energy in the European Union after Germany.[4] In that year, residential solar thermal installations in France increased by 45% for single-family homes, totaling 46,500 m² of collector surface area, while projects for collective housing rose by 7%. However, the solar thermal market struggled in 2023, with an overall decline of 10%.[5]Solar thermal is one of the most important renewable energy technologies that provides renewable heating. This technology is still not well developed in France compared to the heat

[4] https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-energies-renouvelables/pdf/pages/partie1/partie1.pdf

[5] https://solarthermalworld.org/news/hopes-of-improved-market-framework-at-the-french-general-state-of-solar-heat-conference

pumps and solar PV. In 2023, the primary consumption of renewable energies for heating purposes amounted to 181 TWh. It is 58% wood energy and 28% renewable heat from heat pumps and only 2% from solar thermal (SDES, 2025). According to the French Ministry of Ecological Transition (Ministère de la Transition écologique, 2025), the consumption of solar thermal in 2022 was 1.5 TWh, and the target of solar thermal generation will be 10 TWh in 2035. [6]

To accelerate the deployment of renewable heating, of which solar thermal collectors are a part, France has introduced a complete system of financial subsidies that targets both individual households and large-scale projects. In this country, the current solar heat support system consists of the Fonds Chaleur[7], particularly for large-scale installations, and MaPrimeRénov , certificat d'économie d'énergie (CEE)[8], and coup de pouce chauffage[9] for renovations in the residential sector. Since the start of 2020, the MaPrimeRénov [10] program has offered incentives to low-income households for the installation of a variety of energy-saving measures and technologies, such as solar hot water, solar space heating, heat pumps, solar thermal, biomass boilers, and insulation. There are two types of this financial support, MaPrimeRénov large-scale renovation and MaPrimeRénov renovation by gesture. To qualify for MaPrimeRénov large-scale renovation, households must complete a set of energy efficiency renovations in their homes, covering at least one of the following six categories: thermal insulation of exterior walls, thermal insulation of ground floors, thermal insulation of roofs/attics, thermal insulation of exterior windows and doors, ventilation systems and heating or domestic hot water production systems. Renovation must include at least two building envelope improvements from four categories: wall insulation (interior or exterior),

[6] https://www.consultations-publiques.developpement-durable.gouv.fr/IMG/pdf/02__projet_de_ppe_3_en.pdf

[7] Can be translated as heat fund

[8] Can be translated as energy-saving certificates

[9] Can be translated as heating upgrade grant

[10] Can be translated as home renovation grant

ground floor insulation, roof insulation (including lost attic floors or flat roofs) and Window/door replacement or installation of secondary glazing. For each selected type of project, the treated surfaces must cover at least 25% of the dwelling.

However, MaPrimeRénov gesture-based renovation is developed for heating and hot water projects[11], thermal insulation, ventilation system (VMC), and additional performance of energy audit service (non-regulatory requirement). Household incomes are taken into account in the amount of these subsidies. In addition, households can benefit from EPTZ, CEE, heating upgrade grant, local authority renovation funding programs, other ANAH assistance options and VAT of 5.5%instead of 20%.[12] Details of the amount of each subsidy are presented in section 6.

4 Theoretical model

Based on the model proposed by Durmaz et al. (2022), we develop an extended theoretical model in this section for optimizing thermal comfort and electricity consumption. In this model, the utility depends on electricity consumption and comfort. The consumption includes the electricity that the household purchases from the grid g_j, and generates with solar panels $x\overline{K}$ and $y\overline{K}$, where x and y are the proportions of the maximum possible solar PV generation that are realized in periods 2 and 3, respectively, due to stochastic weather conditions $\overline{K}$ is the solar PV capacity, less where what is sold to the grid if the household has a smart meter ($g_j < 0$), and less the electricity that the compressor consumes to run the heat pump h_j. Suppose the household decides to add more flexibility. In that case, he can adopt a storage battery to store the excess electricity generated by solar PV that has not been consumed yet or store electricity bought on the grid. Then the consumption

[11] Solar thermal and heat pumps are among these projects

[12] https://www.service-public.fr/particuliers/vosdroits/F35083

also includes the energy previously stored ϕs_{l-1}, net of the amount allocated to storage for future use, s_l, as we assume that the energy stored cannot be carried over from one day to the next, where ϕ represents the round-trip efficiency parameter and l is the storage period with $l = 1,2,3$. The electricity stored in the battery in period l denoted by s_l should be inferior or equal to the maximum capacity of the battery $\bar{s}$.

The comfort depends on the heat generated by the solar thermal collectors, the heat pump[13], and storage. The solar thermal collectors produce heat in periods 2 and 3, with generation subject to stochastic weather conditions $x\overline{K}_{th}$ and $y\overline{K}_{th}$ respectively, where $\overline{K}_{th}$ denotes the maximum solar thermal capacity. In addition, the household meets its comfort needs through the heat generated by the heat pump complemented with the excess heat released from the buffer tank $\psi s_{th_{t-1}}$ net of the heat newly stored for use in the following period s_{th_t}. The parameter ψ represents thermal retention efficiency during periods, $t = 1,2,3$. We assume there is no storage in period 4 with $0 < \psi \leq 1$. The heat pump can operate during periods of solar thermal generation. By storing the thermal energy produced by the solar collectors, the household can rely on it during periods when there is no solar radiation. This reduces the need to run the heat pump at night, when outside temperatures are lower or electricity prices are higher. In this way, the model dynamically distributes heat production and storage over different periods to maintain comfort.

For a household equipped with a solar thermal system coupled with a heat pump and solar PV system in addition to a storage battery and a smart meter, the objective for each season (i= summer,

[13]The heat provided by the heat pump is determined by the electricity consumed at the compressor level, denoted by h_j. Once the compressor is running, the heat pump extracts energy from the renewable source (air, water, ground) to generate heat for the house. In this paper, we use an air-water heat pump.

fall, winter and spring) is to maximize the following surplus:

$$
\begin{aligned}
&\max_{\{s_{th},\, s_l,\, g_j,\, h_j\}} \quad U_1(h_1,\, g_1, s_1) - p_1 g_1 \\
&+ \int_0^1 \Bigg[U_2\,(\, x\overline{K}_{th},\, h_2,\, s_{th_2}(x),\, x\overline{K},\, g_2(x),\, s_2(x),\, \phi s_1) - p_2 g_2(x) \\
&+ \int_0^1 \Bigg[U_3\,(y\overline{K}_{th},\, h_3,\, s_{th_3}(x,y),\, \psi s_{th_2}(x,y),\, y\overline{K},\, g_3(x,y),\, s_3(x,y),\, \phi s_2(x,y)) \\
&+ U_4\,(h_4,\, \psi s_{th_3}(x,y),\, g_4(x,y),\, \phi s_3(x,y)) - \sum_{j=3,4} p_i g_i(x,y) \Bigg] dF^y(y) \Bigg] dF^x(x) \\
&\qquad\qquad s.t. \quad s_l \leq \bar{s}, \quad s_l \geq 0 \\
&\qquad\qquad\quad s_{th_t} \leq \bar{s}_{th}, \qquad s_{th_t} \geq 0
\end{aligned}
\tag{1}
$$

where F^x and F^y are the cumulative distribution functions of x and y, respectively. In addition, the price of electricity purchased from the grid at period j is denoted by p_j.

4.1 Utility Function Specification

In this section, we specify the utility function by supposing a two-part additive utility function: $U(h_{i,j}, e_{i,j}) = U^c_{i,j}(h_{i,j}) + U^e_{i,j}(e_{i,j})$ with i, the season and j the period of the day. The electricity consumption part $U^e_{i,j}$ is specified as a Stone-Geary utility function to account for a subsistence level noted $\overline{e}_{i,j}$:

$$U^e(e_{i,j}) = \frac{\delta(e_{i,j} - \overline{e}_{i,j})^{1-\gamma}}{1-\gamma}$$

where $e_{i,j} = g_{i,j} - h_{i,j} - s_{i,j} + \phi s_{i,j-1}$ with $s_{i,4} = 0$. Furthermore, δ is a scale parameter and γ the degree of risk aversion.

The comfort utility function must take into account the contribution of solar thermal heat $H_{th\ i,j}$ to indoor temperature. Since solar thermal directly provides thermal comfort, the heat demand from the heat pump will be reduced. We assume that the utility function of comfort U^c is a quadratic function of the indoor temperature T_{ind}. So, solar thermal works, and the heat pump contributes to generating the rest of the heat needed. We then denote the utility function $U^c(T_{ind}) = aT_{ind}^2 + bT_{ind} + c$ where a, b and c are three unknown parameters. Assuming that $[15-27]$ is the range of indoor temperature values such that the utility becomes negative outside this range (hence with a maximum utility reached for 21°C), we then have $U^c(15) = 0$, $U^c(27) = 0$. These two conditions provide values for b and c, as functions of a. We have $T_{ind} = T_{out} + H_{th} + H_{hp}$ where H_{hp} represents the total heat generated by the heat pump and H_{th} is the solar thermal generation. For instance, the solar thermal heat generated in the second period is $H_{th_2} = x\overline{K}_{th} - s_{th_2}$ where s_{th_2} represents the heat stored from the solar thermal in the heating tank during the second period.

The heat generated by the heat pump takes the form of an exponential function of the electricity consumed by the heat pump, which we denote $H_{hp} = Ah^{\mu}$. In addition, the heat pump is used only for heating, as the household uses natural cooling during the summer season.

