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A Comparative Analysis of Solar Thermal and Photovoltaic Systems with Heat-Pump Integration in a New-Build House Under Controlled Conditions

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Abstract: This study investigates the relative benefits of solar thermal (ST) and photovoltaic (PV) systems integrated with air-source heat pumps for domestic hot water production in newly built residential buildings. Using calibrated DesignBuilder simulations of "The Future Home" located in Energy House 2.0, an environmental chamber, the study analyzes energy performance and carbon emissions for eight scenarios: (1) baseline heat pump only, (2) heat pump with 4 m^2 PV panels, (3) heat pump with 4 m^2 ST panels, (4) heat pump with 2 m^2 PV + 2 m^2 ST panels, and (5–8) variants with increased hot water demand. While ST systems directly heat water through thermal energy transfer, PV systems contribute to water heating indirectly by providing electricity to power the heat pump. The results show that the ST system provides 964.6 kWh of thermal energy annually, increasing to 1528 kWh with enhanced hot water demand, while a similarly sized PV system generates 532.5 kWh of electricity. The research reveals that Standard Assessment Procedure methodology's fixed hot water demand assumptions could significantly underpredict solar thermal benefits, potentially discouraging UK house builders from adopting this technology.

Keywords: solar thermal; solar photovoltaic; dynamic thermal simulation; heat pump; domestic hot water heating; the future home; environmental chamber; controlled conditions; calibrated model

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1. Introduction

The UK's legally binding commitment to reach net zero by 2050 has pushed the residential sector to the foreground [1], as homes account for roughly 17% of the nation's direct CO_2 emissions [2]. The forthcoming Future Homes Standard (FHS) will require all new dwellings to be zero carbon ready and deliver 75% carbon savings compared to the 2013 edition of UK energy standards [3,4]. Parallel to the implementation of the FHS, the Standard Assessment Procedure (SAP), the UK's official method for assessing and comparing the energy performance of residential buildings, is undergoing significant updates [5]. The government has confirmed that SAP 10.2 will be replaced by the open-source Home Energy Model (HEM, also referred to as SAP 11 in draft form), which will be introduced alongside the FHS [6].

1.1. Problem Statement

Most decarbonisation roadmaps for new-build housing rely primarily on air-source heat pumps (ASHPs) [3,7,8]. However, as the output temperature increases when delivering domestic hot water (DHW) at temperatures around 55 °C [9], real-world seasonal performance factors (SPF) are often 30–40% lower than laboratory or manufacturer-stated efficiencies, particularly during colder months [10,11]. In some homes, this phenomenon means there may be insufficient capacity to run both space heating and hot water via a heat pump alone. As introduction of heat pumps in all UK homes would "more than double peak GB electricity demand" [12]; currently, there is insufficient electrical power capacity to support a wide heat-pump rollout. Integrating solar thermal could therefore help reduce the hot water load on the heat-pump system [13]. Hence, the introduction of solar thermal systems can be seen as an enabling factor for heat-pump installations in these circumstances. Given these technical complexities, there is a clear need for systematic evaluations that can reliably inform policy and practice.

1.2. Contribution of This Research

This research distinctly contributes to addressing these technical complexities by systematically evaluating renewable energy systems, specifically photovoltaic (PV) and solar thermal (ST), integrated with heat-pump systems under controlled yet realistic conditions. The study evaluates energy performance and carbon emissions across multiple system configurations and hot water demand scenarios. To achieve the aim, this study utilizes "The Future Home" (TFH), built by Bellway Developments, a three-bedroom detached home built using timber frame construction (Figure 1a). It is located in Energy House 2.0 environmental chamber one, a research facility featuring two environmental chambers capable of simulating extreme weather conditions from −24 °C to +51 °C, including wind, rain, snow, and solar radiation [14]. DesignBuilder (v7.3.0.044), incorporating EnergyPlus (v9.4) as its simulation engine, was used to develop the Dynamic Thermal Simulation (DTS) models due to its capability to model complex interactions within building systems dynamically [15]. A comprehensive DesignBuilder model was developed to evaluate the energy performance of Bellway's TFH from an earlier dataset [16] (Figure 1b). The model calibration involved updating as-built U-values measured using heat flux plates [17] and air permeability values assessed with blower door tests [18]; these testing procedures were detailed in Fitton et al. [19]. Initially, the predicted Heat Transfer Coefficient (HTC) based on design values was 75.4 W/K. After incorporating as-built measurements, the HTC increased to 81.6 W/K, aligning well with the aggregate heat-loss test measurement of 82.2 W/K [16,20–22]. The findings can inform the ongoing development and refinement of UK regulatory assessment methodologies, which underpin national building energy ratings but often rely on simplified assumptions. By employing a calibrated DesignBuilder model, this approach significantly enhances prediction accuracy and helps to identify potential discrepancies between real-world system performance and standardized modelling assumptions. Information on the building's thermal needs, heating system, and sanitary equipment will be described in full detail in Sections 3.1 and 3.2 of the paper.

