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Comparative study of PV, PVT, and solar thermal systems for residential applications in Europe

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ABSTRACT

Solar energy is a key renewable resource for addressing increasing energy demands and reducing emissions. This study examines photovoltaic (PV), photovoltaic-thermal (PVT), and solar thermal (ST) systems for residential use across 26 European countries, focusing on energy provision, economic feasibility, and environmental impact. Key findings reveal that PV systems demonstrate economic advantages with a low payback time. The average payback time across the 26 countries is 9.5 years, with all countries achieving cost recovery within the system's lifetime, and consistently showing high life cycle savings, averaging 6646 € over their lifespan. Although PVT systems, achieve higher annual energy savings (44.7 %), they exhibit intermediate economic performance, 18 out of 26 countries achieve cost recovery within the system's lifetime, with average life cycle savings of 2519 €. Environmentally, PV systems show a higher average CO_2 emission reduction of 1528 $kgCO_2$/year compared to PVT systems (1275 $kgCO_2$/year) and ST systems (334 $kgCO_2$/year). The research highlights the impact of geographic and climatic variations on system suitability, identifying optimal conditions in southern coastal regions like Spain and Portugal and reduced suitability in landlocked northeastern countries such as Sweden. Furthermore, energy price fluctuations, particularly rising natural gas prices, can enhance the economic attractiveness of PVT systems. This research provides insights for the strategic deployment of solar technologies in Europe, contributing to informed policy and investment decisions aligned with EU renewable energy goals.

Nomenclature

Acronyms		Greek symbols	
EU	European union	α	Heat loss coefficient
PV	Photovoltaic	β	Temperature coefficient (K^{-1})
PVT	Photovoltaic-thermal	η	Efficiency (%)
ST	Solar thermal	**Subscripts**	
Symbols		a	Ambient
A	Area (m^2)	b	Boiler
C	Cost (€)	cov	Covered
c	Specific heat capacity (J kg^{-1} K^{-1})	dem	Demand
d	Discount rate (rate)	el	Electrical
f	CO_2 emission factor (gCO_2 kWh^{-1})	exc	Excess
G	Irradiance (W m^{-2})	f	Fluid
I	Investment (€)	gen	Generated
i	Inflation rate (rate)	hw	Heating water

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LCOE	Levelized cost of energy (Euro kWh^{-1})	ng	Natural gas
LCS	Life cycle savings (Euro)	r	Reduced
M	Mass (kg)	ref	Reference
n	System lifespan (years)	s	Saving
PBT	Payback time (Euro)	sh	Space heating
R	Annual energy saving ratio (rate)	O&M	Operation and management
T	Temperature (°C)	th	Thermal
ER	Emission reduction ($kgCO_2$)	W	Water
EPCS	Environmental penalty cost saving (Euro)	WT	Water tank

1. Introduction

Buildings are major contributors to global energy challenges. Their operations consume 30 % of global final energy and were responsible for

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26 % of global energy-related CO_2 emissions in 2022 [1]. Furthermore, these emissions have been growing at an average rate of 1 % per year since 2015 [2]. This substantial contribution and continued growth underscore the urgent need to decarbonize the building sector. This requires a fundamental shift towards renewable energy sources. In Europe, this essential transition is underpinned by robust policies promoting renewable energy adoption and strict regulations aimed at reducing carbon emissions. These efforts are formalized in ambitious targets, such as the European Union's Renewable Energy Directive goal of achieving 45 % energy consumption from renewables by 2030 [3]. Individual nations, like Germany, aim even higher, targeting a 65 % renewable energy share by the same year [4]. Solar energy technologies such as photovoltaic (PV), solar thermal (ST), and photovoltaic-thermal (PVT) systems play a crucial role in achieving these targets.

Over the past decade, PV panels have seen a dramatic 82 % reduction in solar power costs, establishing them as a highly competitive electricity source in many EU regions [5]. This cost reduction has led to rapid adoption, with EU cumulative installed solar PV capacity growing from 100 GW in 2018 to 200 GW in 2022, reaching 269 GW by the end of 2023 and contributing approximately 10 % to the EU's total electricity production, and this strong growth trend is expected to continue [6,7]. On the other hand, solar thermal (ST) technology converts solar energy into thermal energy for a variety of applications across the industrial, residential, and commercial sectors. A typical ST system primarily consists of collectors, which are optimized for maximum solar-to-heat conversion [8], and thermal energy storage systems, which store the heat for later use. These systems are designed to be compact, affordable, and durable [9]. ST applications are diverse, ranging from space heating and hot water production to process heat applications like drying or desalination [10]. In some cases, solar collectors are integrated with phase change materials for latent heat storage [11], or with absorption cooling systems and heat pumps for indirect cooling in buildings [12]. Finally, PVT systems represent a hybrid approach, combining the functionalities of both PV and ST in a single collector. They integrate photovoltaic cells and a thermal absorber to generate both electricity and thermal energy [13,14]. The PVT market, though smaller than PV and ST markets, has seen a surge in interest, yielding diverse commercial products and configurations [15]. Research focuses on optimizing both electrical and thermal efficiencies [16], adjusting factors like the spectral properties of PV cells and improving internal heat transfer mechanisms. The potential of PVT systems is particularly significant in the building sector, where space optimization is crucial [15]. On the other hand, PV modules may contain toxic substances such as lead in solder, the cell metallization layer, or cadmium in thin-film modules. These materials require specialized disposal procedures [17]. to prevent environmental contamination and associated health risks [18]. Proper end-of-life management strategies include reuse and repair for reuse, recycling, storage, and disposal. Recycling is a preferred option due to its potential to reduce environmental impact and recover valuable raw materials [17]. PVT systems present greater recycling challenges. Their integrated design, incorporating both photovoltaic and thermal components, complicates material separation and recovery [19]. On the other hand, ST collectors generally contain fewer hazardous substances [20]. However, their HTFs, often glycol-based, require proper handling and disposal to prevent environmental contamination.

Despite receiving a lot of solar radiation, common silicon PV panels have a solar-to-electricity conversion efficiency between 15 % and 23 %. This limited efficiency results in a substantial portion of the absorbed energy turning into heat, which contributes to the PV cell's self-heating [21]. Higher solar radiation and ambient temperatures can significantly increase PV cell operating temperatures. This rise in temperature shortens their lifespan and lowers their performance. For crystalline silicon PV cells, a 1 °C rise in temperature above the standard 25 °C can lead to a 0.2–0.5 % relative decrease in electricity production [22]. Consequently, thermal management systems for PV cells have become a focus to enhance its energy efficiency [23,24]. PVT collectors efficiently harvest the waste heat from PV cells for thermal energy use, while simultaneously cooling the cells to boost overall efficiency and energy yield per unit area. This is especially beneficial when installation space is limited. Studies have explored various cooling techniques, employing water or air to dissipate heat [25,26]. Also, the trend towards Building-Integrated (BI) solar systems is notable. These systems replace parts of the building itself, such as facades, and include Building-Integrated Photovoltaics (BIPV) and Building-Integrated Photovoltaic-Thermal (BIPVT) systems. They offer aesthetic and functional benefits [27]. Various BIPVT configurations, including facade-integrated systems with Fresnel-transmission PVT concentrators [28] and air-based BIPVT [8,29,30] with dual inlets, are being explored for enhanced energy-efficient building designs.

While research has explored different solar device configurations, such as various PVT collector designs [31], comparisons of PVT systems with conventional PV and solar thermal systems have been conducted [15]. However, much of the existing research tends to be focused on specific regions, climate conditions, or applications, limiting the universal applicability of findings. For example, studies have simulated systems for Norwegian residential buildings [32], analyzed performance based on data from Algiers [31], or compared technologies for UK applications [33] or for specific cities [34]. While some studies have performed multi-location analyses, they often focus on specific aspects like life cycle assessment for industrial applications [35] or technoeconomic assessments of specific system configurations across a few climates [34, 36], focusing on heating and cooling rather than combined heat and power [37]. Despite these efforts, a significant gap remains in conducting comprehensive, multi-country comparisons of different solar heating and power systems, which is needed to provide universally applicable insights and bridge current research limitations.

While residential energy system selection must ultimately be tailored to specific building energy demands and contextual factors (e.g., user behavior, space constraints), comparative technology assessment under standardized conditions serves several critical purposes for advancing renewable energy deployment. First, it provides a methodological framework that can be adapted to diverse residential contexts while maintaining analytical consistency. Second, it enables the identification of optimal technology and deployment strategies under similar climatic and economic conditions. Third, standardized performance benchmarking supports evidence-based technology selection and informs both individual decision-making and broader energy policy development.

Although individual technologies have been extensively studied, direct holistic comparisons under consistent boundary conditions across varying climatic contexts remain limited. Addressing this research gap, this study presents a comprehensive, multi-country comparative analysis of three key solar technologies (PV, PVT, and ST systems) for single-family houses (SFHs) to maintain consistency in the comparative analysis across 26 European countries. These countries were selected due to the availability of consistent, detailed, and complete datasets, ensuring data integrity and accurate cross-country comparisons.

