

Article

Hydrogen Conversion Pathways for Zero-Emission Residential Heating Using Air-to-Water Heat Pumps

Ivan Dimchev ^{1,*}, Penka Zlateva ^{2,*} and Angel Terziev ¹¹ Faculty of Power Engineering and Power Machines, Technical University of Sofia, 1756 Sofia, Bulgaria; aterziev@tu-sofia.bg² Department of Thermal Engineering, Technical University of Varna, 9010 Varna, Bulgaria

* Correspondence: ivan.dimchev@tu-sofia.bg (I.D.); pzlateva@tu-varna.bg (P.Z.)

Abstract

The use of hydrogen for heating is one of the pathways toward zero-emission buildings. Two possibilities for using hydrogen in combination with heat-pump systems were analyzed: an electrically driven heat pump powered by a fuel cell and a mechanically driven heat pump powered by a hydrogen internal combustion engine (ICE). Heat-pump operation was adapted to local climatic conditions using typical meteorological year datasets for 30 representative locations across Bulgaria. The seasonal coefficient of performance (SCOP) values were further adjusted toward actual operating conditions using a field-performance correction factor. The results reveal a thermodynamic transition between the two pathways, defined by a critical seasonal coefficient of performance, $SCOP_{crit}$. For the reference ICE heat-recovery fraction of 0.45 and without direct fuel-cell heat recovery, $SCOP_{crit}$ is 2.53. Above this threshold, the fuel-cell-driven pathway requires less hydrogen, whereas below it, the mechanically driven pathway requires less hydrogen. A strong correlation was identified between pathway dominance and the mean outdoor temperature during the heating period, with a transition temperature of about 2.4 °C. The sensitivity analysis shows that $SCOP_{crit}$ ranges between 1.40 and 3.52. Overall system efficiencies ranged from approximately 1.2 to 1.8 on a lower heating value (LHV) basis, exceeding typical direct hydrogen-combustion efficiencies.

Keywords: hydrogen conversion; zero-emission; heat pumps; fuel cells; hydrogen internal combustion engines

Academic Editor: Maria Founti

Received: 12 June 2026

Revised: 23 July 2026

Accepted: 2 August 2026

Published: 4 August 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Decarbonization of the building sector has become one of the main objectives of European policy on climate change and fossil fuel independence. Buildings represent a significant share of the energy consumption and greenhouse gas emissions in the European Union. This leads to the need for a transition to highly efficient heating solutions that do not rely on fossil fuels [1]. The revised Energy Performance of Buildings Directive (EPBD), adopted in 2024, requires future buildings to have zero emissions generated on site. According to the directive, all new buildings owned by public authorities must meet the requirements for zero-emission buildings from January 1, 2028, and from January 1, 2030, all new buildings will be required to meet these requirements [2]. The Directive [2] defines a zero-emission building as a building with very high energy

performance and no on-site carbon emissions from fossil fuels. These regulatory changes make it necessary to evaluate alternative heating methods capable of meeting these requirements for future residential buildings.

Electrically driven heat pump systems are widely used as one of the most efficient technologies for decarbonizing the building sector, as they transfer heat energy from low-temperature environmental sources rather than generating heat through combustion. This principle allows for a heating efficiency significantly above 1, with the typical coefficient of performance (COP) and seasonal coefficient of performance (SCOP) exceeding 3 under operating conditions [3]. In this regard, heat pumps are considered a key technology for achieving nearly zero and zero-emission buildings, enabling significant reductions in primary energy consumption and greenhouse gas emissions [4].

At the European level, the electrification of heating through the introduction of heat pumps is considered one of the most effective ways to reduce emissions in the building sector. System-level analyses show that large-scale electrification of heating could reduce total energy-related emissions by up to 17%, provided that electricity generation continues to decarbonize [5]. Additional studies show that between 1.1 and 1.6 TW_{th} of heat pump capacity could be integrated into European energy systems, corresponding to approximately 29–45% of total space heating demand [5]. These results underline the strategic role of heat pumps not only as highly efficient end-use technologies, but also as flexible components supporting decarbonization.

Despite their high theoretical performance, the seasonal efficiency of heat pumps is highly dependent on local climate conditions and actual operating conditions. Field studies often report significant discrepancies between the SCOP declared by the manufacturer and the SCOP calculated based on field measurements. Climate adaptation of declared SCOP values can reduce the seasonal performance of air-to-water heat pumps (AWHPs) by up to 19%, while additional operational effects, such as partial load cycles, control limitations, and defrosting, can lead to a total reduction approaching 26% compared to the declared values [6,7]. Other studies show that defrost cycles alone can reduce SCOP from 5 to 13%, depending on climatic conditions and system design [8]. These findings indicate that realistic seasonal modelling is essential when evaluating heating systems, particularly when estimating the future energy consumption of buildings, especially in predictive analyses where performance assumptions directly influence thermodynamic comparisons.