The utility function for the comfort part is then written as follows:

$$U^c(h_{i,j}) = a\left(T_{out_{i,j}} + H_{th_{i,j}} + Ah_{i,j}^{\mu}\right)^2 - 42a\left(T_{out_{i,j}} + H_{th_{i,j}} + Ah_{i,j}^{\mu}\right) + 405a$$

Where

$$H_{th_{i,j}} = \begin{cases} 0 & \text{in period 1} \quad (j=1) \\ x\overline{K}_{th} - s_{th_2} & \text{in period 2} \quad (j=2) \\ y\overline{K}_{th} - s_{th_3} + \psi s_{th_2} & \text{in period 3} \quad (j=3) \\ \psi s_{th_3} & \text{in period 4} \quad (j=4) \end{cases}$$

In scenarios when the household does not invest in either a solar thermal system or a heat pump, we assume that heating needs are met by a standard electric system. In this case, the household's utility depends only on one electrical part, which we can specify using the same Stone-Geary utility function. Unlike the heat pump scenarios, electric heating is considered a fixed necessity rather than a flexible choice. Consequently, this requires a given and constant electricity consumption that is included directly in the subsistence level, $\overline{e}_{i,j}$. Net electricity is therefore defined as $e_{i,j} = g_{i,j} - s_{i,j} + \phi s_{i,j-1}$, where $s_{i,4} = 0$.

4.2 Model resolution

We solve the model in reverse order, starting from the fourth period and progressing period by period. The first order condition yields the following optimal level of grid purchases:

$$\delta(e_4 - \overline{e})^{-\gamma} = p_4 \Leftrightarrow g_4^* = \left(\frac{p_4}{\delta}\right)^{-\frac{1}{\gamma}} + h_4 - \phi s_3 + \overline{e} \tag{2}$$

$g_4^* > 0$ if $U^{e'}(-h_4 + \phi s_3 - \overline{e}) > p_4$. When the price of electricity is sufficiently low, or when the heat pump's demand for electricity is large compared to the available stored energy, the optimality condition for grid purchases stipulates that electricity is purchased from the grid.

This first-order condition also gives the optimal level of electricity consumed by the heat pump, denoted by the following equation:

$$U^{c'}(h_4) = \delta(e_4 - \overline{e})^{-\gamma} \Leftrightarrow U^{c'}(h_4) = p_4 \tag{3}$$

The price of electricity negatively impacts the optimal electricity consumption of the heat pump. The optimal storage of electricity requires the writing of a Lagrangian that takes into account constraints on the storage flow. Specifically, the quantity stored at period 3 must be non-negative and less than the battery capacity. The part of the Lagrangian that is relevant for s_3 is noted $\mathscr{L}_{3,4}$:

$\mathscr{L}_{3,4}(.) = U_3(y\overline{K}_{th} + h_3 - s_{th_3} + \psi s_{th_2}, y\overline{K} + g_3 - s_3 - h_3 + \phi s_2) - p_3 g_3 + U_4(h_4 + \psi s_{th_3}, g_4^* + \phi s_3 - h_4^*) - p_4 g_4^* + \eta_3 s_3 + \upsilon_3(\overline{s} - s_3)$

where η_3 and υ_3 are constraints on non-negativity and storage capacity, respectively. Using the first-order condition related to the optimal storage at the third period and equation (3) we find (see Appendix A):

$$-p_3 + \phi p_4 = \upsilon_3 - \eta_3 \tag{4}$$

As the household has the ability to feed electricity into the grid, the storage decision is fully determined by the difference between the price of electricity in the third and fourth periods after taking into account the round-trip parameter. If $-p_3 + \phi p_4 > 0$, then $\upsilon_3 > 0$ and the storage device is charged to its maximum capacity: $s_3^* = \overline{s}$. In contrast, if $-p_3 + \phi p_4 < 0$, then $\eta_3 > 0$ and there is no storage: $s_3^* = 0$.

The optimal thermal storage also requires a Lagrangian that is relevant for s_{th_3} noted $\mathscr{L}_{3,4}$:

$$\mathscr{L}_{3,4}(.) = U_3(y\overline{K}_{th} + h_3 - s_{th_3} + \psi s_{th_2}, y\overline{K} + g_3 - s_3 - h_3 + \phi s_2) - p_3 g_3 + U_4(h_4 + \psi s_{th_3}, g_4 + \phi s_3 - h_4) - p_4 g_4 + \lambda_3 s_{th_3} + \alpha_3(\bar{s}_{th} - s_{th_3})$$

The first-order condition with respect to thermal storage is used to derive the optimal storage levels for both corner and interior solutions at the third period (see Appendix B).

The thermal storage in period 3 becomes positive if and only if the combined heat generated in period 3 (from solar thermal, heat pump and residual storage) exceeds not only the immediate comfort needs of the current period but also the anticipated heating need of period 4 adjusted for storage efficiency, $(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} + Ah_3^{\mu} > \psi(T_{out_4} + Ah_4^{\mu}) + 21(1-\psi))$. In this case, the period 3 generates a surplus of usable heat that can be optimally stored and be used during the next period, compensating for the absence of solar thermal input in that period (period 4), then $s_{th_3} > 0$ which means thermal energy can be stored up, according to the equation of optimal thermal storage in the third period (see Appendix B), to the maximum capacity of the heating tank ($s_{th_3} = \bar{s}_{th}$). Otherwise, all thermal energy generated by different devices in period 3 is fully absorbed by contemporaneous comfort needs and nothing is stored for the night $s_{th_3} = 0$.

The household solves the problem for the second and first periods following the same methodology, with the clarification that in Period 2, $x\overline{K}$ weather conditions are taken into account because there is no sun in Period 1. The same steps are used to solve the model with other equipment combinations. This enables the comparison of the surplus obtained by the household under different scenarios.

5 Data and calibration

5.1 Data

We consider a 170 m² French house based in Bourget-du-Lac, occupied by two people from 01/01/2021 to 31/12/2021. The house is equipped with 2.5 m^2 solar thermal collectors Viessmann Vitosol 200 FM [14] and five 1.325 kWp solar photovoltaic panels. The household uses a 6 kW air-to-water heat pump with an integrated buffer tank for heating, ventilation, and air conditioning (HVAC) and a domestic hot water tank.

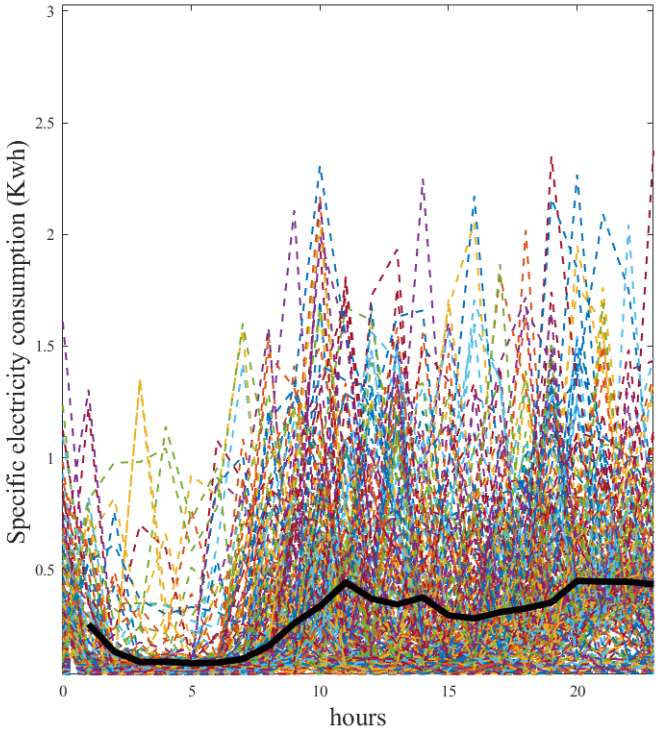
Based on these characteristics, simulations generate hourly data for the household's heating and electricity requirements. To meet heating and domestic hot water needs, the solar thermal system generates heat, while the heat pump consumes electricity to generate the additional heat required by the household that the solar thermal system is unable to provide. In addition, the simulation generates hourly indoor temperature. In order to determine the amount of heating supplied by the two heating systems, we need information on the hourly outdoor temperature. For this reason, Bourget-du-Lac's weather file is used for the hourly outdoor temperature.

Specific electricity consumption observations for daily needs are shown in Fig. 1, for each day (24h) throughout the year. The bold black line presents the hourly averages of specific electricity consumption and suggests dividing the day into 4 periods. The period between 00:00 - 06:00 AM is the first period (night and early morning); This is the lowest consumption of the day as people are sleeping. Electricity is only used for appliances such as refrigerators and other non-stop electrical appliances. The second period shows the morning peak in electricity consumption. The third period shows reduced household activity, leading to a decline in electricity usage, though

[14] https://wallux.com/marque/catalogue/lecteur.php?cat=1555#p=172

levels remain higher than in the first period. The fourth period marks the evening peak, coinciding with households returning home. However, the heat pump can impact significantly the electricity demand. This profile is quite consistent with recent RTE[15] figures.

Fig 1 *Specific electricity consumption (observations and average)*



[15] Réseau Transport electricité in France, https://www.services-rte.com/en/view-data-published-by-rte/daily-load-curves.html

Figure 2 shows electricity consumption data for the heat pump over the year, with the bold black line showing averages over four periods. During the first period (00:00-06:00), the heating system consumes extremely low amounts of electricity. Consumption rises as households wake up (06:00-12:00) . This is consistent with the often low night-time temperatures (around 15°C), as the heat pump gradually warms up the house until it reaches the desired comfort level. Third and fourth periods (12:00-24:00) show smaller peaks in consumption, mainly linked to changes in outside temperature. The heat pump automatically adjusts to the heating curve defined by the regulator to guarantee the desired indoor temperature level.