This study addresses this gap by systematically comparing these systems to reveal their relative technical, environmental, and economic performance under diverse climatic and economic conditions. Our central innovation is the development and application of a uniform mathematical model for hourly transient simulations across 26 European countries. This modeling framework enables consistent, robust, and directly comparable assessments, overcoming the limitations of prior region-specific studies. The study evaluates each system's energy performance, economic feasibility, and environmental impact using this unified model. Through multidimensional assessment and a wide set of performance indicators, the analysis captures region-specific variations while also identifying broader trends. Given that solar technologies vary in their capabilities and suitability, selecting the most suitable system depends not only on its ability to meet energy demands but also on its environmental benefits, economic viability, and sensitivity to local climate and energy price conditions. By providing insights for system pre-selection, early-stage planning, and policy evaluation, this study offers practical insights to guide the strategic deployment of solar energy systems technologies tailored to national contexts and support Europe's transition to a sustainable, low-carbon future.

The structure of this study is organized as follows: Section 2 outlines the system descriptions and the mathematical models developed for the PV, PVT, and ST systems, along with the methods used for economic and environmental evaluation. Section 3 describes the sources and characteristics of the input data, including solar irradiance, ambient temperature, energy demand, energy prices, and other economic parameters. Section 4 presents and discusses the results on the energy, economic, and environmental performance of the systems with a comparative lens. Finally, Section 5 summarizes the key findings and conclusions of the study.

2. Methodology

In this study, models were developed for three types of solar systems: PV, ST, and PVT, using transient simulations to assess their performance across 26 different European countries. These models account for both electrical and thermal properties, using hourly analyses throughout the year, incorporating local weather data and actual energy consumption patterns (both electricity and heat demand), as well as economic parameters to ensure realistic simulations. The models capture the dynamics between power generation, storage, and consumption. Each model integrates validated engineering equations and manufacturer data for all components (e.g., PV, PVT, storage tanks, and so on). Simulations and thermodynamic calculations are carried out using MATLAB [38] and REFPROP [39].

2.1. Systems description

The system models are composed of interconnected components, including solar collectors (PV, ST, or PVT depending on the system type), a thermal storage tank, an auxiliary gas heater, a coil, a mixing device, and associated mechanisms such as bypass and pump. These components follow a consistent logical framework as illustrated in Fig. 1.

PV panels generate only electrical energy, while ST collectors produce solely thermal energy. In contrast, PVT collectors combine both functionalities, delivering simultaneous electrical and thermal output from incident solar radiation. The electricity produced by solar collectors is used directly to power household appliances, lighting, and circulation pumps. The model does not incorporate on-site battery storage. Instead, it employs a net metering approach: when the solar electricity generation falls short of demand, the grid supplies the remaining load; conversely, any surplus electricity is fed back into the grid through a net metering system, with compensation provided via feed-in tariffs. In the PV system, which produces only electricity, all thermal energy demand is met by this auxiliary heater due to the absence of thermal generation. In contrast, the ST system, which provides only thermal output, relies entirely on electricity from the grid to meet household electrical demand. In a hybrid setups, PV systems may also contribute to meeting this electrical demand if integrated.

2.2. Model design

2.2.1. Photovoltaic-thermal system

The model operates on an hourly time step, with its core design built around the interconnection of all system components to form a continuous simulation loop. At each hour, the simulation uses key input parameters, including solar irradiance, ambient temperature, electrical and heating demand, and water tank temperature. The PVT collector is modeled using thermal and electrical efficiency curves, in accordance with the standards outlined in EN ISO 9806:2017 [40], a widely accepted approach in the literature [16,41,42] as follows:

$$\eta_{\mathrm{th}} = \frac{\dot{m}_{\mathrm{f}} \cdot c_{\mathrm{f}} \cdot (T_{\mathrm{fo}} - T_{\mathrm{fi}})}{G \cdot A} = \eta_0 - \alpha_1 \cdot T_{\mathrm{r}} - \alpha_2 \cdot G \cdot T_{\mathrm{r}}^2 \tag{1}$$

with,

$$T_{\mathrm{r}} = \frac{T_{\mathrm{fm}} - T_{\mathrm{a}}}{G}, \tag{2}$$

where $\dot{m}_{\mathrm{f}}$ represents the mass flow rate of fluid through the collector, c_{f} is the specific heat of the fluid, G denotes the total solar irradiance, and A stands for the collector area. T_{fo} and T_{fi} are the fluid temperatures at the collector outlet and inlet, respectively. Additionally, T_{r} is defined as the reduced temperature, T_{fm} as the average fluid temperature between the

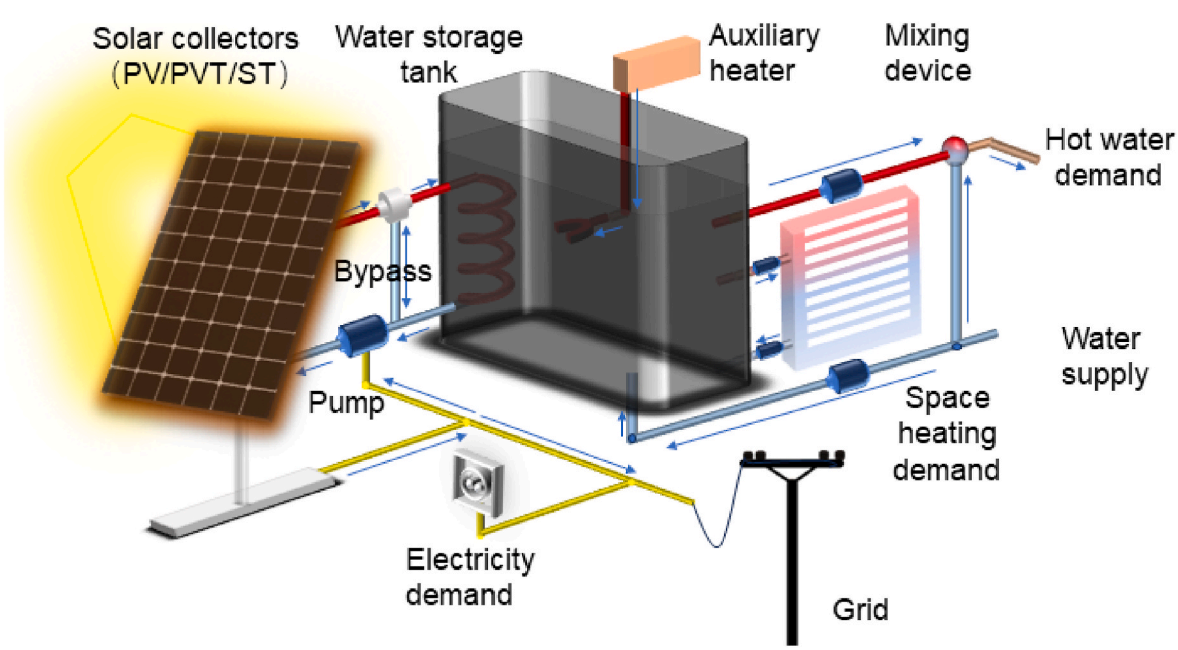

Fig. 1. Schematic representation of the integrated solar energy systems, featuring three types of solar collectors: photovoltaic (PV), solar thermal (ST), and hybrid photovoltaic-thermal (PVT) collectors.

inlet and the outlet, and T_a as the ambient temperature.

The coefficients η_0, α_1, and α_2, representing the zero-loss efficiency, first-order heat loss coefficient, and second-order heat loss coefficient, respectively, are critical to the model. These are determined by plotting instantaneous thermal efficiency against the reduced temperature and fitting the data with a second-order least-squares curve. It is important to note that these coefficients vary across different collectors, influenced by factors such as manufacturing quality and absorber design.

PV electrical efficiency (η_{el}) decreases linearly with the cell operating temperature (T_{ce}), Equation (3) [43–46] is applied to determine the electrical energy conversion efficiency and output of solar systems.

$$\eta_{el} = \frac{\dot{E}}{G \cdot A} = \eta_{ref} \cdot \left[1 + \beta \cdot \left(T_{ce} - T_{ref}\right)\right]. \quad (3)$$

Here, $\dot{E}$ represents the generated electricity, β is the temperature coefficient, and η_{ref} is the reference electrical efficiency established at a standard collector temperature T_{ref} of 25 °C and solar irradiance of 1000 W/m^2. PV cell temperature (T_{ce}) assumed to be equal to the ambient temperature (T_a) when the panels are not working.

The water storage tank in our study is modeled as a fully mixed reservoir, where the effects of stratification on its efficiency are not considered. While stratification can significantly influence the thermal performance of storage systems, this assumption is commonly applied in system-level simulations to reduce model complexity and computational burden. In this context, the model prioritizes overall energy balancing rather than intra-tank thermal gradients. Energy balance, governed by the following equation:

$$M_t c_w \frac{dT_{wt}}{dt} = \dot{Q}_{coil} - \dot{Q}_{loss} - \dot{Q}_{cov,hw} - \dot{Q}_{cov,sh}. \quad (4)$$

In this equation, M_t denotes the mass of water in the tank, c_w the specific heat capacity of water, and T_{wt} the water temperature. The equation accounts for thermal input from the solar collectors ($\dot{Q}_{coil}$, by the submerged heat exchanger), thermal losses to the surroundings ($\dot{Q}_{loss}$), and energy supplied for hot water ($\dot{Q}_{cov,hw}$) and space heating ($\dot{Q}_{cov,sh}$).