While electrification through heat pumps represents the dominant pathway toward building decarbonization, hydrogen is increasingly considered a complementary energy carrier capable of providing long-duration storage and supporting energy-system flexibility [9]. In residential applications, hydrogen enables alternative energy conversion pathways that can operate independently from direct grid electrification while maintaining compatibility with highly efficient heat pump technologies. Recent studies emphasize that the integration of hydrogen within building energy systems should not be viewed as a direct replacement of electrification, but rather as a flexible option for seasonal storage and peak-demand balancing. Comparative analyses indicate that hybrid hydrogen-heat pump configurations may provide the most efficient hydrogen-based solution among various residential systems, especially when hydrogen is used strategically during peak heating periods while heat pumps operate under favorable conditions [10].

Hydrogen also offers significant advantages as a long-term energy storage medium capable of addressing the seasonal mismatch between renewable electricity generation and residential heating demand. In many regions, photovoltaic electricity production peaks during summer months, whereas heating demand reaches its maximum during winter. Through power-to-hydrogen conversion, surplus renewable electricity can be

stored and later utilized when heating requirements increase, thereby enhancing the flexibility and resilience of residential energy systems. The broader role of hydrogen as a cross-sectoral energy carrier has also been emphasized by Staffell et al. [11], who focused their study on the importance of hydrogen for seasonal storage, sector coupling, and balancing renewable electricity generation. Techno-economic analyses of residential heating systems indicate that hydrogen produced through electrolysis and stored seasonally can provide long-term energy-system flexibility, while fuel-cell waste heat can contribute to meeting residential heating demand during winter [12]. The economic feasibility of such storage concepts remains strongly dependent on hydrogen production costs and electricity prices. Recent analyses indicate that large-scale deployment of electrolyzers and continued reductions in renewable electricity costs are expected to improve the competitiveness of green hydrogen pathways in the coming decades [13]. Comparative assessments further suggest that hydrogen can play an important role in future decarbonization strategies when applied in sectors where direct electrification is difficult or where long-duration energy storage is required [9,11]. At the residential scale, however, economic viability remains a key constraint, with practical 1–2 kW domestic fuel-cell micro-CHP systems requiring long-term system costs of approximately USD 3000–5000 to become commercially competitive [14].

The integration of hydrogen technologies into residential buildings is closely linked to the broader concept of sector coupling, where electricity, heating, and gas infrastructures interact to improve overall system performance. Within this framework, heat pumps, electrolyzers, hydrogen storage systems, and fuel cells can operate synergistically, enabling more effective utilization of renewable energy while reducing dependence on fossil fuels. Techno-economic assessments have shown that integrated configurations combining photovoltaic systems, heat pumps, electrolyzers, and fuel cells can provide a cost-effective pathway toward residential decarbonization while simultaneously offering additional flexibility to the wider energy system [10].

Fuel cell technologies have attracted considerable attention for residential heating applications due to their ability to simultaneously generate electricity and useful thermal energy with high overall efficiencies. Unlike conventional combustion-based heating systems, fuel cells convert hydrogen directly into electricity through electrochemical processes while recovering heat that can be utilized for domestic space heating and hot water production. As a result, fuel cell micro-combined heat and power (micro-CHP) systems are increasingly regarded as a promising pathway for reducing greenhouse gas emissions and improving energy efficiency in residential buildings [15]. The economic viability and long-term deployment potential of residential fuel-cell micro-CHP systems have also been extensively investigated, with studies indicating that continued cost reductions and technology maturation could significantly improve their competitiveness in future low-carbon residential energy systems [16]. Furthermore, comprehensive reviews of PEM fuel-cell technologies have confirmed their suitability for residential applications due to their high efficiency, low emissions, and compatibility with distributed energy systems [16]. Previous studies have highlighted the potential role of fuel cells within future low-carbon heating strategies, particularly in regions where seasonal heating demand coincides with periods of increased electricity consumption [15,16].

The practical feasibility of residential fuel-cell systems has been demonstrated through several large-scale deployment programs and field studies. Operating experience from residential proton exchange membrane fuel cell (PEMFC) micro-CHP installations has confirmed their capability to provide reliable electricity generation while simultaneously contributing to domestic heating demand [17]. Furthermore, life-cycle assessments indicate that fuel-cell micro-CHP systems can achieve lower greenhouse gas

emissions than conventional gas heating technologies, particularly when supplied with low-carbon or renewable hydrogen [18]. These findings support the growing interest in fuel-cell-based residential energy systems as a complementary solution alongside heat pumps in future zero-emission buildings.