Fig 2 *Heat pump electricity consumption (observations and average)*

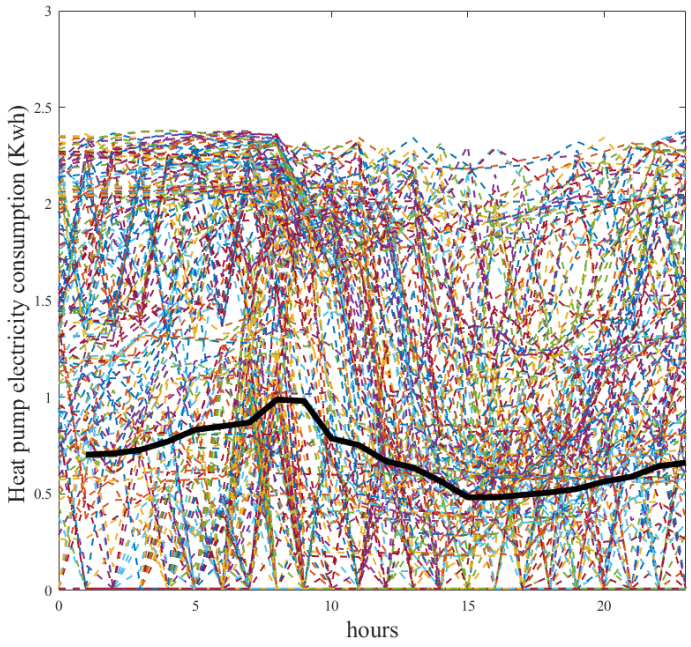


Figure 3 presents observations for hourly solar thermal heat generation on the left side and solar PV generation on the right side of the figure. The black lines correspond, respectively, to the hourly averages of solar thermal and PV generation. Based on four 6-hour periods during the day, Figure 3 illustrates that solar thermal and photovoltaic production are highest in the second and third periods, while they are virtually nonexistent in the first and last periods. This is a reflection

of the predictable intermittency of solar production, conditioned by the daily cycle of solar radiation. In addition, the solar photovoltaic observations are in line with the California duck curve (see California ISO, 2022), as the mismatch between solar photovoltaic and solar thermal production and both electricity and heating demand is well illustrated.

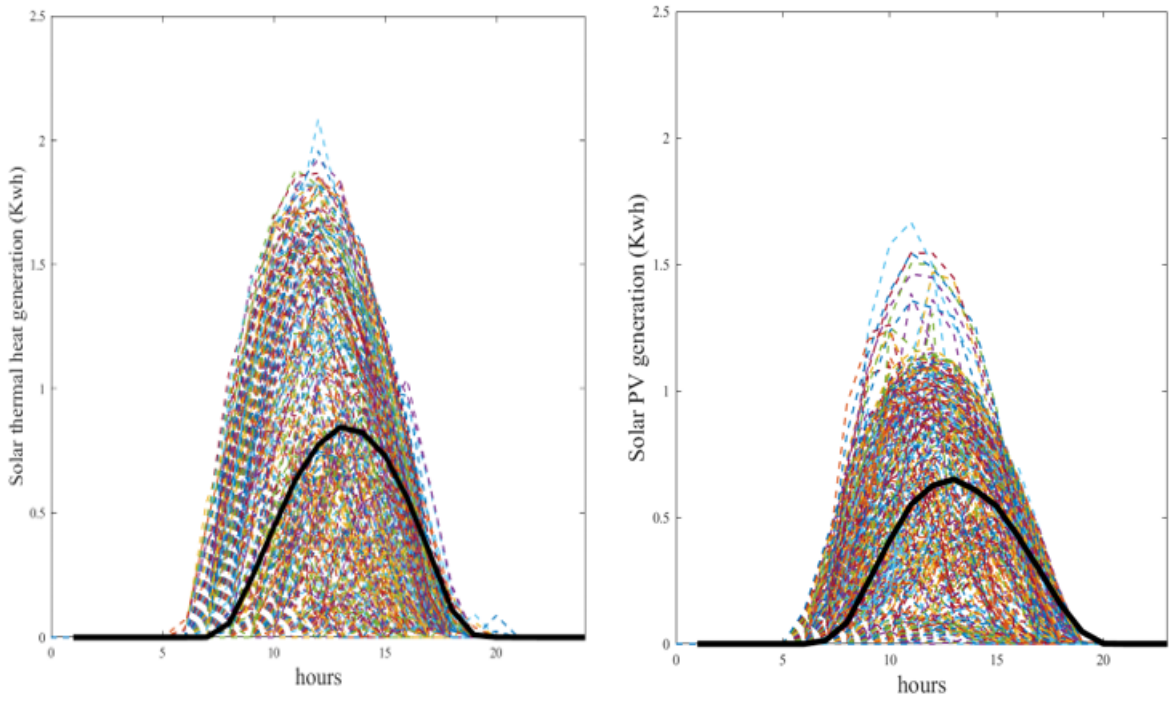
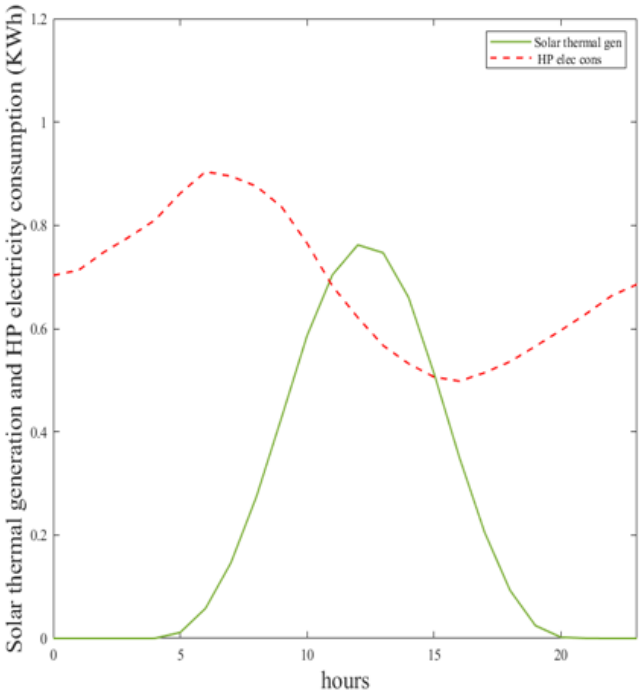


Fig 3 *Solar thermal heat generation & Solar PV generation (observations and average)*

Figure 4, using the same division of the day into four equal periods, shows that the annual average of solar thermal generation exceeds the average electricity consumption of the heat pump during periods 2 and 3. This situation no longer holds in winter, when solar radiation is particularly low. The figure illustrates how solar thermal collectors and the heat pump can complement each other. The heat pump consumes electricity to produce heat when solar thermal generation is insufficient, offering the household an optimal combination to maintain thermal comfort throughout the

year. In addition, the heat produced by the solar thermal collectors can be stored in the buffer tank, which helps to reduce the electricity consumed by the heat pump.

Fig 4 *Heat pump electricity consumption and solar thermal generation*



5.2 Calibration

In this subsection, we calibrate the key parameters needed to compute the economic surplus across different scenarios. Firstly, we start by calibrating parameters of the utility related to the electricity consumption part $U^e_{i,j}$, we approximate the level of subsistence consumption using our data. The lowest consumption recorded over 6 hours appears on summer evening (period 3) with $\overline{e}_{S,3} = 0.2335$ kWh, which we have set as the subsistence level for this period. Using average consumption for the same period and season and uniform electricity prices, we derive δ by applying the first-order condition for electricity consumption. We calculate subsistence levels for all other periods by equalizing marginal utilities, since electricity prices are uniform. We set the relative risk aversion

parameter at $\gamma = 5$, consistent with the higher range found in Gollier (2001), we find $\delta = 1.7085$.

Secondly, we calibrate the comfort part parameters U^c. As comfort utility is a quadratic function of indoor temperature T_{ind}: $U^c(T_{ind}) = aT_{ind}^2 + bT_{ind} + c$ where a, b and c are three unknown parameters. We assume that 21 °C is the temperature that provides the maximum comfort and $[15-27]$ is the range of indoor temperature values. We get then $b = -42a$ and $c = 405a$.

For the case where the heat pump operates as a complementary device, we calibrate the parameters A and μ starting from the equation $T_{ind} = T_{out} + H_{th} + Ah^{\mu}$, we linearize it by taking logarithms $ln|(T_{ind} - T_{out} - H_{th})| = ln(A) + \mu\ ln(h)$, for $T_{ind} > T_{out} + H_{th}$. Otherwise, the data are deleted for the regression. Parameters A and μ are computed for each season individually, and then we take their average across seasons. Simulated data calibration returns $A = 9.4772$ and $\mu = 0.1621$.

Furthermore, the calibration of the parameter a in the utility function is based on periods in which the heat pump is actually in operation. After verification of the data, we observe that during warm weather, typically in the spring and summer seasons, the heat pump is not used due to negligible heating needs. Consequently, these periods are excluded from the calibration procedure. In contrast, heating demand is substantially higher in winter and fall, so the calibration focuses on these two seasons. We first compute a period-specific value of a for each period within the winter and fall seasons. The final calibrated parameter is obtained by averaging these two seasonal means across all periods, yielding $a = -0.00008632$ (see Appendix C).

When the household does not install either solar thermal or a heat pump, heating is provided solely by electricity. Using the same calibration strategy and maintaining the risk aversion parameter at $\gamma = 5$ (Gollier, 2001), we obtain a new value of the scale parameter, $\delta = 0.0258$, which is kept constant across all seasons. The minimum level of electricity consumption in this case occurs during the summer night (period 1), with $\bar{e}_{(s,1)} = 0.2030$.