The hot water demand met by the water storage tank, indicated by $\dot{Q}_{cov,hw}$, is calculated based on the following conditions:

$$\dot{Q}_{cov,hw} = \begin{cases} \dot{Q}_{dem,hw} & T_{wt} \geq T_{dem,hw} \\ \left(\dfrac{T_{wt} - T_{mains}}{T_{dem,hw} - T_{mains}}\right)\dot{Q}_{dem,hw} & T_{mains} < T_{wt} < T_{dem,hw} \\ 0 & T_{wt} \leq T_{mains} \end{cases} \quad (5)$$

Here, coverage of hot water demand ($\dot{Q}_{dem,hw}$), factoring in the required delivery temperature ($T_{dem,hw}$), the main supply temperature (T_{mains}), and the water temperature in the tank (T_{wt}).

Similarly, the space heating requirement met by the water storage tank, denoted as $\dot{Q}_{cov,sh}$, is determined using the following formula:

$$\dot{Q}_{cov,sh} = \begin{cases} \dot{Q}_{dem,sh} & T_{wt} \geq T_{dem,sh} \\ \left(\dfrac{T_{wt} - T_{out,sh}}{T_{dem,sh} - T_{out,sh}}\right)\dot{Q}_{dem,sh} & T_{out,sh} < T_{wt} < T_{dem,sh} \\ 0 & T_{wt} \leq T_{out,sh} \end{cases} \quad (6)$$

where, $\dot{Q}_{dem,sh}$ is the space heating demand, $T_{dem,sh}$ is the required delivery temperature for space heating, and $T_{out,sh}$ refers to the outlet temperature of the radiator used for space heating

The system compensates for any heating shortfall with an auxiliary natural gas heater. Concurrently, the heat transfer fluid, cooled in the water tank, is circulated back to the panel's inlet, creating a temperature differential critical for determining the next hour's PV cell temperature (T_{ce}'). This cyclical process, forming a single-hour loop, is essential for understanding the solar energy system's operation hour by hour. The operation of other components, such as the coil, pump, and auxiliary heater, and specific calculation steps, will be elaborated in the supplemental information. Additionally, key PVT panel parameters like η_0, α_1, α_2, T_{ref}, and β are listed in Table S2.

2.2.2. Photovoltaic system

As mentioned earlier, the PV system in this study is solely used for electricity generation, as illustrated in Fig. 1, and does not include thermal energy production. The electricity produced is primarily utilized for household electricity needs, with any excess fed back into the grid through net-metering. Conversely, electricity shortfalls are compensated with electricity from the grid. For backup, an auxiliary natural gas heater is used for space heating and hot water. The PV panel's specific parameters, obtained from a commercial vendor, are detailed in Table S2.

2.2.3. Solar thermal system

The ST system's design, corresponding to the thermal generation segment in Fig. 1, excludes electricity generation. This system exclusively produces thermal energy for hot water and space heating, relying on grid electricity for all electirical needs. Its thermal efficiency is modeled using Equations (1) and (2), while the water storage tank and solar collector pump operations are represented by Equations (4)–(6). An auxiliary natural gas heater supplements any heating deficits. The ST collector, also sourced commercially, is detailed in Table S2.

2.3. Energy indicators

The proportion of the yearly energy demand (in the form of heat or power) met by the solar-based systems is a critical energy performance metric. This encompasses the portion of the annual hot water demand covered, denoted as $f_{cov,hw}$, the portion of the annual space heating demand covered, referred to as $f_{cov,sh}$, and the portion of the annual electricity demand covered, known as $f_{cov,el}$:

$$f_{cov,hw} = \frac{\dot{Q}_{cov,hw}}{\dot{Q}_{dem,hw}}, \quad (7)$$

$$f_{cov,sh} = \frac{\dot{Q}_{cov,sh}}{\dot{Q}_{dem,sh}}, \quad (8)$$

and

$$f_{cov,el} = \frac{E_{cov}}{E_{dem}} \quad (9)$$

Here, $\dot{Q}_{dem,hw}$, $\dot{Q}_{dem,sh}$, and E_{dem} represent the annual demands for hot water, space heating, and electricity, respectively. Correspondingly, $\dot{Q}_{cov,hw}$, $\dot{Q}_{cov,sh}$, and E_{cov} represent the annual demands covered by the proposed solar systems for hot water, space heating, and electricity.

The annual energy savings (E_s) represent the amount of energy provided by the solar system over the year. This includes both the covered electricity demand (E_{cov}) and the energy saved by providing thermal output (converted to equivalent electricity). Mathematically, it is expressed as:

$$E_s = E_{cov} + \frac{\dot{Q}_{cov,hw} + \dot{Q}_{cov,sh}}{\eta_b} \quad (10)$$

Here, η_b represent the efficiency of the natural gas boiler, which is 82 % according to the manufacturers [34].

The annual energy saving ratio, (R_s), quantifies the proportion of the annual energy saved by the proposed solar systems, and it is expressed as:

$$R_s = \frac{E_s}{E_{dem} + \frac{\dot{Q}_{dem,hw} + \dot{Q}_{dem,sh}}{\eta_b}} \tag{11}$$

2.4. Economic and environmental evaluation

The annual operational cost savings (C_s) are determined as the disparity between the existing annual expenses required to fulfill all energy needs and the annual expenses that once the solar system has been implemented [34]:

$$C_s = E_{cov} \cdot c_{el} + E_{exc} \cdot s_{el} + \frac{\dot{Q}_{cov,hw} + \dot{Q}_{cov,sh}}{\eta_b} \cdot c_{ng} - C_{O\&M}. \tag{12}$$

The payback time (*PBT*) signifies the duration needed to recuperate the investment expenses associated with the suggested solar system, and is calculated as follows [34]:

$$PBT = \frac{\ln\left[\frac{C_0(i_F - d)}{C_s} + 1\right]}{\ln\left(\frac{1 + i_F}{1 + d}\right)}, \tag{13}$$

where C_0 is the investment cost, i_F is the inflation rate, and d is the discount rate. C_0, are estimated using the latest price lists obtained from various solar equipment vendors.

The levelized cost of energy, LCOE, is obtained by:

$$LCOE_{eq,el} = \frac{C_o + \sum_{i=1}^{n} C_{prod}\left(1 + i_f\right)^{i-1}(1 + d)^{-i}}{\sum_{i=1}^{n} (Q_{el} + Q_{th}\ \eta_{th})(1 + d)^{-i}} \tag{39}$$

Here, C_{prod} is the yearly cost is related to energy production, Q_{el} , Q_{th} are the net annual production of electricity and heat, respectively. For PV, production is solely the actual electricity generated; for ST, it is the electricity equivalent converted from the thermal energy output; for PVT, both outputs are combined. Equivalent electricity from thermal energy is calculated using a 0.55 [47] conversion factor (η_{th}), reflecting typical natural gas power plant efficiency. The system lifespan (n) is set at 25 years [48].

The life-cycle cost saving, LCS, is defined as the present value of the total energy cost savings over the lifetime, n, of each system:

$$LCS = \frac{C_s}{d - i_F}\left[1 - \left(\frac{1 + i_F}{1 + d}\right)^n\right] - C_0. \tag{15}$$

The environmental advantages, particularly the capability to reduce CO_2 emissions, are increasingly recognized. Some countries have already implemented carbon pricing mechanisms, and this number is expected to grow in the future [49].

This study focuses on operational CO_2 emissions as the primary environmental indicator, evaluating the annual reduction in CO_2 achievable by implementing the proposed renewable energy systems. This assessment incorporates specific CO_2 emission factors for natural gas and electricity, denoted as f_{ng} and f_{el}, respectively. The analysis takes into account the current energy mix and the potential shift towards more sustainable sources, offering a comprehensive understanding of the environmental impact of these systems. The emission reduction (ER) is calculated as:

$$ER = E_{cov} \cdot f_{el} + E_{exc} \cdot f_{el} + \frac{\dot{Q}_{cov,hw} + \dot{Q}_{cov,sh}}{\eta_b} f_{ng} \tag{16}$$

The total environmental penalty cost saving, EPCS [34] over the lifetime of the systems is:

$$EPCS = \frac{ER \cdot C_{CO2}}{d - i_F}\left[1 - \left(\frac{1 + i_F}{1 + d}\right)^n\right], \tag{17}$$

where C_{CO2} is the cost of unit CO_2 emission.