The integration of fuel cells with heat pumps has recently emerged as a promising strategy for improving the overall utilization efficiency of hydrogen in residential applications. In such systems, the fuel cell primarily supplies electricity while the heat pump upgrades ambient thermal energy to satisfy space-heating demands, thereby reducing the hydrogen consumption required to achieve a given heating output. Compared with conventional fuel-cell micro-CHP systems, the incorporation of a heat pump enables a more effective use of the electricity generated by the fuel cell while simultaneously benefiting from the high seasonal performance of modern heat pump technologies [19,20].

Several studies have investigated the potential benefits of combining fuel cells and heat pumps in residential buildings. Kwan et al. performed a comparative assessment of different heat pump technologies integrated with fuel-cell micro-CHP systems and demonstrated that vapor-compression heat pumps provide the highest hydrogen utilization efficiency due to their superior coefficient of performance [19]. More recently, Andrade et al. evaluated an integrated fuel cell and air-to-water heat pump system across multiple European climates and reported energy savings exceeding 20% compared with fuel-cell-only configurations, while also reducing the required fuel-cell capacity by more than 40% [20]. These findings indicate that fuel-cell-powered heat pump systems can significantly improve overall system efficiency and represent a viable pathway toward low-carbon residential heating.

One promising pathway involves hydrogen conversion through fuel cells, supplying electricity to conventional electrically driven heat pumps. Fuel-cell-based combined heat and power (CHP) systems offer high electrical efficiencies, with proton exchange membrane (PEM) fuel cells reaching electrical efficiencies of approximately 60% while simultaneously producing useful heat [15,16]. Integrating fuel cells with air-to-water heat pumps has been shown to significantly improve system performance compared to fuel-cell-only heating approaches. Recent residential simulations across European climates demonstrate that coupling a fuel cell with a heat pump can reduce fuel cell size by at least 40% and achieve energy savings of around 20% compared with systems without heat pumps [20]. The combination allows the heat pump to amplify the electrical output of the fuel cell through a high COP, thereby reducing overall hydrogen consumption and improving seasonal energy efficiency.

An alternative and less explored pathway is the use of hydrogen internal combustion engines (H₂-ICE) to provide direct mechanical drive to the heat pump compressor. Hydrogen ICE technology has demonstrated rapid progress in recent years, with reported peak fuel conversion efficiencies approaching 50% and average efficiencies above 35% under optimized conditions. Such systems offer the additional advantage of waste heat recovery from exhaust and cooling circuits, which can be utilized for domestic hot water or space heating, potentially increasing total system efficiency [21]. Although hydrogen ICEs have mainly been investigated for transportation or stationary power applications, their integration as mechanical drives for heat pumps represents a realistic near-future concept that could combine robust compressor operation with simultaneous thermal recovery. Compared with fuel-cell systems, ICE-driven configurations may provide higher power density and simpler mechanical integration, but at the expense of lower electrical conversion efficiency and greater thermodynamic complexity.

Recent studies comparing hydrogen conversion technologies have highlighted important differences between fuel-cell and hydrogen-engine pathways. Fuel-cell systems

generally achieve higher hydrogen utilization efficiencies due to the direct electrochemical conversion of hydrogen into electricity, whereas hydrogen internal combustion engines benefit from lower capital costs, higher technological maturity, and compatibility with existing engine manufacturing and servicing infrastructure. In addition, hydrogen engines offer high power density and rapid load-following capability, making them attractive for applications characterized by variable heating demand. Although the lower conversion efficiency of hydrogen engines represents a thermodynamic disadvantage, the possibility of recovering waste heat from engine cooling and exhaust systems can partially compensate for this limitation and significantly improve overall system performance. Consequently, hydrogen internal combustion engine-driven heat pumps should be considered a viable alternative to fuel-cell-powered heat pump systems, particularly in applications where waste heat recovery can be effectively utilized [21–23].

A practical technological reference for mechanically driven hydrogen heat pump systems can be found in existing gas-engine-driven heat pumps (GEHPs), which have been commercially deployed using natural gas engines. GEHP systems operate by mechanically driving the heat pump compressor via an internal combustion engine while simultaneously recovering waste heat from engine cooling and exhaust gases, thereby increasing overall system efficiency. Experimental and modelling studies report that such configurations can achieve primary energy ratios significantly higher than conventional heating systems, particularly when waste heat is effectively utilized for space heating and domestic hot water production. Seasonal analyses have shown that GEHP performance strongly depends on part-load operation and climatic conditions, but the integration of engine waste heat provides an additional thermal contribution that improves system performance under low outdoor temperatures [24].