5.3 Estimation of probability density functions for solar radiation

In this section, the Weibull distribution is used as an approximation method to obtain PDFs of photovoltaic electricity and solar thermal heat generation in the second and third periods for all seasons (see Durmaz et al. (2022)). The objective is to estimate the parameters λ_2, β_2, λ_3, and β_3 in each case. Considering these parameter distributions in the theoretical model allows us to account for the uncertainty in solar PV and solar thermal generation in the analysis.

Fig 5 *Estimated PDFs for period 2 and 3*

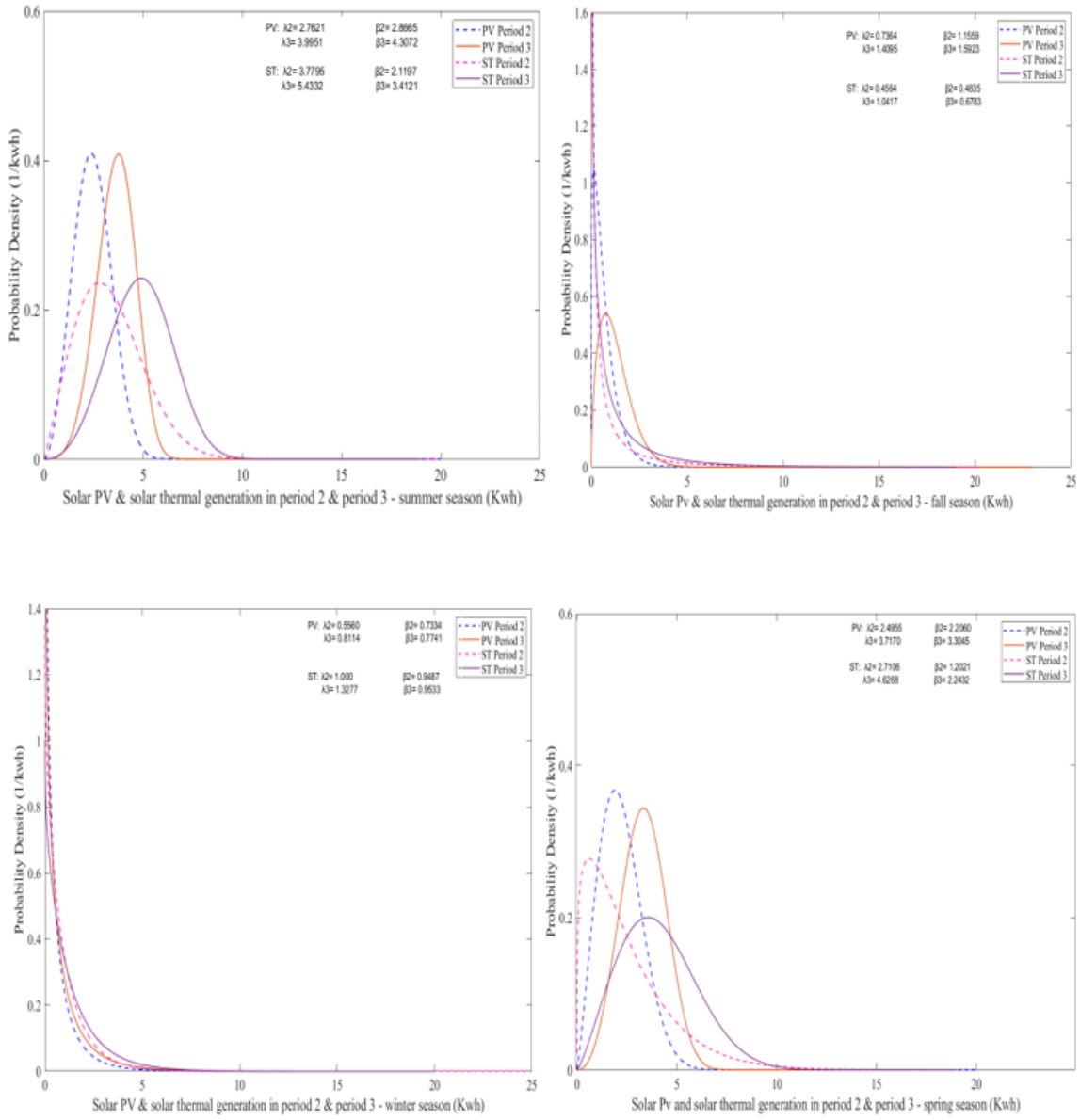


Figure 5 shows that the estimated PDFs are quite similar from summer to spring, with higher solar PV and solar thermal production in period 2 and 3. The fall season experiences very low solar thermal generation, accompanied by moderate electricity production from solar panels. However, during the winter season, the thermal and electricity production are very low as the weak availability of sun and the short days. Concerning the electricity tariff, we adopt a dual tariff[16], consistent with the regulated EDF electricity tariff with the Peak / Off-Peak (Heures Pleines / Heures Creuses) option in 2021. We assume that $P_1 = 0.1360 < P_2 = P_3 = P_4 = 0.1821$ €/kWh. The average price is 0.1705 €/kWh. [17]

6 Results

In this section, we present the results of different combinations that the household can adopt. To allow a meaningful comparison of the economic surplus results, fourteen scenarios are selected. The following table presents the different scenarios used in our analysis.

[16]This tariff differentiates electricity prices according to the time of day, with lower prices during off-peak periods when demand is relatively low, and higher prices during peak demand periods when consumption is greater.https://www.info.gouv.fr/actualite/electricite-la-tarification-heures-pleines-heures-creuses-pour-faire-baisser-la-facture?

[17]See https://www.kelwatt.fr/fournisseurs/edf/prix/tarifs-2021

Table 1 : Devices in each scenario

Scenarios	Grid	Solar Thermal	Heat Pump	Solar Panels	Battery	Thermal Storage
1	X	X				
2	X	X				X
3	X	X		X		
4	X	X		X	X	
5	X	X		X		X
6	X	X		X	X	X
7	X	X	X			
8	X	X	X			X
9	X	X	X	X		
10	X	X	X	X		X
11	X	X	X	X	X	X
12	X			X		
13	X					
14	X			X	X	

Scenario 13 is our baseline scenario when the household uses only the grid. The aim is to show how solar thermal, solar panels, heat pump, battery storage, and thermal storage can impact the economic surplus of the household. To do so, we compute the economic surplus change over the lifetime of the equipment when the household switches from scenario 13 to another scenario. We fix the lifetime of all equipment at 20 years and the discount rate r at 5%. This later gives a discount factor $\beta = \frac{1}{(1+r)} = 0.95$.

So, between the scenario i and the benchmark scenario, the surplus change is computed using the following equation:

$$Surplus\ change = \frac{(S_i - S_{13})}{\hat{r}}$$

The annual surplus obtained in the scenario i is represented by S_i and $\hat{r} = \frac{1-\beta}{1-\beta^{21}} = 0.0758$.

If the household installs solar thermal collectors, the surplus change over 20 years can reach 24464.56€. The most profitable scenario is when the household adopts solar thermal with a heat pump, solar panels, battery storage, and thermal storage, as the surplus change is 30376.04€. In addition, adding a heat pump and solar panels to the existing solar thermal generates 3663.04€ of surplus change[18]. The surplus change can reach 4749.00€ [19] if the household combines solar panels, battery, and thermal storage with existing solar thermal.

The results demonstrate a positive synergy between the technologies installed. Scenario 3, which combines solar thermal and photovoltaic systems, generates a total surplus of 28052.06€. This value is higher than the sum of the surpluses obtained when the systems are installed independently, totaling 27589.44€.[20] This indicates that the equipment operates more efficiently as a combined system than as separate parts.

The following tables give the surplus change from the baseline scenario to another one over the lifetime of each equipment with installation costs and renewable subsidies:

[18] Switching from scenario 1 to scenario 9 generates 3663.04€.

[19] Switching from scenario 1 to scenario 6 generates 4749.00€

[20] Scenario 12 (solar PV) and Scenario 1 (solar thermal) generate surpluses of 3124.88€ and 24464.56€, respectively. Together, they contribute to a total surplus of 27589.44€.

Table 2 : Net surplus change with costs over 20 years

Scenarios	Surplus change	Cost	Net surplus change
13 $\longrightarrow$ 1	24464.56€	2250.00€	22214.56€
13 $\longrightarrow$ 2	24468.16€	3027.09€	21441.07€
13 $\longrightarrow$ 3	28052.06€	5430.00€	22622.06€
13 $\longrightarrow$ 4	29210.20€	12430.00€	16780.20€
13 $\longrightarrow$ 5	28055.64€	6207.09€	21848.55€
13 $\longrightarrow$ 6	29213.56€	13207.09€	16006.47€
13 $\longrightarrow$ 7	24562.43€	13527.00€	11035.43€
13 $\longrightarrow$ 8	24565.76€	14304.09€	10261.67€
13 $\longrightarrow$ 9	28127.60€	16707.00€	11420.60€
13 $\longrightarrow$ 10	28130.90€	17484.09€	10646.81
13 $\longrightarrow$ 11	30376.04€	24484.09€	5891.95€
13 $\longrightarrow$ 12	3124.88€	3180.00€	-55.12€
13 $\longrightarrow$ 14	4336.22€	10180.00€	-5843.78€

Note: Taxes are already included in costs.

Solar thermal collectors used in our analysis are similar to the ones marketed by Viessmann, the household in scenario 2 installs two collectors of 2.5 m^2 that cost 2250€.[21] In addition, a Dietrich air-water heat pump of 6 Kw costing 11277€ and five solar panels of 1.325 KWp from

[21] In France, the cost of solar thermal collectors ranges from 900€ to 1700€ per m^2, which gives 2250€ for 2.5m^2 installed by a household with low incomes.
https://www.solairepro.comparateur-panneau-solaire.fr/panneaux-solaires-thermiques-comprendre-les-prix-pour-un-meilleur-investissement/

BAXI[22] that cost 3180€[23] with a Tesla Powerwall 1 as a battery storage for electricity with a capacity of 6.5 Kwh costing 7000€[24]. Furthermore, the household can add a 150 L Combi-Pack 3 buffer tank from Charot[25], which costs 777.09€ (all taxes included).[26] The net surplus change is negative when there is no solar thermal, no heat pump, and no thermal storage because the costs of the equipment exceed the surplus change, leading to a negative net surplus change. Taking into account only the cost of each equipment, the most profitable scenario is when the household installs solar thermal collectors with thermal storage, as the net surplus change reaches 22622.06€.