3. Data acquisition

3.1. Solar irradiance and ambient temperature

For accurate performance calculations, this study utilizes hourly solar irradiance and ambient temperature data for 26 European countries. To ensure the broader applicability of the results, data from each country's capital city, considering geographical and population density factors, is selected. While this enables a consistent cross-country comparison, it does not fully capture the intranational climatic and demand variability, particularly in geographically large countries. As such, the results should be interpreted as indicative of general national trends rather than region-specific performance.

An optimized fixed collector tilt angle [51] is applied to all collectors throughout the year to maximize daily solar energy capture. The data for 12 of these countries is presented in Fig. S7, while complete annual solar irradiance data appears in Fig. S6. All climate data was sourced from the Photovoltaic Geographical Information System (PVGIS) [51].

3.2. Annual electricity demand profile

This section outlines the methodology for acquiring annual electricity demand data with hourly variations. Due to the complexity of capturing specific demand fluctuations, data is sourced from the Hotmaps project [52], a toolbox that supports heating and cooling planning processes. This project provides normalized yearly electricity demand variations per dwelling. By combining these yearly consumption figures with data from the Odyssee and Mure databases [53], the study achieves a precise hourly variation in electricity demand, as shown in Fig. S8. The Odyssee database, managed by Enerdata, offers extensive data on energy efficiency and CO_2 indicators, while the Mure database, coordinated by Fraunhofer-ISI and supported technically by Enerdata, includes comprehensive descriptions and impact evaluations of energy efficiency measures at the EU and national levels. The annual data for all countries are displayed in Fig. S9.

3.3. Annual heating demand profile

The approach for obtaining normalized residential space heating and hot water demand data is similar to that used for electricity demand. This data was sourced from Hotmaps, with annual demand per dwelling [53] provided by the same source referenced in Fig. S9. The final data for a subset of the study is displayed in Fig. S10, while comprehensive annual data for all countries is presented in Fig. S11 and S12. This method ensures consistency in the data collection process across different energy demands.

3.4. Installation area and roof area

In the study of residential solar power systems, the installation area is identified as a key factor. To determine this, the average size of a single-family home in European countries was sourced from Entranze [54], a database co-funded by the Intelligent Energy Europe Program of the European Union. The available installation area for solar panels is set at a fixed ratio of 50 % of the floor area [55]. The floor areas for European countries are depicted in Fig. S13.

3.5. Electricity price and natural gas price

In the economic analysis of solar power systems, energy prices are key factors. Besides electricity prices, this study uses natural gas to satisfy heating demand. Data on domestic electricity and natural gas prices were obtained from the Eurostat database [5]. The detailed pricing information for each country is presented in Fig. S14.

3.6. Inflation rate

In economic terms, inflation refers to the general rise in prices, typically measured by the consumer price index, which leads to a reduction in the purchasing power of money [56]. In this study, the inflation rate, a key measure of inflation, is incorporated into several calculations, including Payback Time (PBT), Levelized Cost of Electricity (LCOE), Life Cycle Savings (LCS), and Environmental Penalty Cost Savings (EPCS), as outlined in Equations (S25), (S26), (S27), and (S29) in the Supplemental Information. The study utilizes the Harmonized Index of Consumer Prices (HICP) for energy, including electricity and natural gas, sourced from the Eurostat database, focusing on the year 2019 [5]. Annual data on inflation rates are presented in Fig. S15, providing a critical metric for the economic analysis of solar power systems.

3.7. Discount rate

To enhance the financial analysis in this study, cash flows are transformed into net present values (NPV) over 25 years using the Weighted Average Cost of Capital (WACC) as the discount rate. This approach, integral in financial assessments, calculates WACC by aggregating the costs of individual capital components, weighted by their respective proportions. Widely recognized by EU authorities, national regulators [57], and utility practices [58], WACC effectively gauges expected investment returns [59]. The data in Fig. S16, drawn from the DiaCore project, reflects EU-wide analysis on renewable energy investments [60] and provides country-specific WACC values. This project's findings on investment risks in renewable energy projects are crucial for accurately computing WACC, validating its use as a discount rate in calculating the LCOE for renewable energy systems [55,60].

3.8. CO_2 emission intensity

This section of the study discusses the crucial role of the emission reduction parameter in both economic and environmental analyses, particularly concerning the displacement of natural gas and electricity. The CO_2 emissions per unit of electricity vary across different countries due to diverse power generation technologies and national energy mixes, which may include varying shares of fossil fuels, nuclear power, and renewables. For example, countries with a high dependence on coal or natural gas for electricity production typically exhibit higher emission factors (e.g., Poland: 745 gCO2/kWh), whereas those with a greater share of low-carbon sources such as hydropower or nuclear power (e.g., France 63 gCO2/kWh).

Therefore, this study uses electricity-related CO_2 emission data from the European Environment Agency [61], as presented in Fig. S17.

For natural gas, a standard average emission value of 55 gCO_2/kWh is employed, based on data from the EIA database [62]. This consistent value reflects the typical carbon intensity associated with direct combustion of natural gas.

3.9. Carbon tax

A carbon tax is imposed on carbon emissions associated with the production of goods and services, highlighting the societal costs often indirectly felt, such as extreme weather events. This tax aims to reduce greenhouse gas emissions by making fossil fuels more expensive, thereby decreasing demand for high-emission products and services and promoting low-carbon alternatives [63]. In this study, we adopt the average EU carbon emission tax rate of 25 €/tCO_2, as per the European Union Emissions Trading System,. This data is sourced from the Eurostat database [50].

4. Results and discussion

In this section, we present and discuss the detailed results of the analysis. We begin with a monthly energy performance assessment focusing on three representative countries: Germany, Spain, and Sweden. This is followed by a comparative annual energy analysis across all 26 European countries. Next, the economic and environmental performances of the investigated systems are presented and discussed. Finally, we analyze how variations in electricity and natural gas prices affect the comparative performance of the PV, PVT, and ST systems.

4.1. Comparative energy analysis

4.1.1. Monthly energy analysis for three selected countries

Seasonal variations in sunlight availability, temperature, and energy demands significantly influence solar energy system operation. This section presents a detailed month-by-month performance analysis for solar energy systems across 26 European countries, highlighting results from Germany, Spain, and Sweden.

Spain: Known for its high solar irradiance and warm climate, Spain serves as an ideal location to assess solar energy systems. The country's abundant sunshine and lower heating demand, particularly compared to Germany and Sweden, allow for an in-depth examination of solar systems primarily geared towards electricity production.

Germany: As a country with moderate solar irradiance levels and one of the world's highest PV capacity installations, Germany offers a balanced perspective. Its central European location presents a contrasting scenario to Spain, making it a valuable case for studying solar energy utilization in a different climatic setting.

Sweden: Positioned in the north with low average temperatures and high electricity consumption, Sweden poses unique challenges for solar energy systems. The significant heating demand during the winter months, coupled with its distinct geographical and climatic conditions, provides a contrasting environment for evaluating the performance of solar systems.

Fig. 2A, shows the monthly operational outputs of the PV systems. Their ability to meet electricity demand can be seen in Germany and Spain. The results demonstrate high consistency in the electricity coverage ratio (the percentage of electricity demand covered by solar generation). This ratio is represented by the blue area (E_{cov}) relative to the grey area (E_{dem}). Also note that this metric is distinct from the broader annual energy saving ratio, which accounts for total energy savings including thermal output.

The annual average electricity coverage ratios for Germany and Spain are 43.9 % and 47.4 %, respectively. These values represent the annual electricity from the PV system that directly meets instantaneous demand, based on hourly simulations, where surplus electricity is fed back to the grid. To clarify the interpretation: PV systems in Germany, generating a total of 4893 kWh (1409 kWh coverage + 3485 kWh excess), resulting in 43.9 % coverage ratio. On the other hand, Spain's PV systems generate a total of 7951 kWh (1851 kWh coverage + 6099 kWh excess), achieving 47.4 % coverage ratio. Notably, in Spain, this ratio is maintained throughout the year, and in Germany, it persists from February through October, indicating periods of significant excess in electricity generation (shown by the red area representing E_{exc}) compared to demand. This suggests that the PV systems in both countries possess considerable potential. With the implementation of effective energy storage solutions, these systems could feasibly satisfy the annual electricity demand. However, Sweden's PV systems, with an annual electricity coverage ratio of 28.8 %, show substantial seasonal performance variation. During June and July, electricity generation exceeds demand, hitting peak coverage ratios of 55.0 % and 53.0 %, comparable to Germany's and Spain's summer peaks of 61.8 % and 57.0 %, respectively. However, in the winter months of November through January, Sweden's ratios fall to 8 %, 5 %, and 9 %, significantly lower than Germany's and Spain's more stable 30 %. These discrepancies are