Although previous studies have compared PV, ST, and hybrid PV/T systems, most have relied on default assumptions for hot water demand and have not examined how these assumptions may bias comparative outcomes (see Section 2 for a detailed literature review). The primary contribution of this study is a scenario-based comparative analysis of PV, ST, and hybrid systems using both SAP default and realistic hot water demand. This approach enables a direct quantification of how SAP regulatory methodologies may underestimate solar thermal benefits. By highlighting the policy and design implications of these findings, the study contributes to both the technical understanding and practical implementation of new-build, low-carbon homes.

(**a**) (**b**)

Figure 1. TFH in Energy House 2.0 environmental chamber one: (**a**) front elevation; (**b**) model in DesignBuilder.

1.3. Research Questions

Based on the problem statement, the following research questions have been formulated:

1. How can combined benefits of solar PV and solar thermal be evaluated when working with an air-source heat pump used for space heating and domestic hot water?
2. What is the relative benefit of solar thermal compared to PV in houses heated with air-source heat pumps?

2. Modelling PV, ST, and Hybrid PV/T Systems in Residential Buildings

Recent studies have primarily employed DTS tools such as TRNSYS, EnergyPlus, and DesignBuilder, recognized for their flexibility and accuracy in modelling solar systems in residential buildings. For PV systems, Bagalini et al. simulated a residential PV system with battery storage in Shanghai, China, demonstrating economic feasibility under projected future cost reductions for batteries and rising electricity prices, despite current limitations related to initial high costs and low electricity rates [23]. Similarly, Albatayneh et al. [24] analyzed the effects of rooftop PV arrays on residential cooling and heating loads in a humid subtropical climate. They found that PV panels effectively reduced summer cooling demands through shading but slightly increased heating loads in winter due to reduced solar gains, indicating the necessity of climate-specific analysis [24].

In studies specifically focusing on ST systems, Ma et al. utilized TRNSYS to investigate a hybrid solar-assisted heat-pump system for DHW supply in Nanjing, China, reporting substantial annual energy savings and consistent hot water provision year-round, although they identified optimization potential in system control strategies [25]. Rezapour et al. [26] performed extensive dynamic simulations across multiple climatic regions in Iran to rank the performance of residential solar water heaters. Their analysis highlighted significant variability in solar fractions due to climatic conditions, providing valuable geographical insights into optimal deployment strategies [26]. Antoniadis and Martinopoulos modelled a solar thermal system integrated with seasonal thermal storage in Thessaloniki, Greece. Their TRNSYS simulations demonstrated optimal collector sizing and storage tank configurations, achieving substantial annual solar fractions but noted diminishing returns at larger scales due to practical storage volume constraints [27].

Integrated and comparative studies evaluating both PV and ST or hybrid PV/T systems also contribute valuable insights. Da et al. [28] developed and validated a dynamic simulation model combining PV and air-source heat pumps with thermal storage in a residential context in China, achieving improved solar energy self-consumption and enhanced system efficiency. The study emphasized careful sizing and system integration for maximizing performance [28]. Calise et al. [29] investigated a novel residential-scale hybrid system combining PV/T panels, heat pumps, and solar-driven cooling systems using TRNSYS simulations. Their results demonstrated high combined thermal and electrical efficiencies across diverse Mediterranean climates, although acknowledging significant sensitivity to initial system sizing and economic factors [29]. Pater performed long-term performance simulations of hybrid PV/T systems in Poland, finding that active cooling strategies for PV/T collectors modestly increased annual electricity output, underscoring the importance of thermal management strategies to enhance overall efficiency [30]. Hawila et al. [31] explored the potential for residential 'plus-energy' buildings in Beirut, Lebanon, integrating PV arrays and solar thermal systems via TRNSYS modelling. Their simulations showed that integrated design significantly reduced energy demand and generated annual energy surpluses, highlighting opportunities for achieving net-positive residential buildings [31]. Finally, Bee et al. [32] conducted simulations of residential PV and air-source heat-pump systems across nine different European climates, demonstrating variations in self-consumption rates of solar-generated electricity. They noted substantial improvements in solar utilization when battery storage or properly sized thermal storage systems were incorporated, advocating tailored solutions for specific climatic conditions to maximize energy savings [32].

3. Materials and Methods

The methodology for answering the research questions is introduced in this section. It consists of the development of a calibrated model of the building that includes a detailed HVAC system model; the modelling of renewable energy systems, including the heat pump, solar PV, and solar thermal; and developing system integration and increased hot water demand scenarios.