Further experimental investigations confirm that gas-engine-driven heat pumps can maintain stable operation across a wide range of heating loads while achieving substantial fuel savings compared to traditional boiler-based systems [25]. The proven operational concept of GEHP systems demonstrates that mechanical compressor drive combined with thermal recovery is technically viable and offers a realistic engineering foundation for future hydrogen-fueled systems. Replacing natural gas with hydrogen in such architectures represents a logical near-future development pathway toward zero-emission heating. In this perspective, hydrogen internal combustion engine-driven heat pumps can be interpreted as a technological evolution of existing GEHP solutions, benefiting from established mechanical integration while enabling carbon-free operation when supplied with renewable hydrogen.

Despite growing research interest in hydrogen-based energy systems, existing studies primarily examine fuel-cell-powered heat pumps, hydrogen internal combustion engines, and gas-engine-driven heat pumps independently [19–25]. Direct comparisons between electrochemical hydrogen conversion coupled with electrically driven heat pumps and thermomechanical conversion through hydrogen internal combustion engine-driven heat pumps remain limited [20–24]. Furthermore, these pathways have not been systematically compared within a unified framework that incorporates climate-adapted and field-corrected seasonal heat-pump performance [6–8]. Consequently, a quantitative performance boundary defining the transition between the two pathways, together with its relationship to local climatic conditions, remains insufficiently investigated.

To address this research gap, the present work develops a forecast analysis of hydrogen conversion pathways for zero-emission residential heating using air-to-water heat pumps. Two system configurations are investigated: (a) hydrogen conversion through fuel cells supplying electrically driven heat pumps and (b) hydrogen internal combustion engine-driven heat pumps with simultaneous waste-heat recovery, representing a near-future evolution of gas-engine heat-pump technology. The main

contribution of the study is the derivation of a critical seasonal coefficient of performance, $SCOP_{crit}$, that defines the thermodynamic transition between the two pathways under a unified seasonal climate-correction framework. This criterion is subsequently related to the climatic conditions of representative locations in Bulgaria to establish a climate–technology mapping of pathway dominance. The resulting framework identifies both the seasonal heat-pump performance and the mean heating-period outdoor temperature at which each hydrogen conversion pathway becomes advantageous in terms of hydrogen utilization.

2. Materials and Methods

2.1. Framework

The present study performs a forward-looking thermodynamic assessment of hydrogen conversion pathways for zero-emission residential heating using air-to-water heat pumps (AWHPs). Two reference conceptual system configurations are analyzed:

- Hydrogen-to-electricity conversion via a fuel cell driving an electrically powered heat pump, without direct FC waste-heat recovery, presented in Figure 1a;
- Hydrogen-to-mechanical conversion via a hydrogen-fueled internal combustion engine (ICE) directly driving the heat pump compressor, with simultaneous recovery of engine waste heat, presented in Figure 1b.

The analysis is formulated as a seasonal forecast using temperature-bin methodology, allowing realistic representation of climatic variation and partial-load operation.