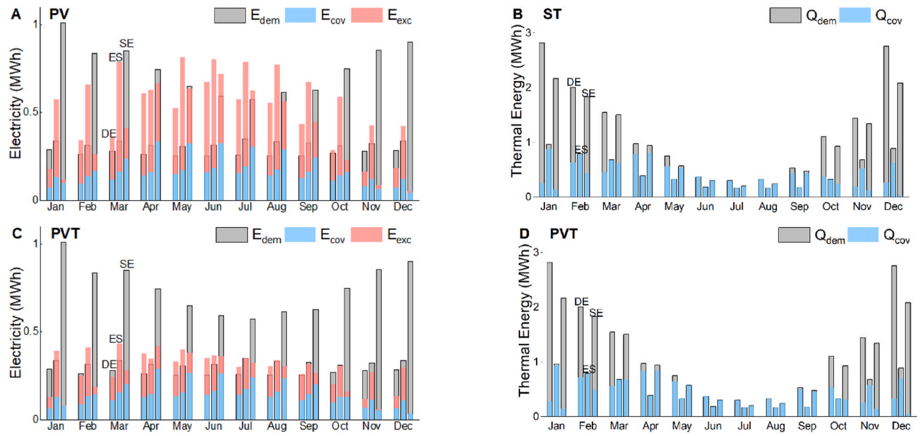

Fig. 2. Monthly performance comparison of PV, PVT, and ST systems in Germany (DE), Spain (ES), and Sweden (SE). (a) PV system electricity performance: monthly electricity demand (E_{dem}), coverage (E_{cov}), and excess (E_{exc}). (b) ST system thermal performance: monthly thermal demand (Q_{dem}) and coverage (Q_{cov}). (c) PVT system electricity performance: monthly electricity demand (E_{dem}), coverage (E_{cov}), and excess generation (E_{exc}). (d) PVT system thermal performance: monthly thermal demand (Q_{dem}) and coverage (Q_{cov}).

largely due to Sweden's increased winter electricity demand and lower solar irradiance, which highlight the country's reliance on supplementary energy sources during this period. Despite a commendable summer performance, Sweden's PV systems face challenges in winter, suggesting a need for system enhancements to improve year-round efficiency.

Fig. 2C illustrates the electrical performance of PVT systems. Annually, the electricity coverage ratios for Germany (39.7 %), Spain (43.8 %), and Sweden (23.8 %) are lower than previously discussed PV systems (43.9 %, 47.4 %, and 28.8 %, respectively). These reductions, by 4.2 %, 3.6 %, and 5 % respectively, are consistent throughout the year, indicating a uniform performance gap rather than one concentrated in specific seasons. This trend suggests that both PV and PVT systems respond similarly to climatic variables and operational factors. The slightly lower electricity coverage ratio of PVT systems is principally attributable to the intrinsic differences between the two system designs. When considering electricity generation in isolation, PVT systems exhibit a modest shortfall in performance relative to PV systems. However, this drawback is offset by their ability to recover thermal energy, improving overall solar energy utilization.

Fig. 2D demonstrates that Spain achieves a notably high annual total heating energy coverage ratio of 94.2 % of PVT systems. From March to September, heating demand is fully met, making Spain the most efficient among the three countries. December registers Spain's lowest heating coverage ratio at 78.4 %. A key factor underpinning Spain's superior performance is its comparatively lower annual heating demand, which is approximately half that of Germany and Sweden. In contrast, Germany and Sweden achieve near-complete coverage during summer (June to August), but ratios drop below 10 % in the colder months of January and December. By comparing Fig. 2C and 2D, both ST and PVT systems display a similar pattern of adaptation to climatic and other environmental conditions.

As illustrated in Fig. S4 (in the Supplementary), the drop in January can be attributed to the reduced solar irradiance and ambient temperatures, which result in lower heat input to the tank from collectors, thereby preventing the storage tank from reaching adequate temperatures. It also coincides with peak heating demand.

In conclusion, it can be deduced from Fig. 2 that the analysis reveals a substantial seasonal impact on the performance of these systems, with a marked reduction in energy coverage during the winter months for countries like Sweden and Germany.

To see seasonal operational trends during typical winter (first week of January) and summer (first week of July) conditions, please see the graphs in the Supplementary Information (Fig. S1–S4).

4.1.2. Comparative energy analyses in Europe

As shown in Fig. 3A, PV systems demonstrate strong performance across most European nations. The total electricity generated by PV systems surpasses the demand in the corresponding countries, with exceptions for Estonia, Finland, France, and Sweden. The electricity coverage ratio—defined as the percentage of demand covered by PV generation— varies significantly. For example, Italy generating 7206 kWh total (1292 kWh covers demand and 5914.7 kWh is excess) resulting in 49.2 % coverage, compared to Finland's 4076 kWh total

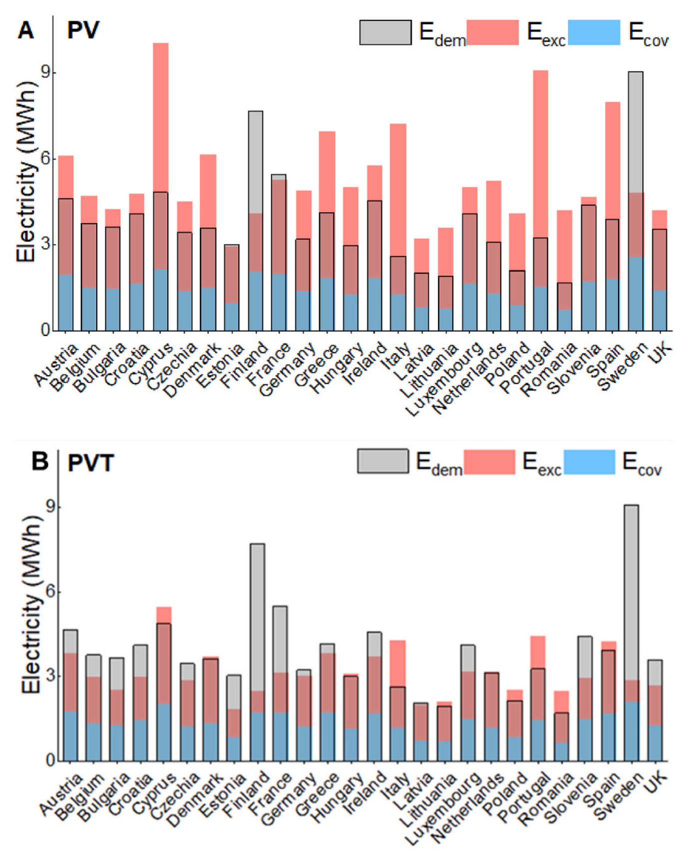

Fig. 3. Annual comparative analysis of PV and PVT electricity performance across various European countries. (a) PV system electricity performance, detailing total electricity demand (E_{dem}), excess generation (E_{exc}), and demand coverage (E_{cov}). (b) PVT system electricity performance.

(2096 kWh covers demand and 1981 kWh is excess) with 27.4 % coverage. On average, the electricity coverage ratio stands at 41.4 % across the 26 countries analyzed. Lower electricity coverage ratios were observed in northern countries such as Finland (27.3 %) and Sweden (28.8 %), reflecting climate influence. France, despite a moderate coverage ratio of 36.8 %, achieves a substantial actual covered electricity demand (2.02 MWh/year), ranking fourth highest among the countries studied. This discrepancy arises due to its high electricity demand and a relatively small amount of excess electricity. This indicates that countries with high overall demand can achieve significant energy coverage in absolute terms even with a lower relative ratio. Conversely, Italy achieves the highest electricity coverage ratio in PV systems at 49.2 %, showing a distinct dynamic: only 17.9 % of its total generated electricity contributes to meeting on-site demand (1.30 MWh/year). This highlights how varying demand levels and the balance between generation and consumption shape PV system utilization, even without accounting for the potential benefits of exporting surplus electricity back to the grid. The data underscore the versatility of PV systems, highlighting their capacity to deliver efficient energy coverage under diverse climatic and demand scenarios. In certain instances, countries exhibit efficient energy coverage despite relatively lower coverage rates, a phenomenon attributed to the interplay between demand levels and the generation of excess electricity.

When compared to PV system performance (Fig. 3A), the electrical performance of PVT systems (Fig. 3B) exhibits a lower average excess electricity generation, with a reduction of approximately 3.9 % across the studied countries. This decline is attributed to the diversion of a portion of solar energy to thermal production, illustrating the inherent trade-off in PVT systems: enhanced thermal utility at the expense of reduced electrical output. Examining PVT electrical performance in Fig. 3B reveals high electricity coverage ratios in countries like Italy and Spain, suggesting good system capacity alignment with demand. Conversely, countries with colder climates such as Finland and Sweden, exhibit higher electricity demands coupled with lower covered electricity demand, suggesting a greater need for either enhanced system efficiency or additional capacity to meet demand. Furthermore, the presence of significant excess electricity is notable in several countries, like the United Kingdom, which highlights opportunities for energy storage.

Fig. 4A illustrates the annual thermal performance of PVT systems. As expected, contries with colder climates with prolonged heating seasons, such as Sweden and Finland, exhibit higher total thermal demands for hot water and space heating. For instance, Spain achieves a high heating coverage of 94.2 % by providing 5388.6 kWh of thermal energy. In contrast, Sweden delivers 4423.2 kWh of thermal energy, yet achieves a lower coverage percentage (35.2 %) due to significantly higher heating needs. On the other hand, the coverage rates in Latvia, Lithuania, and Luxembourg report the lowest coverage levels, at 26.1 %, 30.1 %, and 29.8 %, respectively. These are well below the average coverage rate of 48.4 % for the 26 countries, placing them towards the bottom of the ranking. This could be indicative of several factors, such as suboptimal system performance, less favorable climatic conditions, or potentially higher relative demands that are not being met by the current PVT system capacities in these countries.