Subsidies for renewable energies can improve the net surplus change. Taking advantage of them, households reduce the cost of purchasing and installing equipment in each scenario. As the renewable subsidies in France are essentially dependent on household income, we study the case of a household with very low income. The following table shows the results, taking into account the various financial aids available in France. The net surplus change is calculated now by :

$$Net\ surplus\ change = Surplus\ chnage - Cost + Subsidies$$

[22] BAXI, originally a British brand founded in 1866, is a key pillar of the BDR Thermea Group. Its extensive product portfolio includes high-efficiency condensing boilers, air-to-water heat pumps and hybrid heating systems, as well as the Baxi Foton photovoltaic range and intelligent thermal and battery storage systems. In the French market, BAXI's advanced sustainable technologies, including the Baxi Foton solar PV line, are integrated with the group's historic French brands, De Dietrich and Chappée. See https://www.bdrthermeagroup.com/en/about-us.

[23] In 2021, the average installation cost of a PV system < 3Kwp in the French market is 2.4 per W, as the household installs a 1.325 Kwp the cost is 3180 € https://iea-pvps.org/wp-content/uploads/2022/07/IEA-PVPS-NSR-France-EN-2021-v5.pdf?

[24] https://www.bobex.be/fr-be/batterie-domestique/tesla-powerwall/

[25] Charot is a leading French manufacturer specializing in industrial and domestic thermal energy storage and hot water production. See https://www.charot.com/

[26] https://www.esc-grossiste.fr/boutique/ballon-tampon-charot/4814-combi-pack-3-version-tampon-150-charot.html

Table 3 : Net surplus change with costs and subsidies over 20 years

Scenarios	Surplus change	Cost	Subsidies	Net surplus change
13 $\longrightarrow$ 1	24464.56€	2250€	2250€	24464.56 €
13 $\longrightarrow$ 2	24468.16€	3027.09€	3027.09 €	24468.16€
13 $\longrightarrow$ 3	28052.06€	5430.00€	2356.00€	24978.06€
13 $\longrightarrow$ 4	29210.20€	12430.00€	2356.00€	19136.20€
13 $\longrightarrow$ 5	28055.64€	6207.09€	3133.09€	24981.64€
13 $\longrightarrow$ 6	29213.56€	13207.09€	3133.09€	19139.56€
13 $\longrightarrow$ 7	24562.43€	13527.00€	12426.81€	23462.24€
13 $\longrightarrow$ 8	2565.76€	14304.09€	13203.90€	23465.57€
13 $\longrightarrow$ 9	28127.60€	16707.00€	12532.81€	23953.41€
13 $\longrightarrow$ 10	28130.90€	17484.09€	13309.90€	23956.71€
13 $\longrightarrow$ 11	30376.04€	24484.09€	13309.90€	19201.85€
13 $\longrightarrow$ 12	3124.88€	3180.00€	106.00€	50.88€
13 $\longrightarrow$ 14	4336.22€	10180.00€	106.00€	-5737.78€

Note: Taxes are already included in costs.

All taxes are included in the costs of all equipments and the household already benefits from the reduced value-added tax (VAT) rate, paying 5.5% instead of 20% for the heat pump. In addition, since October 2025, the reduced VAT rate of 5.5% applies to solar PV systems, replacing the previously applicable 10% VAT rate. As a result, the household saves 135.64€ when installing a solar PV system.[27]

[27]The total cost amounted to 3180€ under the former 5.5% VAT rate for installations less then 9 Kwp, whereas it costs 3315.64€ under the 10% VAT rate, leading to savings of 135.64€. https://www.service-public.gouv.fr/particuliers/actualites/A18469

Similarly, the adoption of a solar thermal system generates savings of 309.24€, due to the application of the reduced VAT rate.[28]

Moreover, the household can benefit from MaPrimeRénov to fully covers the installation of the solar thermal system which costs 2250€ in Scenario 1. Consequently, the net surplus change amounts to 24464.56€. The remaining cost is 0€ as the household can have 10000€ MaPrimeRénov with an estimated 5000€ CEE for a combined solar system and solar heating devices for heating; a system that provides both hot water and space heating.[29]

The addition of a thermal storage may be eligible as part of an energy renovation project to improve an existing solar thermal system, and it is considered part of a combined solar system (and solar devices for space heating). A household with a very low income[30] can then take advantage of MaPrimeRénov to finance the cost of this system, even if it has already benefited from MaPrimeRénov for the installation of the solar thermal system and has access to 10000€.[31] In Scenario 2, when the household installs solar thermal collectors and thermal storage, MaPrimeRénov can cover the full cost of 3027.09€, and then the remaining cost is 0€. This leads to a net surplus of 24468.16 €. The installation of solar PV enables the household to benefit from a 106€ self-consumption grant[32]. The remaining cost of scenario 3 is then 2676.50€, and the household

[28]The total cost is 2559.24€ under the standard 20% VAT rate, compared with 2250€ under the reduced 5.5% VAT rate, resulting in savings of 309.24€.

[29]The household can also take advantage of an energy saving certificate (CEE), but the National Housing Agency called Anah makes the request on behalf of the household, and then automatically includes the CEE in the MaPrimeRénov calculation. https://www.service-public.fr/particuliers/vosdroits/F35083

[30]In this study, the household is classified as having very low income according to the 2026 national housing agency (Anah) classification. For a household composed of two persons located outside Île-de-France, this classification applies if the annual reference tax income is less than or equal to 25393€. See www.anah.gouv.fr/document/guide-des-aides-financieres-0226

[31]www.anah.gouv.fr/sites/default/files/2026-02/202602_guide-aides-financieres_WEB.pdf

[32]The self-consumption grant for the installation of solar PV (prime à l'autoconsommation) decreased from 380€ per kWp in 2021 to 80€ per kWp in 2025 and 2026. In this study, we use the most recent self-consumption grant for a solar PV system of 1.325 Kwp which corresponds to a total of 106€. https://www.hellowatt.fr/panneaux-solaires-photovoltaiques/prime-autoconsommation?srsltid=AfmBOorIdkANHpgm3zjVT0NnGirYb6hu-VaMEJOO4MR8UBvhMo1BerSy/

generates 24978.06€ of net surplus change. However, electricity storage batteries do not qualify for any subsidies.

When the household installs a heat pump with solar thermal, the cost reaches 13527€. MaPrimeRénov can now finance the 2250 € of the solar thermal cost and 5000€ of the heat pump cost. In addition, the household can benefit from 4523€ Coup de pouce [33], which is not combined with CEE. [34] The remaining household cost of 1754€ can be financed through the Éco-PTZ, as both the solar thermal system and the heat pump qualify under this scheme. This gives a discounted gain of 653.81€ (see Appendix E). The total of renewable subsidies is 12426.81€, leading to a net surplus change of 23462.24€.

The results show that the installation of solar PV alone generates a low positive net surplus, but a negative one when they are installed with a battery system. However, all other scenarios where the solar thermal is a part of the investment generate a positive net surplus. Among them, Scenario 5, when solar thermal collectors are coupled with solar PV and thermal storage systems, is the most profitable for the household, yielding a net surplus increase of 24981.64€.

7 Conclusion

This study introduces a novel economic model to assess the economic gains, at the household level, of adopting an integrated renewable energy system that combines solar thermal, solar photovoltaic, heat pumps, thermal and battery storage. The results demonstrate that, within the framework of current French financial aid, such as reduced VAT rates, MaPrimeRénov, Coup de pouce chauffage,

[33] Can be translated as heating boost scheme.

[34] Can be translated as heating upgrade grant. If the household benefits from CEE subsidies, it is not eligible for the Coup de pouce heating scheme. In other words, the two forms of subsidy are incompatible; choosing the CEE excludes the household from the Coup de pouce scheme. see https://www.viessmann.fr/content/dam/public-brands/fr/solutions/rÃl'sidentiel/aides-financieres/A4-AidesRÃl'noEnerg2025_01.2025.pdf/_jcr_content/renditions/original./A4-AidesRÃl'noEnerg2025_01.2025.pdf

CEE scheme, and Eco-PTZ loans, these investments can be economically viable, particularly for very low-income households, except the investment in solar PV with battery storage due to a lack of subsidies. Of all the combinations analyzed, solar thermal systems coupled with solar PV and thermal storage proved to be the most financially advantageous, generating a net surplus in excess of 24981.64€ thanks to the almost total coverage of installation costs by public subsidies. These results underline the essential role of thermal energy and heating optimization in renewable energy strategies. In contrast, solar photovoltaic systems generate a small net surplus on their own, but a negative surplus when combined with storage batteries. This is of limited economic interest, as batteries are not subsidized and support for solar photovoltaics is very low.

A deadweight effect is detected in subsidies distribution especially for solar thermal and heat pump systems, as the surplus exceeds largely their installation costs. A redistribution of these subsidies is therefore necessary. French policy-makers can reduce subsidies for these systems, but must increase those for photovoltaic systems and batteries. The analysis highlights how targeted public support can maximize both financial and environmental benefits for households. The proposed model serves as a decision-support tool for policy-makers, highlighting the need to maintain and adjust support to promote energy efficiency and the integration of residential renewable energy systems. An improvement in the support framework for solar PV and battery systems is therefore needed in France. Measures such as reducing the VAT rate to 5.5% (instead of 20%) for battery storage, combined with an increase in the self-consumption grant for solar PV systems, could significantly improve their profitability and accelerate their deployment. The model can be used in different locations and geographic areas, providing policymakers with the possibility to design effective and region-specific energy policies.