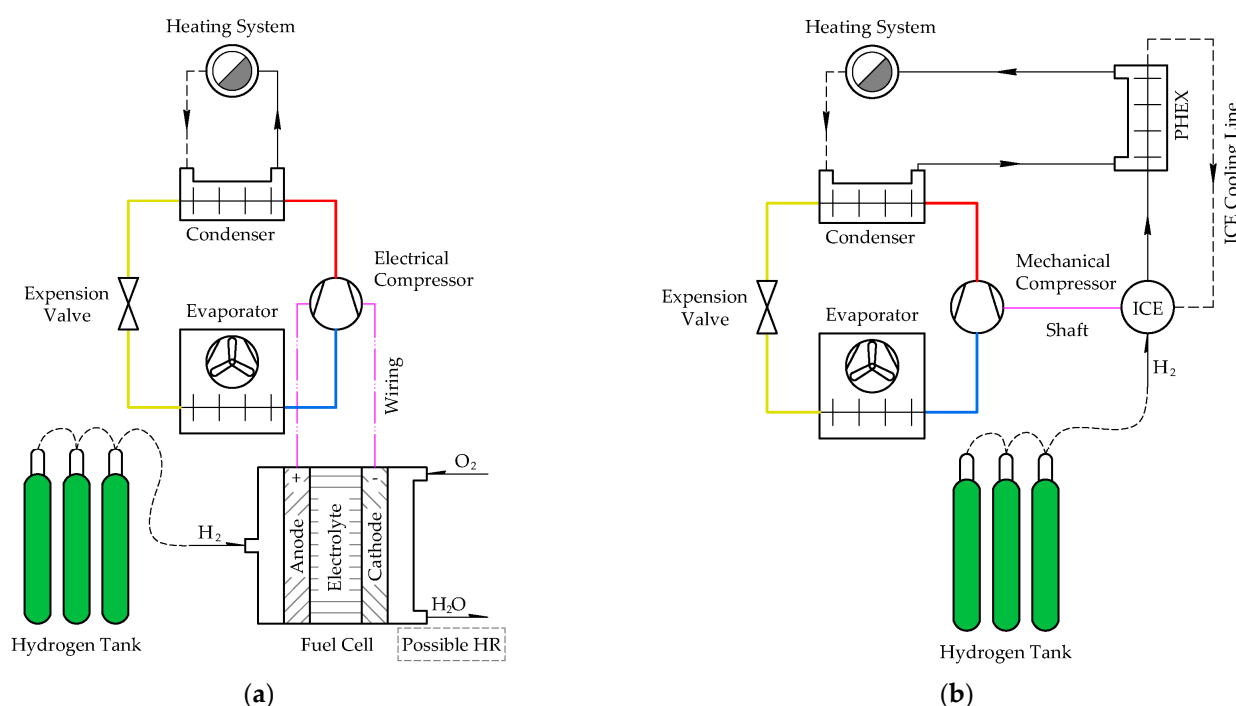


Figure 1. (a) Hydrogen-to-electricity conversion via a fuel cell driving an electrically powered heat pump with/without optional waste-heat recovery; (b) hydrogen-to-mechanical conversion via a hydrogen-fueled internal combustion engine (ICE) directly driving the heat pump compressor, with simultaneous recovery of engine waste heat. Line colors: discharge line—red; liquid line—yellow; suction line—blue.

The electricity-only FC configuration is retained as the reference one because it represents the simplest and most readily deployable near-term integration of a fuel cell

with an air-to-water heat pump. In this configuration, the FC operates solely as the electrical power source, while the heat pump remains a conventional electrically driven unit of the type currently mass-produced in split and monobloc configurations. Consequently, no fundamental modification of the refrigerant circuit, compressor drive, or basic hydraulic arrangement of the heat pump is required, and the integration is mainly limited to the electrical supply and system control. This configuration is therefore considered the most probable option for initial practical implementation. By contrast, direct utilization of FC waste heat requires additional heat exchangers, thermal storage, hydraulic integration, and control strategies, while the seasonally useful heat depends on the FC operating temperature, the heating-system supply temperature, and the temporal matching between FC operation and building demand. For these reasons, FC waste-heat recovery is excluded from the reference configuration and is evaluated separately as an additional sensitivity scenario.

2.2. Climate Data and Bin Method

Hourly outdoor air temperature data were obtained from the TMY datasets for locations all over Bulgaria. For example, the city of Sofia represents an average European climate with a low design outdoor temperature of $-16\text{ }^{\circ}\text{C}$.

The following assumptions were adopted:

- Indoor setpoint temperature: $20\text{ }^{\circ}\text{C}$;
- Heating cut-off temperature: $12\text{ }^{\circ}\text{C}$;
- Bin resolution: $1\text{ }^{\circ}\text{C}$;
- Monovalent heating operation without backup.

Only hours with outdoor temperature below the heating cut-off were included in the seasonal analysis.

The building heating load was assumed to vary linearly with ambient temperature:

$$Q_{(ti)} = Q_{design}((t_{in} - t_i)/(t_{in} - t_{design})), \text{ kW} \quad (1)$$

where

- Q_{design} is the design heating load at design outdoor air temperature, kW;
- t_{in} —the average indoor air temperature, $^{\circ}\text{C}$;
- t_i —the outdoor air temperature of the i -th temperature bin (ranging from -15 to $+12\text{ }^{\circ}\text{C}$);
- t_{design} —design outdoor air temperature, $^{\circ}\text{C}$.

Seasonal heating demand was determined by summing the product of the heating load and the corresponding number of hours in each temperature bin.

2.3. Heat Pump Seasonal Performance

The heat-pump performance calculations were based on the Energy-related Products (ErP) data provided by the manufacturer for a representative residential air-to-water heat pump [26]. For the medium-temperature application, the manufacturer reports a declared seasonal coefficient of performance of:

$$SCOP_{declared} = 3.83 \quad (2)$$

under the average-climate conditions specified in EN 14825. The heat-source condition is represented by the outdoor air temperature, whereas the heat-sink condition corresponds to the W45 application, with a water-supply temperature of $45\text{ }^{\circ}\text{C}$ under design conditions and lower supply temperatures at higher outdoor temperatures according to the applied heating curve.