3.1. Development of a Calibrated Model

Table 1 presents the parameters used as inputs for the DTS models. Note that design values are theoretical thermal performance specifications used during building planning, based on manufacturers' data. In contrast, as-built values are actual measured thermal characteristics determined through field testing after construction, which capture real-world performance that may differ from design intentions due to construction quality and material variations. The "Point Thermal Transmittance" (PTT) metric is employed for ground floors instead of U-values, as it accounts for various influencing factors such as thermal bridging, air brick impact, perimeter effect and insulation geometry [19]. For more information, the calibrated model is detailed in Tsang et al. [20], the dataset in Tsang et al. [16], and measurement results in Fitton et al. [19].

Table 1. Summary of parameters for DTS model inputs (adapted from [3]).

Building Component	Value	Type
Brick external wall U-value	0.17 W/m^{2}K	As-built
Rendered external wall U-value	0.17 W/m^{2}K	As-built
Loft ceiling U-value	0.14 W/m^{2}K	As-built
Ground floor PTT-value	0.14 W/m^{2}K	As-built
Windows U-value	1.20 W/m^{2}K	Design
Windows SHGC	0.51	Design
French Door U-value	1.40 W/m^{2}K	Design

Table 1. *Cont.*

Building Component	Value	Type
External Door U-value	1.00 W/m^{2}K	Design
Air infiltration rate @50 Pa	2.50 m^3/hm^2	As-built
Internal partition U-value	1.89 W/m^{2}K	As-built
Internal floor U-value	1.16 W/m^{2}K	As-built
Internal door U-value	2.82 W/m^{2}K	As-built

3.2. Modelling Building Energy Consumption

Once calibrated, the model integrated DesignBuilder's default occupancy patterns and internal heat gains [15]. These parameters were specified according to the UK National Calculation Method (UKNCM), which defines standardized inputs for regulatory compliance calculations in the UK [33]. The simulations were carried out using the CIBSE TRY weather file for Manchester.

Heating was supplied by a monobloc air-to-water heat-pump system, specifically the WH-MDC05J3E5, manufactured by Panasonic Corporation in Shah Alam, Malaysia, which uses R32 refrigerant (difluoromethane) and delivers 5 kW of heating at a Coefficient of Performance (CoP) of 3.01 with a 55 °C radiator heating configuration. Lighting demand was based on a standard 2.5 W/m^2/100 lux configuration.

For domestic hot water (DHW), a more detailed HVAC schematic was developed within DesignBuilder to allow for an accurate simulation of system dynamics (Figure 2). The configuration uses a 200-litre UK Cylinders indirect unvented heat-pump cylinder (WWA2000HP), manufactured by UK Cylinders Ltd. in Ossett, West Yorkshire, United Kingdom, with an external expansion tank and 3 kW immersion heater. The heat pump is configured specifically for DHW production, with a dedicated water outlet connection. This is a reasonable configuration because it aligns with commercially available products, such as the "Curv ASHP Hot Water Cylinder" used in eHome2, designed for DHW applications [34].

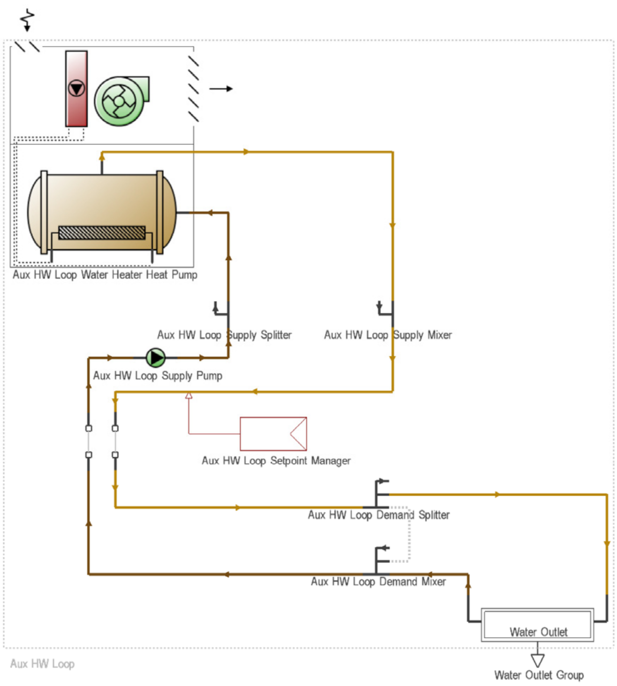


Figure 2. A schematic of the HVAC system (DHW).

It is important to note here that this setup does not occur in typical new-build homes where heat pumps are installed to provide both heating and hot water. The reason for using two storage tanks was due to a limitation of the modelling tool used which was not able to work with solar thermal and solar PV using a single tank.

3.3. Modelling Renewable Energy Systems

Building on the calibrated baseline model described in Section 3.2, this section presents the simulation of renewable energy system configurations. Eight scenarios were developed to evaluate the performance of PV and ST systems, both individually and in combination. The final two scenarios explore the impact of increased hot water demand:

1. Baseline (heat pump only);
2. Heat pump with 4 m^2 PV;
3. Heat pump with 4 m^2 ST;
4. Heat pump with 2 m^2 PV and 2 m^2 ST;
5. Baseline—increased hot water demand;
6. Heat pump with 4 m^2 ST—increased hot water demand;
7. Heat pump with 4 m^2 PV—increased hot water demand;
8. Heat pump with 2 m^2 PV and 2 m^2 ST—increased hot water demand.