In Fig. 4B, the blue bars' relative sizes suggest that countries such as Spain and Cyprus, typically with more favorable solar irradiance, have higher coverage ratios for ST systems. In contrast, countries at higher latitudes with cooler climates, such as Finland and Sweden, have lower coverage ratios, where greater heating demand contributes to lower coverage.

4.2. *Comparative economic-environmental analysis*

4.2.1. *Economic performance*

Fig. 5C illustrates the Payback Times (PBT) for solar energy systems across Europe, revealing a clear hierarchy in economic viability. PV

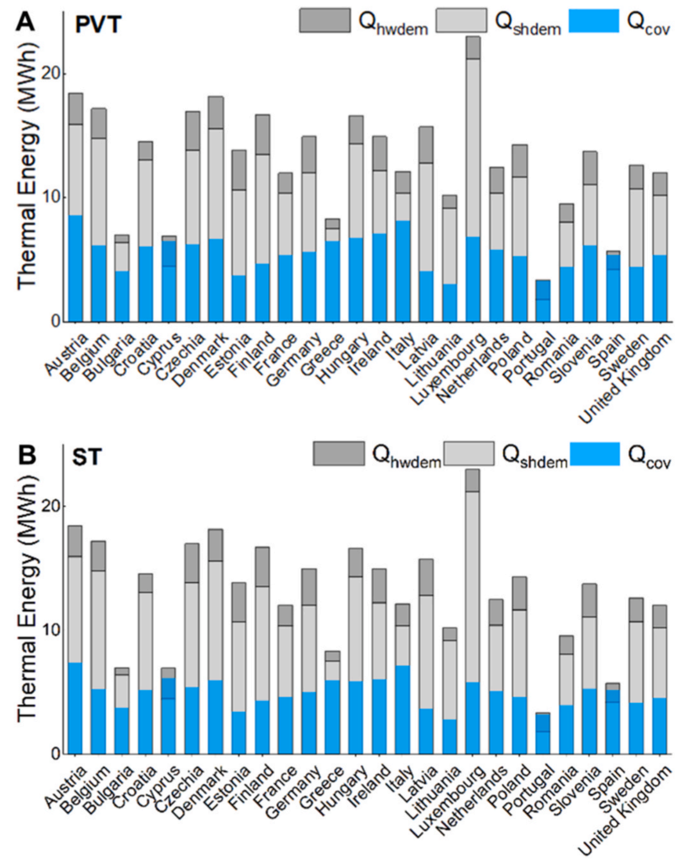

Fig. 4. Annual comparative analysis of ST and PVT thermal performance across various European countries. (a) PVT system thermal energy performance, showing the total thermal demand ($Q_{hw,dem}$), space heating demand ($Q_{sh,dem}$), and coverage (Q_{cov}). (b) ST system thermal energy performance.

systems are the most economically advantageous with an average PBT of 9.5 years, dropping to just 4.8 years in sun-rich Spain, the lowest observed across the continent. PVT systems follow, with a longer average PBT of 22.3 years, reflecting their more complex technology that provides both electricity and heat but also incurs higher initial costs. ST systems have the longest payback period, averaging 50.4 years in European countries, with Latvia experiencing the highest PBT at 115 years. This extended duration is largely attributed to higher upfront investment and the lower economic value of thermal energy, particularly when compared to natural gas prices, which are used as a benchmark for heating costs. This economic assessment underlines the need for strategic investments in solar technologies that balance upfront costs with long-term energy and cost savings.

Fig. 5D illustrates the Life Cycle Savings (LCS) of PV, PVT, and ST systems over a 25-year lifespan across Europe, with color gradients indicating the magnitude of financial benefits by country. PV systems display a heterogeneous pattern of savings, with darker shades suggesting substantial financial benefits, likely due to a combination of high solar irradiance, favorable energy pricing, and supportive policies. In contrast, PVT systems exhibit more varied LCS outcomes, reflecting their sensitivity to both electrical and thermal needs and the efficiency of integrated energy generation. ST systems, conversely, show relatively lower LCS. This likely stems from higher capital costs and the lower economic value of thermal energy compared to electricity. These results highlight that PV systems demonstrate positive LCS across all European countries, indicating that they are most financially advantageous over a 25-year lifespan. PVT systems exhibit intermediate LCS values, positioning them between PV and ST systems in terms of profitability. ST systems remain economically uncompetitive compared to PV and PVT systems. This visual representation underscores the variability in solar technology benefits across Europe, influenced by regional climatic conditions, energy costs, and installation expenses.

Fig. 5A presents the Levelized Cost of Energy (LCOE) for PV, PVT, and ST systems across Europe, offering a detailed perspective on their financial viability. PV systems, with the lowest average LCOE at 0.079 €/kWh, emerge as the most cost-effective solution for electricity generation. This aligns with their shortest average PBT (Fig. 5c) and generally highest LCS (Fig. 5b), underscoring their economic appeal. PVT systems follow with an average LCOE of 0.133 €/kWh; while costlier, their ability to generate both electricity and heat enhances their overall value. The higher economic worth of electricity over thermal energy, combined with PVT systems' dual-output capability, contributes to their intermediate PBT and an LCS of 2519 €, which significantly exceeds that of ST systems. On the other hand, ST systems exhibit the highest average LCOE at 0.199 €/kWh. This corresponds to the longest PBT and generally negative LCS, reflecting lower financial returns over their life cycle, evidenced by their negative LCS of −2291 €. Comparatively higher initial costs for ST systems and the lower relative value of thermal energy are significant factors contributing to this trend. Overall, the LCOE analysis aligns with PBT and LCS metrics, establishing a clear economic hierarchy: PV systems are the most financially viable, followed by PVT systems, while ST systems face substantial economic barriers.

The geographical analysis across Europe highlights a clear regional distinction in solar system economic performance. The trends indicate that countries in the southwestern part of Europe, typically with lower latitudes, enjoy a set of advantages for solar technology deployment. These advantages include abundant solar irradiance, prolonged daylight hours, and generally higher temperatures, which together contribute to