The manufacturer ErP COP data were expressed as a function of the outdoor air temperature:

$$COP_{(ti)} = 0.0826t_i + 3.1565 \quad (3)$$

where t_i is the outdoor air temperature of the corresponding bin, °C. The correlation was obtained from the manufacturer-declared performance data over the investigated outdoor-temperature range and has a coefficient of determination of $R^2 = 0.9974$. The source field study presents the manufacturer performance curve and its regression over the outdoor-temperature range from approximately -15 to $+12$ °C.

The calculation of the climate-adapted seasonal coefficient of performance, $SCOP_{climate}$, follows the temperature-bin procedure standardized in EN 14825. The EN 14825 seasonal calculation approach was retained, while the standardized climatic bin-hour distribution was replaced with location-specific TMY temperature-bin data for each investigated location. The manufacturer ErP performance correlation was applied to each outdoor-temperature bin, and the seasonal useful heating output and corresponding electricity consumption were summed over the heating period:

$$SCOP_{climate} = \frac{\sum_{i=-15}^{12} Q(t_i)h_i}{\sum_{i=-15}^{12} \frac{Q(t_i)h_i}{COP(t_i)}} \quad (4)$$

where $Q_{(ti)}$ is the building heating load calculated using Equation (1), h_i is the number of heating-period hours in the corresponding 1 °C outdoor-temperature bin, and $COP_{(ti)}$ is the manufacturer COP associated with that bin.

To account for the difference between standardized and actual operating conditions, a field-performance correction was subsequently applied using the results reported in [6]. For Sofia, the climate-adapted SCOP was 3.08, whereas the average calculated SCOP based on field measurements was 2.83, corresponding to a correction factor of:

$$f_{field} = \frac{SCOP_{measured}}{SCOP_{climate}} = \frac{2.83}{3.08} = 0.919 \quad (5)$$

The final climate-adapted and field-corrected seasonal performance used in the hydrogen-pathway calculations was:

$$SCOP_{adapted} = f_{field} \cdot SCOP_{climate} \quad (6)$$

The field correction accounts collectively for defrosting, compressor cycling, control limitations, oversizing, and deviations from idealized part-load operation. The referenced field investigation reports a climate-adapted SCOP of 3.08 and a measured SCOP of 2.83, corresponding to an average difference of approximately 8.2%. The resulting $SCOP_{adapted}$ values were used in all subsequent calculations of system efficiency, hydrogen consumption, and critical seasonal performance.

2.4. Hydrogen Conversion Pathways

The following expressions represent seasonal energy balances. The seasonal system efficiency, η_{sys} , is defined as the useful heat delivered to the residential heating system divided by the hydrogen energy input on an LHV basis. The seasonal heating demand, Q_{season} , is calculated by summing the heating load obtained from Equation (1) over all temperature bins and is expressed in kWh. LHV is the lower heating value of hydrogen, expressed in kWh/kg, and m_{H2} is the corresponding seasonal hydrogen consumption in kg. $SCOP_{adapted}$ is the climate-adapted and field-corrected seasonal heat-pump performance calculated using the procedure described in Section 2.3.

2.4.1. Fuel-Cell-Driven System

In the reference configuration, hydrogen is converted into electricity through a fuel cell (FC) system supplying a conventional electrically driven air-to-water heat pump. This configuration represents the simplest integration of the two technologies: the FC operates as the electrical power source, while the AWHP supplies the residential heating demand. The seasonal hydrogen utilization efficiency of the reference FC configuration is expressed as:

$$\eta_{sys,FC} = \eta_{FC} \cdot SCOP_{adapted} \quad (7)$$

where:

- η_{FC} is the net electrical efficiency of the FC system on an LHV basis.

The seasonal hydrogen consumption is calculated as:

$$m_{H2,FC} = Q_{season} / (LHV_{H2} \cdot \eta_{FC} \cdot SCOP_{adapted}) \quad (8)$$

Although the reference configuration considers the FC only as an electricity generator, its thermal output can also cover part of the residential heating demand. Briguglio et al. experimentally investigated a 5 kW pure-hydrogen-fed low-temperature PEMFC system operating between 2.5 and 5 kW. At a stack temperature of 71 °C, the heat-recovery circuit produced water at about 68 °C, and the total electrical and thermal efficiency reached up to 85% at nominal operating conditions [27]. The amount of heat that can be used by the building depends strongly on the operating temperature of the heating system. Gandiglio et al. obtained a useful thermal efficiency of approximately 35% when a 1 kWe PEMFC micro-CHP system was coupled with an underfloor heating operating between 35 and 45 °C [28].