3.3.1. PV System

The PV system modelling utilizes the Clearline Fusion PV16-335-G1 panels, manufactured by Viridian Solar in Papworth, Cambridge, United Kingdom [35]. Table 2 presents the key technical parameters extracted from the manufacturer's specification sheet and the corresponding inputs used in the DesignBuilder model. The PV system is modelled on the south-facing roof of TFH with a total panel area of 4 m^2. It is configured to operate at base load using a direct current (DC) setup with an inverter-based electrical bus configuration. The inverter efficiency is set at 95%, following DesignBuilder's default specifications for residential PV systems.

Table 2. Technical data of PV panel (Clearline Fusion PV16-335-G1).

Parameters	Value
Cell type	Crystalline silicon
Cells in series	60
Active area (m^2)	1.89
Rated electric power output per module (W)	250
Module heat loss coefficient (W/m^2K)	30
Peak Power (Wp)	400
Module efficiency	21.2
Short circuit current (A)	10.3
Module current at max power (A)	9.7
Temperature coefficient of short circuit current (A/K)	0.00515
Open circuit voltage (V)	42
Module voltage at max power (V)	34.7
Temperature coefficient of open circuit voltage (V/K)	−0.126

This configuration represents a typical grid-connected residential installation, where the inverter converts the DC electricity generated by the panels into alternating current (AC) power for household consumption or grid export. The PV system is modelled without battery storage to establish the baseline performance of a standard grid-connected system. It does not supply thermal energy directly to the DHW tank; instead, it supports DHW production indirectly by powering the heat pump.

3.3.2. ST System

The ST system modelling utilizes the GREENoneTEC FK8203 7one frame flat plate collector, manufactured by GREENoneTEC Solarindustrie GmbH in St. Veit an der Glan, Austria [36]. The collector's specifications, derived from the manufacturer's test report, were input into DesignBuilder and are summarized in Table 3.

Table 3. Technical data of solar thermal collectors (GREENoneTEC FK8203 7one).

Parameters	Value
Maximum flow rate (m^3/s)	0.0000810
Gross area (m^2)	2.02
Aperture area (m^2)	1.84
Test flow rate (m^3/s)	0.0000405
Efficiency Equation Coefficient 1	0.73
Efficiency Equation Coefficient 2 (W/m^2K)	−3.96
Efficiency Equation Coefficient 3 (W/m^2K^2)	−0.011
Incident Angle Modifier (IAM) Coefficient 1	1
IAM Coefficient 2	0.1386
IAM Coefficient 3	0

An additional HVAC schematic was created to simulate the DHW system incorporating solar thermal input (Figure 3). Solar thermal systems and heat pumps operate at different temperature levels, with solar thermal collectors capable of achieving significantly higher temperatures. This distinction was addressed in the model using a dual-tank configuration, each with different maximum temperature settings. The heat pump's efficiency would be compromised at elevated storage temperatures; therefore, thermal separation is essential.

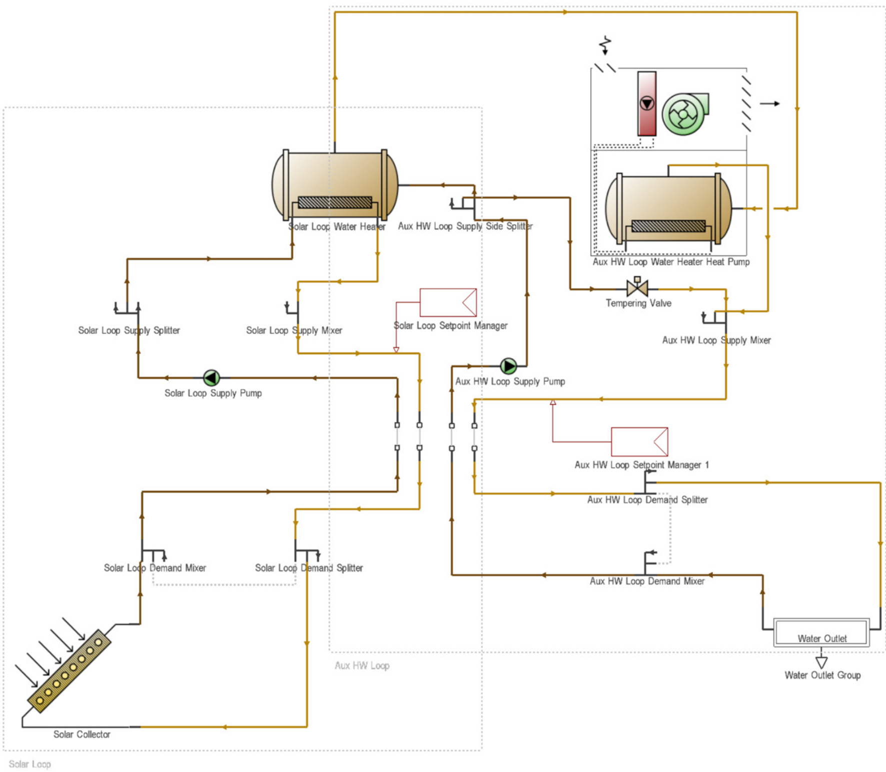


Figure 3. A schematic of the HVAC system (DHW and solar thermal).