Acknowledgements

The author would like to thank Prof. Aude Pommeret for her invaluable guidance and supervision throughout this research. This work was supported by the University of Savoie Mont Blanc and the IREGE (Research Institute in Management and Economics). The author also acknowledges the resources provided by the PhD CIFRE contract in collaboration with Viessmann France. The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aboelwafa, O., Fateen, S.-E. K., Soliman, A., and Ismail, I. M. (2018). A review on solar rankine cycles: Working fluids, applications and cycle modifications. *Renewable and Sustainable Energy Reviews*, 82:868–885.

ADEME (2019). Consommation d'énergie par usage dans le résidentiel. Technical report, Agence de la transition écologique, Angers, France.

ADEME (2021). Agence de la transition écologique. Technical report, ADEME.

Ali, M., Irfan, M., Ozturk, I., and Rauf, A. (2022). Modeling public acceptance of renewable energy deployment: a pathway towards green revolution. *Economic Research-Ekonomska Istraživanja*, 36(2):2159849.

Calise, F., Dentice d'Accadia, M., Figaj, R. D., and Vanoli, L. (2016). A novel solar-assisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization. *Energy*, 95:346–366.

Cui, Y., Zhu, J., Zoras, S., Qiao, Y., and Zhang, X. (2020). Energy performance and life cycle cost assessments of a photovoltaic/thermal assisted heat pump system. *Energy*, 206:118108.

Dato, P., Durmaz, T., and Pommeret, A. (2020). Smart grids and renewable electricity generation by households. *Energy Economics*, 86:104511.

Durmaz, T., Pommeret, A., and Ridley, I. (2022). The welfare gains for prosumers. Available at SSRN: https://ssrn.com/abstract=4086415.

Emmi, G., Tisato, C., Zarrela, A., and De Carli, M. (2016). Multi-source heat pump coupled with a photovoltaic thermal (pvt) hybrid solar collectors technology: A case study in residential application. *Int. J. Energy Prod. Manag.*, 1(4):382–392.

European Commission (2023). Heat pumps.

Eze, F., Egbo, M., Anuta, U. J., et al. (2024). A review on solar water heating technology: Impacts of parameters and techno-economic studies. *Bull Natl Res Cent*, 48(29).

Gollier, C. (2001). *The Economics of Risk and Time*. MIT Press, Cambridge, MA.

Hadorn, J.-C., editor (2015). *Solar and Heat Pump Systems for Residential Buildings*. Ernst & Sohn.

Heiskanen, E. and Matschoss, K. (2017). Understanding the uneven diffusion of building-scale renewable energy systems: A review of household, local and country level factors in diverse european countries. *Renewable and Sustainable Energy Reviews*, 75:580–591.

IEA (2022). International energy analysis 2022. Technical report, International Energy Agency.

IEA (2024). Electricity 2024: Analysis and forecast to 2026. Technical report, IEA, Paris.

Leonzio, G. (2017). Solar systems integrated with absorption heat pumps and thermal energy storages: state of art. *Renewable and Sustainable Energy Reviews*, 70:492–505.

Li, J., Zhang, Y., et al. (2024). Energy–poverty–inequality SDGs: A large-scale household analysis and forecasting in China. *Proceedings of the National Academy of Sciences (PNAS)*, 121(1):e2408167121.

Luthander, R., Widén, J., Nilsson, D., and Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy*, 142:80–94.

Ministère de la transition écologique (2021). Re2020 réglementation environnementale, eco-construire pour le confort de tous. Technical report.

Ministère de la Transition écologique (2025). Stratégie nationale bas-carbone et programmation pluriannuelle de l'énergie : Vers la neutralité carbone 2050. Rapport de synthèse, République Française.

Obalanlege, M. A., Mahmoudi, Y., Douglas, R., Ebrahimnia-Bajestan, E., Davidson, J., and Bailie, D. (2020). Performance assessment of a hybrid photovoltaic-thermal and heat pump system for solar heating and electricity. *Renewable Energy*, 148:558–572.

Palomba, V., Dino, G. E., and Frazzica, A. (2022). Analysis of the potential of solar-assisted heat pumps: Technical, market, and social acceptance aspects. *Solar RRL*.

Qingyang, J., Yang, J., Zeng, Y., and Fu, H. (2021). Energy and exergy analyses of pv, solar thermal

and photovoltaic/thermal systems: a comparison study. *International Journal of Low-Carbon Technologies*, 16(2):604–611.

Ramos, A., Cabal, M., del Cañizo, C., and Datas, A. (2017). Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment. *Energy Conversion and Management*, 149:77–88.

SDES (2025). Bilan énergétique de la France pour 2023. Datalab, Ministère de la Transition écologique, de l'Énergie, du Climat et de la Prévention des risques, Paris, France.

Sharma, A. K., Sharma, S. C., Mullick, S. C., and Kandpal, T. C. (2017). Solar industrial process heating: A review. *Renewable and Sustainable Energy Reviews*, 78:124–137.

Sporleder, M., Rath, M., and Ragwitz, M. (2024). Solar thermal vs. pv with a heat pump: A comparison of different charging technologies for seasonal storage systems in district heating networks. *Energy Conversion and Management: X*, 22:100564.

Usman, M., Kilic, H. S., and Calautit, J. K. (2022). A methodology for multi-criteria assessment of renewable integrated energy supply options and hvac systems in a household. *Energy and Buildings*, 273:112397.

Wang, X., Xia, L., Bales, C., Zhang, X., Copertaro, B., Pan, S., and Wu, J. (2020). A systematic review of recent air source heat pump (ashp) systems assisted by solar thermal, photovoltaic and photovoltaic/thermal sources. *Renewable Energy*, 146:2472–2487.

Yadav, A. S. and Gattani, A. (2022). Solar thermal air heater for sustainable development. *Materials Today: Proceedings*, 60:80–86.

Appendix

Appendix A: Optimal electricity storage

$\mathscr{L}_{3,4}(.) = U_3(y\overline{K}_{th} + Ah_3^{\mu} - s_{th_3} + \psi s_{th_2}, y\overline{K} + g_3 - s_3 - h_3 + \phi s_2) - p_3 g_3 + U_4(Ah_4^{\mu} + \psi s_{th_3}, g_4 + \phi s_3 - h_4) - p_4 g_4 + \eta_3 s_3 + \upsilon_3(\overline{s} - s_3)$

$\frac{\mathscr{L}_{3,4}(.)}{\partial s_3} = 0$

$-\delta(y\overline{K} + g_3 - s_3 - h_3 + \phi s_2 - \overline{e})^{-\gamma} + \phi\ \delta(g_4 + \phi s_3 - h_4 - \overline{e})^{-\gamma} + \eta_3 - \upsilon_3 = 0$

The first-order conditions for optimal grid electricity purchases imply $\delta(e_4 - \overline{e})^{-\gamma} = p_4$ and $\delta(e_3 - \overline{e})^{-\gamma} = p_3$

We find $-p_3 + \phi p_4 = \upsilon_3 - \eta_3$

Appendix B: Optimal thermal storage

$\mathscr{L}_{3,4}(.) = U_3(y\overline{K}_{th} + Ah_3^{\mu} - s_{th_3} + \psi s_{th_2}, y\overline{K} + g_3 - s_3 - h_3 + \phi s_2) - p_3 g_3 + U_4(Ah_4^{\mu} + \psi s_{th_3}, g_4 + \phi s_3 - h_4) - p_4 g_4 + \lambda_3 s_{th_3} + \alpha_3(\overline{s}_{th} - s_{th_3})$

We have $U_{i,j}^c = aT_{ind}^2 + bT_{ind} + c$, the roots of this quadratic function are $T_{ind} = 15$ and $T_{ind} = 27$. These two conditions allow us to find the coefficients b and c as a function of a, we find $b = -42a$, and $c = 405a$ (see the value of a in appendix D).

$U_3^c = a(T_{ind_3})^2 + b(T_{ind_3}) + c$

$U_3^c = a(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu})^2 + b(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu}) + c$

$\frac{\partial U_3^c}{\partial s_{th_3}} = -2a(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu}) - b$

$\frac{\partial U_3^c}{\partial s_{th_3}} = -2a(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu}) + 42a$

$\frac{\partial U_3^c}{\partial s_{th_3}} = -2a(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu} - 21)$

$U_4^c = a(T_{out_4} + \psi s_{th_3} + Ah_4^{\mu})^2 + b(T_{out_4} + \psi s_{th_3} + Ah_4^{\mu}) + c$

$\frac{\partial U_4^c}{\partial s_{th_3}} = 2a\psi(T_{out_4} + \psi s_{th_3} + Ah_4^{\mu}) + b\psi$

$\frac{\partial U_4^c}{\partial s_{th_3}} = 2a\psi(T_{out_4} + \psi s_{th_3} + Ah_4^{\mu} - 21)$

$\frac{\partial}{\partial s_{th_3}}(\lambda_3 s_{th_3} + \alpha_3(\bar{s}_{th} - s_{th_3}) = \lambda_3 - \alpha_3$

$\frac{\partial \mathscr{L}_{3,4}(.)}{\partial s_{th_3}} = -2a(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu} - 21) + 2a\psi(T_{out_4} + \psi s_{th_3} + Ah_4^{\mu} - 21) + \lambda_3 - \alpha_3 = 0$

For an interior solution we have $\alpha_3 = \lambda_3 = 0$, we get:

$-2a(T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} - s_{th_3} + Ah_3^{\mu} - 21) + 2a\psi(T_{out_4} + \psi s_{th_3} + Ah_4^{\mu} - 21) = 0$

$s_{th_3} + \psi^2 s_{th_3} - (T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} + Ah_3^{\mu} - 21) + \psi(T_{out_4} + Ah_4^{\mu} - 21) = 0$

$$s_{th_3}^* = \frac{T_{out_3} + y\overline{K}_{th} + \psi s_{th_2} + Ah_3^{\mu} - \psi(T_{out_4} + Ah_4^{\mu}) - 21(1-\psi)}{1+\psi^2}$$

If $s_{th_3}^* < 0$ then $s_{th_3} = 0$ and $\lambda_3 > 0$

If $s_{th_3}^* > \bar{s}_{th}$ then $s_{th_3} = \bar{s}_{th}$ and $\alpha_3 > 0$

Following the same methodology, the optimal thermal storage in period 2 is :

$$s_{th_2}^* = \frac{T_{out_2} + x\overline{K}_{th} + Ah_2^{\mu} - \psi(T_{out_3} + y\overline{K}_{th} + Ah_3^{\mu} - s_{th_3}) - 21(1-\psi)}{1+\psi^2}$$

As thermal storage is interdependent, we use backward substitution. We solve first for optimal thermal storage in the third period ($s_{th_3}^*$), then we use it to find the optimal thermal storage of the previous period ($s_{th_2}^*$).

$$s_{th_3}^* = \frac{T_{out_3} + y\overline{K}_{th} + \psi\left(\frac{T_{out_2} + x\overline{K}_{th} + Ah_2^{\mu} - \psi(T_{out_3} + y\overline{K}_{th} + Ah_3^{\mu} - s_{th_3}) - 21(1-\psi)}{1+\psi^2}\right) + Ah_3^{\mu} - \psi(T_{out_4} + Ah_4^{\mu}) - 21(1-\psi)}{1+\psi^2}$$

$$s^*_{th_3}\left(1-\frac{\psi^2}{(1+\psi^2)^2}\right)=\frac{T_{out_3}+y\overline{K}_{th}+\psi\left(\frac{T_{out_2}+x\overline{K}_{th}+Ah_2^{\mu}-\psi(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu})-21(1-\psi)}{1+\psi^2}\right)+Ah_3^{\mu}-\psi(T_{out_4}+Ah_4^{\mu})-21(1-\psi)}{1+\psi^2}$$

$$s^*_{th_3}\left(\frac{1+\psi^2+\psi^4}{(1+\psi^2)^2}\right)=\frac{(1+\psi^2)(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu}-\psi(T_{out_4}+Ah_4^{\mu})-21(1-\psi))}{(1+\psi^2)^2}+\frac{\psi\left(T_{out_2}+x\overline{K}_{th}+Ah_2^{\mu}-\psi(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu})-21(1-\psi)\right)}{(1+\psi^2)^2}$$

$$s^*_{th_3}=\frac{\left(1+\psi^2\right)\left(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu}-\psi(T_{out_4}+Ah_4^{\mu})-21(1-\psi)\right)+\psi\left(T_{out_2}+x\overline{K}_{th}+Ah_2^{\mu}-\psi(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu})-21(1-\psi)\right)}{1+\psi^2+\psi^4}$$

$$s^*_{th_2}=\frac{T_{out_2}+x\overline{K}_{th}+Ah_2^{\mu}-\psi\left(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu}-\left(\frac{T_{out_3}+y\overline{K}_{th}+\psi s_{th_2}+Ah_3^{\mu}-\psi(T_{out_4}+Ah_4^{\mu})-21(1-\psi)}{1+\psi^2}\right)\right)-21(1-\psi)}{1+\psi^2}$$

$$\mathrm{s}^*_{th_2}=\frac{\left(1+\psi^2\right)\left(T_{out_2}+x\overline{K}_{th}+Ah_2^{\mu}-\psi(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu})-21(1-\psi)\right)}{(1+\psi^2)^2}+\psi\left(\frac{T_{out_3}+y\overline{K}_{th}+\psi s_{th_2}+Ah_3^{\mu}-\psi(T_{out_4}+Ah_4^{\mu})-21(1-\psi)}{(1+\psi^2)^2}\right)$$

$$s^*_{th_2}=\frac{\left(1+\psi^2\right)\left(T_{out_2}+x\overline{K}_{th}+Ah_2^{\mu}-\psi(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu})-21(1-\psi)\right)+\psi\left(T_{out_3}+y\overline{K}_{th}+Ah_3^{\mu}-\psi(T_{out_4}+Ah_4^{\mu})-21(1-\psi)\right)}{1+\psi^2+\psi^4}$$

Appendix C: Calibration of parameter a

The comfort utility function is specified as a quadratic function of indoor temperature $U^c(T_{ind}) = aT_{ind}^2 + bT_{ind} + c$. We assume that maximum utility is reached at $T_{ind} = 21C$, and that utility is zero outside the temperature range [15,27], We can therefore obtain a utility at $T_{ind} = 21$ which is $U^c(21) = a(-36)$ as $b = -42a$ and $c = 405a$.

We focus specifically on the Winter and Fall seasons to ensure that the parameter a reflects the behavioral threshold where the household actively balances heat pump consumption against thermal comfort. To isolate a, we apply the first-order condition of the Lagrangian with respect to

heat pump energy (h_t) for each individual period. For example, considering Period 3 during the Winter season, the value of a is extracted from the optimality condition as follows:

$$\frac{\partial U_{W,3}}{\partial h_{W,3}} = 0$$

$$a = \frac{\delta(e_{w,3} - \bar{e}_{w,3})^{-\gamma}}{2A\mu h_{w,3}^{\mu-1}(T_{out_{w,3}} + y\bar{K_{th}} - s_{th_{w,3}} + \psi s_{th_{w,2}} + Ah_{w,3}^{\mu} - 21)} \tag{5}$$

Using the outside temperature, solar thermal generation, heat from solar thermal stored in the buffer tank and heat pump consumption, we isolate a discrete estimate for the parameter a within each temporal interval. We repeat this calculation for every period of the winter and fall seasons. After that, we calculate independent mean values for both seasons. The final value adopted for our simulation, $a = -0.00008632$, is derived from the average of these two seasonal means.

Appendix D: Computation of gain from EPTZ

The constant annual payment A over N years of a B€ loan at a $i\%$ interest rate is :

$A = \frac{Bi}{1-(1+i)^{-N}}$. Hence for $B = 1754$€, $N = 15$ and $i = 6.49\%$, we obtain $A = 186.42$€. If there is no interest payment, we have $A_0 = \frac{1754}{15} = 116.93$€. $A - A_0 = 69.49$€ is the annual gain. The total discounted gain is then $(A - A_0)\frac{1-(1+i)^{-N}}{i} = 653.81$€.

Appendix E: Detailed results

Table 4 : Daily Surplus for all scenarios.

	Summer	Fall	Winter	Spring	Total
S1	-20.1127	-24.2640	-26.454060	-20.4668	-22.7015
S2	-20.1104	-24.2639	-26.454050	-20.4664	-22.7007
S3	-19.0022	-23.9170	-25.956692	-19.4572	-21.9564
S4	-18.7615	-23.6765	-25.716225	-19.216770	-21.7159
S5	-18.9999	-23.9169	-25.956680	-19.4568	-21.9557
S6	-18.7549	-23.6764	-25.716213	-19.2163	-21.7152
S7	-20.1127	-24.2275	-26.410738	-20.4628	-22.6811
S8	-20.1104	-24.2273	-26.410716	-20.4626	-22.6804
S9	-19.0022	-23.8805	-25.934781	-19.4531	-219407
S10	-18.9999	-23.8803	-25.934755	-19.4529	-21.9401
S11	-18.7549	-23.1493	-25.265844	-19.2124	-21.4738
S12	-20.2910	-30.3111	-34.3770	-26.1881	-27.5601
S13	-21.4015	-30.6548	-34.4346	-27.1978	-28.2090
S14	-20.0505	-30.0702	-34.0859	-25.9476	-27.3085

Scenario 11, when the household installs a solar thermal with solar PV, heat pump, thermal storage, and battery storage, represents the most profitable scenario. The household can use the solar thermal and heat pump for heating and the solar PV for daily needs.