Studies combining FC systems with air-source heat pumps generally use the recovered FC heat to cover part of the building thermal load, while the heat pump covers the remaining demand. Andrade et al. considered a pure-hydrogen PEMFC supplying all household electrical loads, including the AWHP, while the thermal outputs of both the FC and the heat pump were delivered to a common thermal-storage system [20]. Kwan et al. similarly modelled a dynamically controlled system in which the electrochemical heat from the FC and the output of the heat pump jointly supplied a water-storage tank, with a battery and an energy-management system balancing the electrical and thermal loads [19].

More detailed micro-CHP configurations demonstrate that FC thermal integration also affects system operation. Arsalis et al. analysed a natural-gas-fed HT-PEMFC micro-CHP system in which recovered heat was used as the primary contribution to the residential heating load, while the heat pump operated only when additional heat was required [29]. Sorace et al. modelled a natural-gas-fed PEMFC operating between 57 and 67 °C, with net electrical and thermal outputs of 2.18 kW and 2.39 kW, respectively. In their configuration, recovered FC heat first increased the water temperature, after which an air-to-water heat pump completed the heating process to a storage supply temperature of 55 °C [30].

Based on these findings, an additional sensitivity scenario is introduced in which useful FC heat recovery contributes directly to the residential heating demand. The parameter $\eta_{rec,FC}$ is defined as the seasonally useful FC heat-recovery fraction relative to the hydrogen LHV. It represents the portion of FC thermal output that is effectively delivered to the building after accounting for temperature compatibility, heat-exchanger and distribution losses, thermal storage, auxiliary consumption, and temporal matching between FC operation and thermal demand.

The seasonal hydrogen utilization efficiency of the extended FC heat-recovery configuration is expressed as:

$$\eta_{\text{sys,FC+HR}} = \eta_{\text{FC}} \cdot \text{SCOP}_{\text{adapted}} + \eta_{\text{rec,FC}} \quad (9)$$

The corresponding seasonal hydrogen consumption becomes:

$$m_{\text{H2,FC+HR}} = Q_{\text{season}} / (\text{LHV}_{\text{H2}} \cdot (\eta_{\text{FC}} \cdot \text{SCOP}_{\text{adapted}} + \eta_{\text{rec,FC}})) \quad (10)$$

This extended expression provides a seasonal sensitivity assessment of FC thermal integration. It does not represent a detailed dynamic model of the heat-recovery circuit, thermal storage, or system control.

2.4.2. Hydrogen ICE-Driven System

In the second configuration, hydrogen is supplied to an internal combustion engine that directly drives the heat-pump compressor. In addition to the mechanical power delivered to the compressor, part of the heat released through the engine cooling and exhaust systems is recovered and supplied directly to the residential heating system. Waste-heat recovery is one of the principal advantages of gas-engine-driven heat pumps and reduces their dependence on the seasonal performance of the vapor-compression cycle [24,25].

The performance of the mechanically driven heat pump is derived from the climate-adapted and field-corrected $\text{SCOP}_{\text{adapted}}$ of the electrically driven AHP. A constant correction factor $k_{\text{ICE}} = 0.93$ is applied to represent the 7% reduction in heat-pump performance associated with the mechanically driven configuration, as adopted in the present analysis based on [24].

Seasonal system efficiency becomes:

$$\eta_{\text{sys,ICE}} = \eta_{\text{ICE}} \cdot k_{\text{ICE}} \cdot \text{SCOP}_{\text{adapted}} + \eta_{\text{rec,ICE}} \quad (11)$$

where:

- η_{ICE} is the ICE brake efficiency on an LHV basis;
- $\eta_{\text{rec,ICE}}$ is the seasonally useful fraction of engine waste heat delivered to the heating system relative to the hydrogen LHV input.

The seasonal hydrogen consumption for this system can be calculated as:

$$m_{\text{H2,ICE}} = Q_{\text{season}} / (\text{LHV}_{\text{H2}} \cdot (\eta_{\text{ICE}} \cdot \text{SCOP}_{\text{adapted}} \cdot k_{\text{ICE}} + \eta_{\text{rec,ICE}})) \quad (12)$$

2.5. Assumed Parameters

The reference system parameters and sensitivity ranges adopted in the forecast analysis are summarized in Table 1. All hydrogen conversion efficiencies and useful heat-recovery fractions are defined on a lower heating value (LHV) basis. Accordingly, η_{FC} represents the net electrical output of the FC relative to the hydrogen LHV input, whereas η_{ICE} represents the ICE brake output relative to the same hydrogen energy input. The parameters $\eta_{\text{rec,ICE}}$ and $\eta_{\text{rec,FC}}$ represent the useful recovered heat delivered to the heating system relative to the hydrogen LHV input. Literature-derived values and study-defined assumptions are identified separately, and the sensitivity ranges were selected to reflect reported operating conditions.