In this setup, the solar thermal system charges the high-temperature tank when solar radiation is available, while solar PV supports the heat pump in heating the lower-temperature tank. This configuration allows both tanks to be charged simultaneously under favourable solar conditions. The dual-tank setup facilitates a clear operational boundary between the solar thermal and heat-pump systems, allowing for a precise evaluation of each system's contribution to DHW production.

It should be noted that this configuration is not typical in standard new-build homes. However, due to limitations in the modelling tool, it was necessary to adopt this arrangement to evaluate both systems independently. The rationale described above also applies here in justifying the dual-tank design.

3.3.3. Increased Hot Water Demand

Following preliminary simulations, it was identified that the default DHW consumption assumptions in DesignBuilder may limit the thermal contribution from solar thermal systems under standard occupancy conditions. This led to the creation of Scenarios 5 to 8, designed to investigate system performance under higher water demand.

DesignBuilder applies an annual DHW consumption rate of 35.14 m^3, which closely aligns with the Standard Assessment Procedure (SAP) estimate of 35.55 m^3. However, a study by Zukowski et al., conducted in Poland on solar hot water usage in an apartment building, reported significantly higher consumption levels [37]. The study recorded 1288.8 m^3 of DHW usage over a conditioned floor area of 1462.41 m^2 (equivalent to approximately 0.88 m^3 per m^2) substantially above the ~0.41 m^3/m^2 assumed in both SAP and DesignBuilder. Based on this higher usage, thermal energy generation of 469.18 kWh per m^2 of solar thermal panels was observed.

According to a Department for Energy Security and Net Zero (DESNZ) report, standard residential occupancy is defined as 2.4 persons per dwelling, with a median annual water usage of 33 m^3 [38]. The baseline model in this study, using 4 m^2 of solar thermal collectors, assumed 35.14 m^3, which closely matches both SAP and DESNZ guidance.

To simulate higher water demand conditions, the DesignBuilder model was adjusted to represent a four-person household. A multiplier of 1.67 (i.e., $4 \div 2.4$) was applied to the default DHW consumption rate, resulting in an annual hot water demand of 58.53 m^3.

4. Results and Discussion

4.1. Annual Electricity Consumption and Renewable Generation

Table 4 summarizes the electricity consumption and renewable energy generation across eight scenarios. Scenario 1 serves as the baseline case without renewable energy integration and forms the reference for comparative analysis. In this scenario, DHW electricity consumption was 1264.93 kWh, based on an annual hot water usage of 35.14 m^3 in TFH. Heating and lighting electricity consumption totaled 1198.7 kWh, yielding a combined building electricity consumption of 2463.6 kWh. These heating and lighting values remain constant across all scenarios.

In Scenario 2, the PV panels generated 532.5 kWh of electricity annually, of which 290.7 kWh was consumed on site and 241.8 kWh was exported to the grid. DesignBuilder's default occupancy pattern was used, meaning the model exports PV electricity back to the grid when on-site generation exceeds the building's electrical demand. When there are no occupants using electricity (for heating, DHW or lighting), the excess energy is exported. Note that in Scenario 2 all the DHW is supplied via the heat pump only, and it is not possible to accurately quantify the percentage of the PV generation used for DHW.

Table 4. Building electricity consumption and renewable energy generation of eight scenarios.

Scenario	Description	Renewable Generation (kWh/year)	DHW Electricity Consumption (kWh/year)	Heating and Lighting Electricity Consumption (kWh/year)	Building Electricity Consumption (kWh/year)
1	Baseline	0	1264.9	1198.7	2463.6
2	4 m^2 PV	532.5 electricity generated (241.8 exported to grid, 290.7 consumed)	1264.9	1198.7	2172.9
3	4 m^2 ST	964.6 solar thermal energy generated	944.5	1198.7	2143.2
4	2 m^2 PV + 2 m^2 ST	482.3 solar thermal energy generated and 272.2 electricity generated by PV (93.7 exported to grid, 178.5 consumed)	1104.7	1198.7	2124.9
5	Baseline—increased DHW consumption rate	0	1993.4	1198.7	3192.1
6	4 m^2 ST—increase DHW consumption rate	1528 thermal energy generated	1485.8	1198.7	2684.5
7	4 m^2 PV—increase DHW consumption rate	532.5 electricity generated (241.8 exported to grid, 290.7 consumed)	1993.4	1198.7	2901.4
8	2 m^2 PV + 2 m^2 ST—increase DHW consumption rate	764 solar thermal energy generated and 272.2 electricity generated by PV (93.7 exported to grid, 178.5 consumed)	1739.6	1198.7	2759.8