Table 5 Grid purchase

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Fall g1	7.928	7.928	7.928	14.428	7.928	14.428	7.940	7.940	7.940	7.940	14.440	17.313	17.313	23.8130
Fall g2	9.082	9.082	8.408	2.233	8.408	2.233	9.091	9.091	8.416	8.416	1.923	18.034	18.701	11.857
Fall g3	5.935	5.935	4.704	4.704	4.704	4.704	5.941	5.941	4.710	4.710	4.710	11.655	12.886	11.655
Fall g4	7.976	7.976	7.976	7.976	7.976	7.976	7.984	7.984	7.984	7.984	7.984	16.557	16.557	16.557
Winter g1	11.555	11.555	11.555	18.0549	11.555	18.054	11.569	11.569	11.569	11.569	18.069	22.165	22.165	28.6658
Winter g2	12.791	12.791	11.183	5.008	11.183	5.008	12.801	12.801	11.278	11.278	4.970	24.288	24.779	17.8354
Winter g3	9.100	9.100	7.886	7.886	7.886	7.886	9.018	9.018	7.902	7.902	7.902	16.666	17.752	16.666
Winter g4	10.367	10.367	10.367	10.367	10.367	10.367	10.377	10.377	10.377	10.377	3.877	22.745	22.745	22.745
Spring g1	0.993	0.993	0.993	7.493	0.993	7.493	0.996	0.996	0.996	0.996	7.496	13.584	13.584	20.084
Spring g2	2.533	2.533	0.322	-5.852	0.322	-5.852	2.533	2.533	0.322	0.323	-5.852	12,336	14,546	6.161
Spring g3	2.302	2.302	-1.032	-1.032	-1.032	-1.032	2.302	2.302	-1.032	-1.032	-1.032	3.857	7.192	3.857
Spring g4	2.933	2.933	2.933	2.933	2.933	2.933	2.933	2.933	2.933	2.933	2.933	10.207	10.207	10.207
Summer g1	0.797	0.797	0.797	7.297	0.797	7.297	0.797	0.797	0.797	0.797	7.297	0.920	0.920	7.420
Summer g2	1.709	1.709	-0.752	-6.927	-0.752	-6.927	1.709	1.709	-0.752	-0.752	-6.927	1.208	3.670	-4.996
Summer g3	1.798	1.798	-1.838	-1.838	-1.838	-1.838	1.798	1.798	-1.838	-1,838	-1.838	-1,115	2,520	-1.115
Summer g4	2,468	2,468	2,468	2,468	2,468	2,468	2,468	2,468	2,468	2,468	2,468	3,383	3,383	3.383

Table 6 Solar thermal generation

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Fall eth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fall eth2	0.9728	0.9728	0.9728	0.9728	0.9728	0.9728	0.9728	0.9728	0.9728	0.9728	0.9728	0	0	0
Fall eth3	1.3050	1.3050	1.3050	1.3050	1.3050	1.3050	1.3050	1.3050	1.3050	1.3050	1.3050	0	0	0
Fall eth4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter eth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter eth2	1.0883	1.0883	1.0883	1.0883	1.0883	1.0883	1.0883	1.0883	1.0883	1.0883	1.0883	0	0	0
Winter eth3	1.4174	1.4174	1.4174	1.4174	1.4174	1.4174	1.4174	1.4174	1.4174	1.4174	1.4174	0	0	0
Winter eth4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring eth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring eth2	2.5486	2.5486	2.5486	2.5486	2.5486	2.5486	2.5486	2.5486	2.5486	2.5486	2.5486	0	0	0
Spring eth3	4.0980	4.0980	4.0980	4.0980	4.0980	4.0980	4.0980	4.0980	4.0980	4.0980	4.0980	0	0	0
Spring eth4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer eth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer eth2	3.3473	3.3473	3.3473	3.3473	3.3473	3.3473	3.3473	3.3473	3.3473	3.3473	3.3473	0	0	0
Summer eth3	4.8820	4.8820	4.8820	4.8820	4.8820	4.8820	4.8820	4.8820	4.8820	4.8820	4.8820	0	0	0
Summer eth4	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7 Solar PV generation

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Fall ePV1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fall ePV2	0	0	0.6744	0.6744	0.6744	0.6744	0	0	0.6744	0.6744	0.6744	0.6744	0	0.6744
Fall ePV3	0	0	1.2312	1.2312	1.2312	1.2312	0	0	1.2312	1.2312	1.2312	1.2312	0	1.2312
Fall ePV4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter ePV1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter ePV2	0	0	1.6072	1.6072	1.6072	1.6072	0	0	1.6072	1.6072	1.6072	1.6072	0	1.6072
Winter ePV3	0	0	1.1240	1.1240	1.1240	1.1240	0	0	1.1240	1.1240	1.1240	1.1240	0	1.1240
Winter ePV4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring ePV1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring ePV2	0	0	2.2101	2.2101	2.2101	2.2101	0	0	2.2101	2.2101	2.2101	2.2101	0	2.2101
Spring ePV3	0	0	3.3344	3.3344	3.3344	3.3344	0	0	3.3344	3.3344	3.3344	3.3344	0	3.3344
Spring ePV4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer ePV1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer ePV2	0	0	2.4618	2.4618	2.4618	2.4618	0	0	2.4618	2.4618	2.4618	2.4618	0	2.4618
Summer ePV3	0	0	3.6366	3.6366	3.6366	3.6366	0	0	3.6366	3.6366	3.6366	3.6366	0	3.6366
Summer ePV4	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8 Thermal storage

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Fall sth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fall sth2	0	0.0816	0	0	0.0816	0.0816	0	0.1064	0	0.1064	0.1064	0	0	0
Fall sth3	0	0.0892	0	0	0.0892	0.0892	0	0.1387	0	0.1387	0.1387	0	0	0
Fall sth4	0	0.0758	0	0	0.0758	0.0758	0	0.1179	0	0.1179	0.1179	0	0	0
Winter sth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter sth2	0	0.0067	0	0	0.0067	0.0067	0	0.0134	0	0.0134	0.0134	0	0	0
Winter sth3	0	0.0113	0	0	0.0113	0.0113	0	0.0287	0	0.0287	0.0287	0	0	0
Winter sth4	0	0.0096	0	0	0.0096	0.0096	0	0.0244	0	0.0244	0.0244	0	0	0
Spring sth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring sth2	0	0.0486	0	0	0.0486	0.0486	0	0	0	0	0	0	0	0
Spring sth3	0	0.6610	0	0	0.6610	0.6610	0	0.7421	0	0.7421	0.7421	0	0	0
Spring sth4	0	0.5618	0	0	0.5618	0.5618	0	0.6308	0	0.6308	0.6308	0	0	0
Summer sth1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer sth2	0	0.1250	0	0	0.1250	0.1250	0	0.1250	0	0.1250	0.1250	0	0	0
Summer sth3	0	3.1713	0	0	3.1713	3.1713	0	3.1713	0	3.1713	3.1713	0	0	0
Summer sth4	0	2.6956	0	0	2.6956	2.6956	0	2.6956	0	2.6956	2.6956	0	0	0

Table 9 Heat pump electricity consumption

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Fall h1	0	0	0	0	0	0	0.0123	0.0123	0.0123	0.0123	0.0123	0	0	0
Fall h2	0	0	0	0	0	0	0.0083	0.0083	0.0083	0.0083	0.0083	0	0	0
Fall h3	0	0	0	0	0	0	0.0064	0.0064	0.0064	0.0064	0.0064	0	0	0
Fall h4	0	0	0	0	0	0	0.0079	0.0079	0.0079	0.0079	0.0079	0	0	0
Winter h1	0	0	0	0	0	0	0.0149	0.0149	0.0149	0.0149	0.0149	0	0	0
Winter h2	0	0	0	0	0	0	0.0102	0.0102	0.0102	0.0102	0.0102	0	0	0
Winter h3	0	0	0	0	0	0	0.0078	0.0078	0.0078	0.0078	0.0078	0	0	0
Winter h4	0	0	0	0	0	0	0.0094	0.0094	0.0094	0.0094	0.0094	0	0	0
Spring h1	0	0	0	0	0	0	0.0031	0.0031	0.0031	0.0031	0.0031	0	0	0
Spring h2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring h3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring h4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer h1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer h2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer h3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summer h4	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10 Utility

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Fall util1	-4.797	-4.797	-4.797	-4.797	-4.797	-4.797	-4.785	-4.785	-4.785	-4.785	-4.785	-4.902	-4.902	-4.902
Fall util2	-4.773	-4.773	-4.773	-4.773	-4.773	-4.773	-4.767	-4.767	-4.767	-4.767	-4.767	-4.876	-4.876	-4.876
Fall util3	-4.729	-4.729	-4.729	-4.729	-4.729	-4.729	-4.720	-4.720	-4.720	-4.720	-4.720	-4.876	-4.876	-4.876
Fall util4	-4.734	-4.734	-4.734	-4.734	-4.734	-4.734	-4.723	-4.723	-4.724	-4.723	-4.723	-4.876	-4.876	-4.876
Winter util1	-4.805	-4.805	-4.805	-4.805	-4.805	-4.805	-4.791	-4.791	-4.791	-4.791	-4.791	-4.902	-4.902	-4.902
Winter util2	-4.744	-4.744	-4.744	-4.744	-4.744	-4.744	-4.731	-4.731	-4.734	-4.734	-4.330	-4.876	-4.876	-4.876
Winter util3	-4.734	-4.734	-4.734	-4.734	-4.734	-4.734	-4.724	-4.724	-4.724	-4.724	-4.724	-4.876	-4.876	-4.876
Winter util4	-4.740	-4.740	-4.740	-4.740	-4.740	-4.740	-4.728	-4.728	-4.728	-4.728	-4.728	-4.876	-4.876	-4.876
Spring util1	-4.776	-4.776	-4.776	-4.776	-4.776	-4.776	-4.772	-4.772	-4.772	-4.772	-4.772	-4.902	-4.902	-4.902
Spring util2	-4.715	-4.715	-4.715	-4.715	-4.715	-4.715	-4.715	-4.715	-4.715	-4.715	-4.715	-4.876	-4.876	-4.876
Spring util3	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.711	-4.711	-4.711	-4.712	-4.712	-4.876	-4.876	-4.876
Spring util4	-4.713	-4.712	-4.713	-4.713	-4.712	-4.712	-4.713	-4.712	-4.713	-4.712	-4.712	-4.876	-4.876	-4.876
Summer util1	-4.771	-4.771	-4.771	-4.771	-4.771	-4.771	-4.771	-4.771	-4.771	-4.771	-4.771	-4.902	-4.902	-4.902
Summer util2	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.712	-4.876	-4.876	-4.876
Summer util3	-4.719	-4.715	-4.719	-4.719	-4.715	-4.715	-4.719	-4.715	-4.719	-4.715	-4.715	-4.876	-4.876	-4.876
Summer util4	-4.712	-4.714	-4.712	-4.712	-4.714	-4.714	-4.712	-4.714	-4.712	-4.714	-4.714	-4.876	-4.876	-4.876