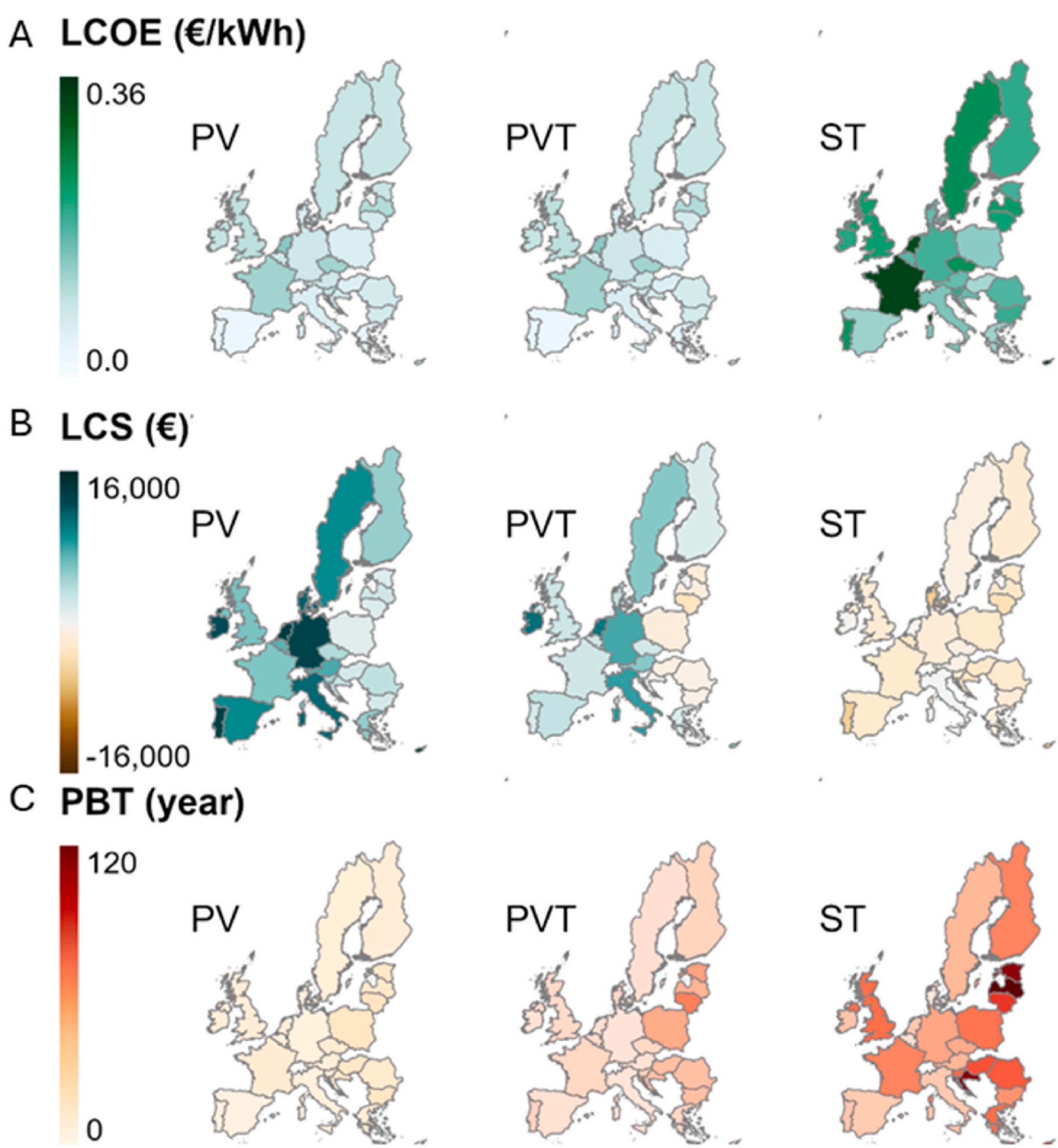

Fig. 5. Geographic comparison of economic and performance metrics for PV, PVT, and ST systems across Europe. Displayed metrics include payback time (PBT, years), levelized cost of electricity (LCOE, €/kWh), and life cycle savings (LCS, €). Color gradients indicate the relative magnitude of each metric, from low (light) to high (dark), for each solar technology across countries.

a reduced need for heating and enhance the efficiency of solar energy systems. The result is lower PBT and higher LCS for these regions, making solar investments particularly profitable. In contrast, north-eastern Europe faces less favorable conditions, with limited sunlight exposure and colder climates, which increase the demand for heating. These factors contribute to higher LCOE values and negative LCS for several Eastern European countries, particularly for PVT systems. The data indicate that the economic viability of PVT systems under the prevailing climatic conditions and existing energy infrastructure in these regions is compromised, making these systems less attractive as an investment compared to their counterparts in the south. This spatial discrepancy underscores the need for region-specific energy policies and solar technology deployment strategies tailored to local climatic realities. It also highlights the importance of considering geographic and environmental factors in the economic assessment of solar energy technologies, ensuring that investments are directed towards systems that are not only technologically feasible but also economically sustainable within their specific regional contexts.

In summary, the overview of solar energy systems' economic viability across Europe, as detailed from the results, shows a promising landscape for PV systems. With consistently positive LCS averaging 6646 € and PBT under 25 years across all 26 surveyed countries, PV systems emerge as the most financially sound investment throughout the continent. PVT systems exhibit a more mixed performance. While 18 countries demonstrate cost recovery and profit generation within the systems' operational lifetime, there are 8 countries, primarily in north-eastern Europe, where PVT systems struggle to achieve economic viability. In these regions, PBT beyond 25 years and negative LCS values, indicating that the systems are unlikely to recoup their initial and operational costs over their lifetime. On the other hand, ST systems face significant economic challenges, with only 4 out of the 26 countries showing the potential for cost recovery within a 25-year lifespan. Such a scenario underscores the necessity for supportive fiscal policies to improve the financial attractiveness of ST systems in less favorable regions.

4.2.2. Environmental potential

Fig. 6 serves as an analytical tool for assessing the environmental impact of solar energy systems across 26 European countries, using annual CO_2 emission reduction (ER) as the primary indicator. The ER quantifies the amount of CO_2 emissions a household avoids by utilizing solar systems per annum. Average ER values are 1528 $kgCO_2$ for PV systems, 1275 $kgCO_2$ for PVT systems, and significantly lower at 334 $kgCO_2$ for ST systems. The variation in average ER among system types is primarily due to differences in their energy outputs. Additionally, the disparities in ER values are strongly affected by country-specific CO_2 emission factors for electricity generation, which vary with national energy mixes and generation technologies. For instance, Cyprus has a high emission factor (642 gCO_2/kWh), whereas Sweden's is significantly lower (8 gCO_2/kWh). The European average stands at 280 gCO_2/kWh, significantly higher than that for the natural gas factor (55 gCO_2/kWh). As ST systems produce only thermal energy, their emissions reduction potential is inherently constrained. On the other hand, the ER of electricity-generating systems (PV and PVT) is highly dependent on geographic location and local electricity emission intensity.

An earlier analysis highlighted the superior electricity generation capability of PV systems compared to PVT systems. This advantage becomes more pronounced in countries with higher CO_2 emissions per unit of electricity, as reflected in the ER values, where PV systems exhibit a slightly higher emission reduction than PVT systems. A country-by-country comparison shows a balanced split: in 13 countries, PV systems achieve greater ER, often where CO_2 emissions per unit electricity are above the European average. Notably, countries like Cyprus (642 gCO_2/kWh), Estonia (734 gCO_2/kWh), and Poland (745 gCO_2/kWh) benefit more significantly from PV due to its ability to offset a carbon-heavy grid. Conversely, the remaining 13 countries show higher ER values for PVT systems, especially where electricity grids have lower emissions. In essence, PVT systems tend to have better environmental performance in countries with cleaner electricity grids, whereas PV systems are more beneficial in regions with higher carbon intensity in electricity generation. This analysis underscores the importance of aligning solar system deployment with national energy profiles to maximize environmental benefits.

4.2.3. Comparative analysis under variable energy source prices

In Fig. 7, we present an analytical perspective on the PBT for solar energy systems—PV, PVT, and ST—across 12 selected European countries under varying electricity and natural gas prices. The reason for selecting these 12 countries primarily stems from the fact that the installed capacity of solar energy systems in these countries ranks among the top in Europe [7], and Sweden and Finland are considered for geographical representation. The data indicate that the PBT for all systems is significantly influenced by energy prices. As natural gas prices increase relative to electricity prices, the economic attractiveness of PVT systems is enhanced by a reduction in their PBT, potentially making them more economically viable than PV systems.

Notably, in an environment where both natural gas and electricity prices are elevated (0.1 €/kWh), ST systems begin to exhibit quicker returns in some countries. For example, in Poland, the PBT is 12.8 years for ST systems, compared to 17.4 years for PV and 13.9 years for PVT

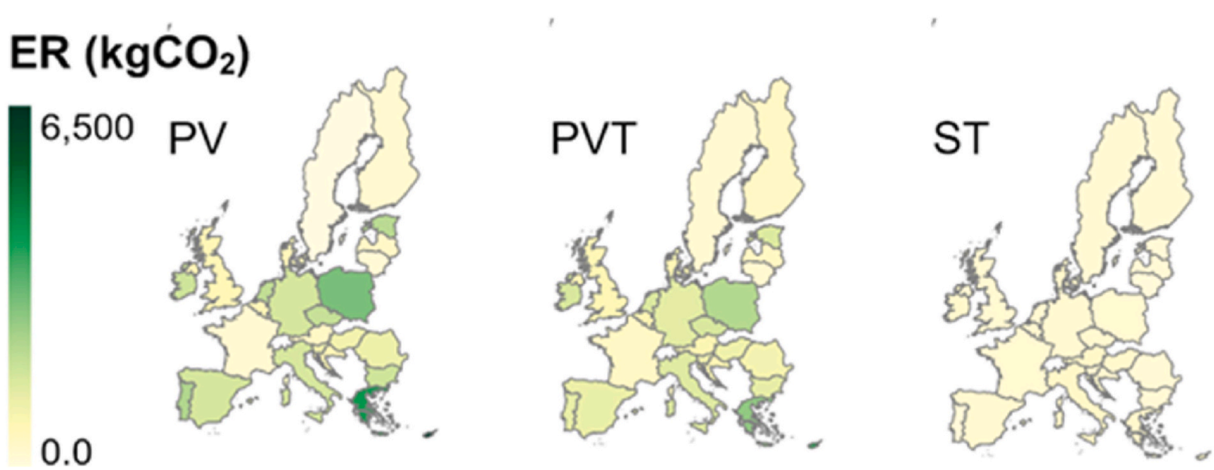

Fig. 6. Geographic comparison of environmental performance metrics for PV, PVT, and ST systems across Europe. The displayed metric is emissions reduction (ER, kg CO_2). Color gradients indicate the relative magnitude of each metric, from low (light) to high (dark), for each solar technology across countries.