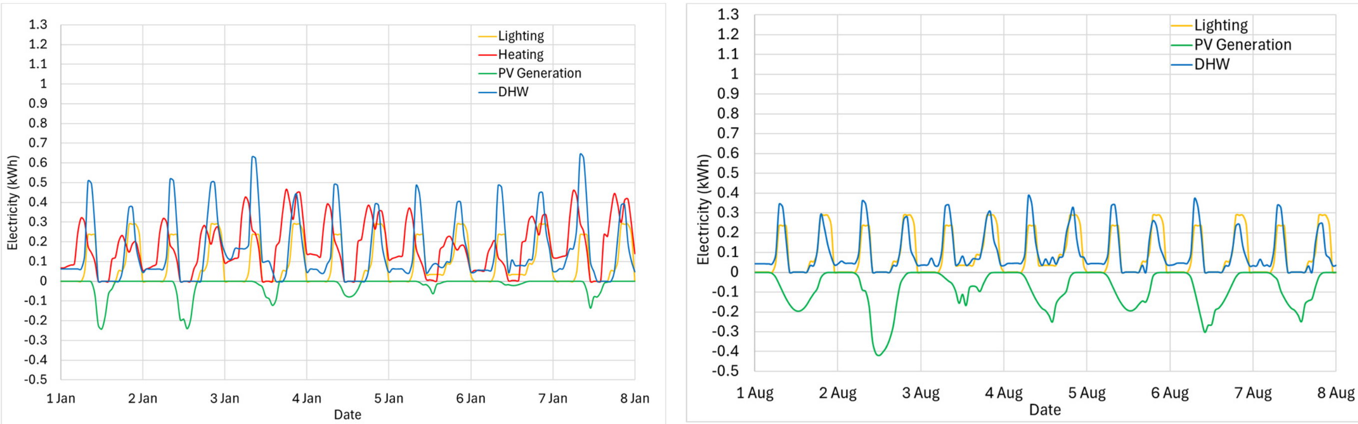
In Scenario 3, DHW electricity consumption is 944.48 kWh, saving 320.5 kWh compared to Scenario 1 (1264.9 kWh). To compare with a UK guidelines provided by the client, this saved electricity is converted to thermal energy using a COP of 3.01, resulting in 964.6 kWh. This thermal output from ST system in Scenario 3 is about 3.5 times greater than the PV system's electrical output in Scenario 2, aligning with previous studies [37].

As a result, the water supply in DesignBuilder increased to 58.53 m^3, and consequently, the ST system thermal energy generation increase from 964.6 kWh to 1528 kWh. Based on these findings, it can be predicted that a similar increase in water usage in SAP calculations would also result in higher thermal energy generation values. The heating and lighting electricity consumption did not change in Scenarios 5–8 (Table 3), since only the hot water demand was increased to align with four occupants, while the number of occupants, the occupancy pattern, and corresponding metabolic and internal gains did not change.

In the current DesignBuilder simulation environment, PV-generated electricity is treated simply as a reduction in the building's overall grid electricity consumption, without the capability to track how that solar power is specifically distributed to individual building systems like heating, DHW, and lighting. While it would be technically possible to develop custom Energy Management System (EMS) scripts to monitor and analyze these power flows in detail, implementing such a solution falls outside the scope of this study. Future work could explore developing EMS scripts to model how PV power is distributed to different building systems in real time, particularly quantifying the portion used for DHW, which would enable a more equitable comparison between ST and PV system performance. Future work could also explore battery integration scenarios using the DesignBuilder model to evaluate potential improvements in self-consumption rates and system efficiency.

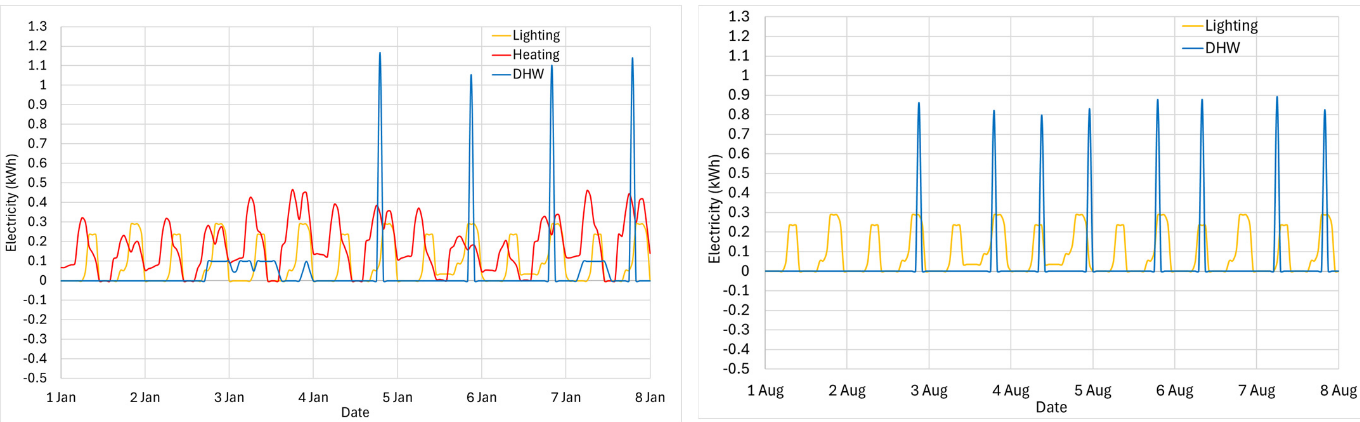
4.2. Hourly Electricity Consumption Patterns

Figure 4a shows moderate peaks of 0.65 kWh in Scenario 2 during the winter week (1–7 January), while Figure 5a exhibits notable sharp spikes in DHW electricity consumption, reaching approximately 1.2 kWh in Scenario 3 with the ST system. In contrast, Figures 4b and 5b show more frequent and regular spikes during the summer week (1–7 August), which is attributed to the limited selection of eight representative days per season. Further analysis of the hourly data revealed that DHW electricity consumption is lower in summer than in winter; for instance, total DHW consumption in January was 85.16 kWh, compared to 14.85 kWh in August.



(**a**) (**b**)

Figure 4. PV system hourly electricity generation and building electricity consumption for Scenario 2 in: (**a**) winter: 1–7 January; (**b**) summer: 1–7 August.



(**a**) (**b**)

Figure 5. ST system hourly electricity generation and building electricity consumption for Scenario 3 in: (**a**) winter: 1–7 January; (**b**) summer: 1–7 August.

These consumption spikes are likely caused by the heat pump rapidly compensating for periods of low solar thermal input or following large DHW draws. This suggests a complex interaction between solar thermal pre-heating and the auxiliary heating provided by the heat pump. Future work could investigate advanced control algorithms for the ST system, incorporating variables such as predicted DHW demand patterns, to optimize the balance between solar thermal input and auxiliary heating operation.

The DesignBuilder simulation was conducted using a two-tank configuration, enabling detailed HVAC modelling (Figure 3). However, in typical real-world installations, DHW systems more commonly employ a single tank with dual heating inputs from both ST and heat-pump systems. To understand the implications of a single-tank arrangement, hourly temperature analysis was performed on the ST tank data across the year.

Given that solar thermal collectors can heat water up to 80 °C, compared to the heat pump's setpoint of 55 °C, the analysis showed that ST alone was able to meet the DHW temperature requirement 39% of the time. This indicates that, in a single-tank configuration, the heat pump would not be required during these periods. As a result, 39% of the energy consumed in Scenarios 2 and 4 (as reported in Table 4) would instead be exported to the grid. While these findings offer valuable insight into the likely operational behaviour of a single-tank system, it should be noted that actual energy performance may differ from the simulated configuration.

4.3. Cost and Carbon Anlaysis

To assess the cost and carbon implications of each scenario, post-simulation analysis was conducted using published electricity tariffs and SAP-derived carbon emission factors. Running costs were calculated based on the Ofgem energy price cap. As of December 2024, the electricity price was 24.50 pence per kWh, with a daily standing charge of 60.99 pence [39]. According to Octopus Energy, the Smart Export Guarantee (SEG) tariff offers a fixed rate of 4.1 pence per kWh for each unit of electricity exported to the grid, including from PV systems [40].

Carbon emissions for various energy uses were calculated using SAP methodology. Heating with a heat pump results in 0.1548 kg CO_2/kWh, DHW using a heat pump produces 0.1406 kg CO_2/kWh, and lighting results in 0.1443 kg CO_2/kWh. Electricity used on-site from PV systems reduces carbon emissions at a rate of 0.1343 kg CO_2/kWh, while electricity exported to the grid achieves a reduction of 0.1175 kg CO_2/kWh. Carbon impact was determined by multiplying each end use (heating, DHW, lighting) by its corresponding carbon factor. PV systems reduce overall carbon emissions through offsetting both on-site consumption and grid export. For ST systems, the carbon benefit arises solely from reducing DHW electricity consumption, and therefore only offsets emissions associated with DHW.

Table 5 presents the annual running cost and carbon impact results across all scenarios, corresponding to the energy consumption patterns shown previously, and these outcomes form the basis for the comparative discussion in Section 4.4. A key limitation of this study is that the PV and ST system sizes were selected for comparative analysis rather than practical installations, and as such, economic analysis including capital cost and payback periods were not provided. Future work could assess more realistic systems sizes with full economic analysis to provide more practical guidance for implementation.