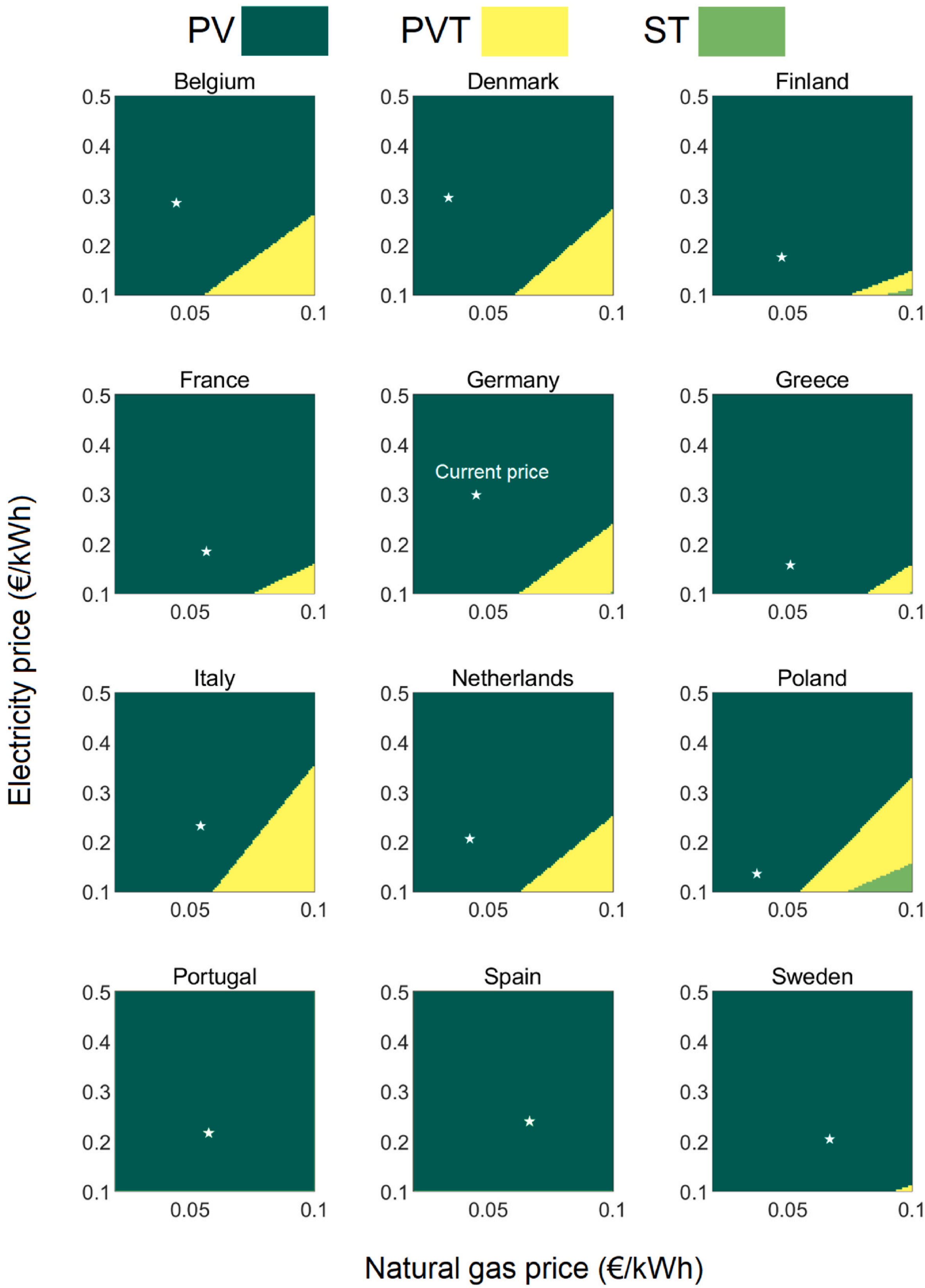

Fig. 7. Payback Time (PBT) analysis for PV, PVT, and ST systems under varying electricity and natural gas prices across 12 European countries. Each plot identifies the current national energy price with a star, situating it within the broader context of potential price variations, thereby guiding the optimal choice of solar system investment based on market conditions.

systems. This trend is further underscored when both energy prices reach their peak (0.5 €/kWh for electricity and 0.1 €/kWh for natural gas), PBT for ST systems holding steady, PV becomes the most favorable with a PBT of 7 years, followed by PVT at 8.6 years, demonstrating the value of dual-output systems in high-cost scenarios. The implication is that in a high-cost energy landscape, PVT systems stand out due to their dual function of electricity and heat generation, facilitating more rapid cost recovery.

Conversely, in sun-rich, low-heating-demand countries like Spain and Portugal, energy price changes have a smaller effect on system selection hierarchy. For instance, in Spain, even under high natural gas prices (0.1 €/kWh) and low electricity prices (0.1 €/kWh), ST systems are less attractive due to a PBT of 22 years, as opposed to 19 years for PV and 21 years for PVT systems. In high energy price scenarios (e.g., 0.5 €/kWh and 0.1 €/kWh respectively), the PBT for all systems shortens notably, especially for PV systems, reflecting the rapid recovery of investment. For example, in Spain, the PBT for the PV system drops to around 4.5 years, while the PVT system is 8.3 years. This remarkable shortening, particularly for PV, reflects the rapid recovery of investment in high energy price scenarios.

The current energy prices (indicated by white dots in the figure) reveal that PV systems offer the shortest PBT across all examined countries, aligning with their currently high installed PV capacities. This observation underscores the interplay between a country's energy policies, pricing structures, and economic conditions in the strategic selection of solar energy systems, highlighting the need for careful consideration of potential future shifts in these variables when making investment decisions.

5. Conclusions

This study conducted a comprehensive comparative analysis of PV, PVT, and ST systems for residential use across 26 European countries, assessing their energy performance, economic viability, and environmental impact. The findings provide quantitative evidence on the strengths and limitations of each technology under diverse climatic and market conditions.

Economically, PV systems emerged as the most attractive option, with an average payback time (PBT) of 9.5 years, dropping to as low as 4.8 years in high-irradiance regions like Spain. PV systems consistently showed the highest life cycle savings (LCS), averaging 6646 € over a 25-year lifespan, and the lowest average Levelized Cost of Energy (LCOE) at 0.079 €/kWh. PVT systems demonstrated an intermediate economic performance with an average LCS of 2519 €, with a longer average PBT of 22.3 years. Economic viability for PVT systems is geographically dependent, with 18 out of 26 countries showing cost recovery within the system's lifetime, yet 8 countries in northeastern Europe faced economic challenges with PBT exceeding their operational lifetime and negative LCS values. ST systems were the least economically favorable, exhibiting the longest average PBT and negative LCS values. This low economic competitiveness is primarily linked to higher upfront investment costs and the lower economic value of thermal energy compared to natural gas prices.

Environmentally, PV systems achieved the highest average annual CO_2 emission reduction (ER) of 1528 $kgCO_2$/year, compared to 1275 $kgCO_2$/year for PVT systems and 334 $kgCO_2$/year for ST systems. The ER of electricity-generating systems (PV and PVT) is strongly influenced by country-specific electricity emission factors. PV systems showed higher ER in countries with higher carbon intensity in their electricity grids, such as Cyprus (642 gCO_2/kWh), Estonia (734 gCO_2/kWh), and Poland (745 gCO_2/kWh), by offsetting more carbon-heavy grids. However, in regions with cleaner electricity mixes, PVT systems may offer a better environmental balance due to their ability to offset both thermal and electrical loads.

The results underscore the significant impact of regional factors, such as solar irradiance, energy pricing structures, and grid carbon intensity, on system performance. Southern European countries, with higher solar irradiance and temperatures, benefit from the highest energy and economic returns for all solar technologies. Conversely, less favorable conditions in northeastern Europe pose challenges (e.g., higher LCOE values), particularly for PVT and ST systems. The sensitivity analysis of energy prices further indicated that rising natural gas prices can enhance the economic attractiveness of PVT systems due to their dual output. Under current energy prices, PV systems consistently offer the shortest PBT.

In conclusion, strategic deployment of solar technologies should be tailored to regional specificities, considering local climate, energy prices, and grid characteristics, to be adaptable to potential future shifts in these factors to maximize both economic returns and environmental sustainability.

Our analysis and results are based on data representative of single-family homes (SFHs). Other residential building types, such as multi-family dwellings, differ in both energy demand and installation area availability. Future studies should extend this comparative framework to additional residential categories, using building-type-specific data to provide comprehensive guidance for solar system integration across the entire residential sector.

Furthermore, while capital city data enabled consistent cross-country comparisons, for larger nations, results should be interpreted as general trends rather than capturing internal regional diversity, and further research could delve into these regional variations.

While this study focuses on operational CO_2 emissions in its environmental assessment, a comprehensive environmental evaluation should encompass broader considerations. Future work should aim to include full Life Cycle Assessment methodologies to account for emissions associated with material production, component manufacturing, transportation, and end-of-life processing. Such comprehensive analysis would provide stakeholders with more complete environmental decision-making tools while supporting policy development for sustainable energy system deployment.

Further research is also recommended to explore the integration of battery technologies to enhance the utilization of solar energy. Additionaly, demand-side management strategies, such as smart home technologies and load shifting techniques, can be included to optimize energy consumption patterns and align them with solar energy availability.

CRediT authorship contribution statement

Haoyu Han: Writing – original draft, Software, Investigation, Formal analysis. **Mustafa Kurses:** Writing – review & editing, Investigation. **Asmaa A. Harraz:** Writing – review & editing. **Jingyuan Xu:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.138368.

Data availability

Data will be made available on request.

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