Table 5. Annual running cost and carbon impact of eight scenarios.

Scenario	Description	Electricity Consumed (kWh)	Electricity Exported (kWh)	Annual Running Cost (GBP)	Electricity Offsetting Carbon Impact (CO_2/year)
1	Baseline	2463.6	0	826.19	355.99
2	4 m^2 PV	2172.9	241.8	745.06	288.54
3	4 m^2 ST	2143.2	0	747.69	310.94
4	2 m^2 PV + 2 m^2 ST	2124.9	93.7	739.36	298.48
5	Baseline—increased DHW consumption rate	3192.1	0	1004.67	458.42
6	4 m^2 ST—increase DHW consumption rate	2684.5	0	880.31	387.04

Table 5. *Cont.*

Scenario	Description	Electricity Consumed (kWh)	Electricity Exported (kWh)	Annual Running Cost (GBP)	Electricity Offsetting Carbon Impact (CO_2/year)
7	4 m^2 PV—increase DHW consumption rate	2901.4	241.8	923.54	390.97
8	2 m^2 PV + 2 m^2 ST—increase DHW consumption rate	2759.8	93.7	894.92	387.75

4.4. Compartive Analysis of PV and ST Systems

Based on this methodology, ST systems show a slightly higher overall carbon impact than PV systems. The installation of 4 m^2 PV systems (Scenario 2) proved most effective in reducing carbon emissions, whereas 2 m^2 PV + 2 m^2 ST systems (Scenario 4) achieve the lowest electricity. In contrast, when DHW consumption rates were increased (Scenarios 5 to 8), the annual running costs and associated carbon impacts also increased. The installation of 4 m^2 ST system (Scenario 6) outperforms Scenarios 5 to 8 in electricity consumption, running cost, and carbon impact. This outcome highlights the relative advantage of ST systems when realistic hot water demand was considered, contrasting with the current SAP methodology that tends to favour PV systems. Thus, this study shows that SAP could underestimate the benefits of ST systems in practice.

The Future Homes Standard will become mandatory in the UK in the near future and will require all new homes to be zero carbon ready, meaning that they will be zero carbon after electricity grid is fully decarbonized. Therefore, using “The Future Home” from environmental chamber in Energy House 2.0 makes results of this research representative for new build homes in the UK.

While this work focuses on the UK context, many countries use a fixed hot water demand in compliance modelling. For instance, the Dutch Energy Performance Certificate (EPC) calculation under NTA 8800 prescribes a flat 11 GJ hot water energy use, irrespective of household size or behaviour [41]. Therefore, the methodology and findings could impact building policy and renewable system integration internationally.

Furthermore, key parameters such as collector efficiency, heat-pump COP variation, and occupancy patterns were held constant in the current comparative analysis to maintain a controlled comparison; future research could benefit from a sensitivity analysis to explore their impact on the comparative outcomes.

5. Conclusions

This study evaluated the integration and comparative effectiveness of ST and PV systems in reducing energy consumption, carbon emissions, and operational costs in TFH. Performance was assessed through detailed simulations under standard occupancy conditions and scenarios reflecting increased hot water demand. The following are the key findings from this study, where the first two bullet points below answer the first research question and the third bullet point below answers the second research question:

- The 4 m^2 ST system provided 964.6 kWh of thermal energy annually under standard occupancy, increasing significantly to 1528 kWh under higher hot water demand conditions.
- The 4 m^2 PV system generated 532.5 kWh of electricity annually, with 290.7 kWh consumed on site and 241.8 kWh exported.

- The relative benefit of ST compared to PV strongly depends on the actual CoP of the heat pump and the assumed hot water demand used in SAP calculations; a lower real COP and higher hot water demand both significantly enhance the benefit and cost-effectiveness of ST systems.

The contribution of this study is the systematic evaluation of ST and PV systems under calibrated, realistic conditions, highlighting how standard SAP methodologies may underestimate ST benefits. Accurate estimations of heat-pump efficiency and realistic hot water usage assumptions are therefore essential for determining the optimal renewable energy solution in residential buildings. Future research focusing on detailed hot water usage patterns, real-world heat-pump performance, and advanced simulations to quantify precise PV power distribution across DHW and other household energy demands will further support optimized renewable energy solutions for residential applications. Engineers should design and size the system based on realistic hot water demand to optimize the benefits of solar thermal applications. Legislators should update regulatory methods like SAP to reflect actual usage of solar thermal's contribution. This research offers practical evidence to improve both engineering practice and policy for renewable energy solution installation in new homes.

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Abbreviations

The following abbreviations are used in this manuscript:

ASHP	Air-source heat pump
DHW	Domestic hot water
PV	Photovoltaic system
SAP	Standard Assessment Procedure
ST	Solar thermal system
TFH	The Future Home
COP	Coefficient of Performance

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