Table 1. Reference parameters and sensitivity ranges adopted in the analysis.

Parameter	Reference Value	Sensitivity Values	Units	Source/Basis
Hydrogen LHV	33.33	Fixed	kWh/kg	Reported in [22]
Fuel cell electrical efficiency, η_{FC}	0.55	0.50, 0.55, 0.60	/	Representative PEMFC efficiency reported in [16]

ICE brake efficiency, η_{ICE}	0.40	0.35, 0.40, 0.45	/	Representative value within the efficiency ranges reported in [21–23]
Mechanical-drive correction factor, k_{ICE}	0.93	Fixed	/	Model assumption representing a 7% performance reduction, adopted with reference to [24]
ICE useful heat-recovery fraction, $\eta_{rec,ICE}$	0.45	0.35, 0.45, 0.50	/	Sensitivity range consistent with GEHP performance and waste-heat-recovery values reported in [24,25,31,32]
FC useful heat-recovery fraction, $\eta_{rec,FC}$	0.00	0.00, 0.05, 0.10, 0.15, 0.20	/	Study-defined sensitivity range informed by FC thermal-integration studies [27–30]
Heat pump supply water temperature at outdoor air design temperature	45	Fixed	°C	Low-temperature AWHF operating condition based on [6,7,26]

2.6. Critical SCOP Analysis

To identify the operating conditions at which both conversion pathways become equivalent, a critical SCOP value was derived:

$$SCOP_{crit} = (\eta_{rec,ICE} - \eta_{rec,FC}) / (\eta_{FC} - k_{ICE} \cdot \eta_{ICE}) \quad (13)$$

The critical SCOP was derived to identify the operating conditions at which both hydrogen conversion pathways become thermodynamically equivalent. Below this threshold, the ICE pathway becomes favorable due to the recovered engine heat.

2.7. Sensitivity Analysis Procedure

The sensitivity analysis evaluates the influence of the FC electrical efficiency, η_{FC} , ICE brake efficiency, η_{ICE} , ICE useful heat-recovery fraction, $\eta_{rec,ICE}$, and FC useful heat-recovery fraction, $\eta_{rec,FC}$, on $SCOP_{crit}$. The investigated values are $\eta_{FC} = 0.50, 0.55$, and 0.60 ; $\eta_{ICE} = 0.35, 0.40$, and 0.45 ; $\eta_{rec,ICE} = 0.35, 0.45$, and 0.50 ; and $\eta_{rec,FC} = 0.00, 0.05, 0.10, 0.15$, and 0.20 . Each parameter is varied individually while the remaining parameters are maintained at their reference values given in Table 1. The corresponding transition value is calculated using Equation (13).

3. Results

3.1. Seasonal Heating Demand and Heat Pump Performance

The seasonal performance calculations were conducted for 30 locations representing all nine climatic zones in Bulgaria [33]. The locations were selected to cover all coastal, continental, and mountainous climate conditions. The weather data, mainly focused on outdoor air temperature, were obtained from typical meteorological year (TMY) databases [34,35], which provide hourly temperature profiles representative for energy consumption modelling. For this purpose, the hourly data were processed in the form of bins. The duration of the heating period varies from 2894 to 5944 h, determined on the basis of meteorological conditions for each location and an accepted outdoor temperature limit of 12 °C at which the HP turns off. According to [36], this value is close enough to the equilibrium temperature at which heat losses are equal to the heat gains, which are

from solar radiation and internal sources. The same reference building is taken into account for all locations, while climatic conditions varied according to local weather data.

The calculated design heating load shows noticeable regional variations, ranging from 4.61 to 12.38 kW (average 7.07 kW), reflecting the difference between the mild coastal climate and the harsh mountain environment. Similarly, the mean outdoor air temperature for the heating period varies between 0.4 and 6.1 °C, with an average value of 4.0 °C close to that of Sofia city. The heating demand of the reference building ranges from 9620 kWh for southern locations such as Sandanski, near the Greek border, to 25,840 kWh at mountainous locations, with an average value of 14,764 kWh. The minimum value is 34.84% below the average, whereas the maximum value is 75.0% above it. These differences in the weather directly affect the seasonal performance of the air-to-water heat pump studied, as shown in Figure 2. The figure compares the declared seasonal coefficient of performance ($SCOP_{declared}$) by the manufacturer according to EN 14825, the climate-adapted $SCOP_{climate}$, and the climate-adapted and field-corrected $SCOP_{adapted}$ obtained using correction factors based on field measurements [6,7].

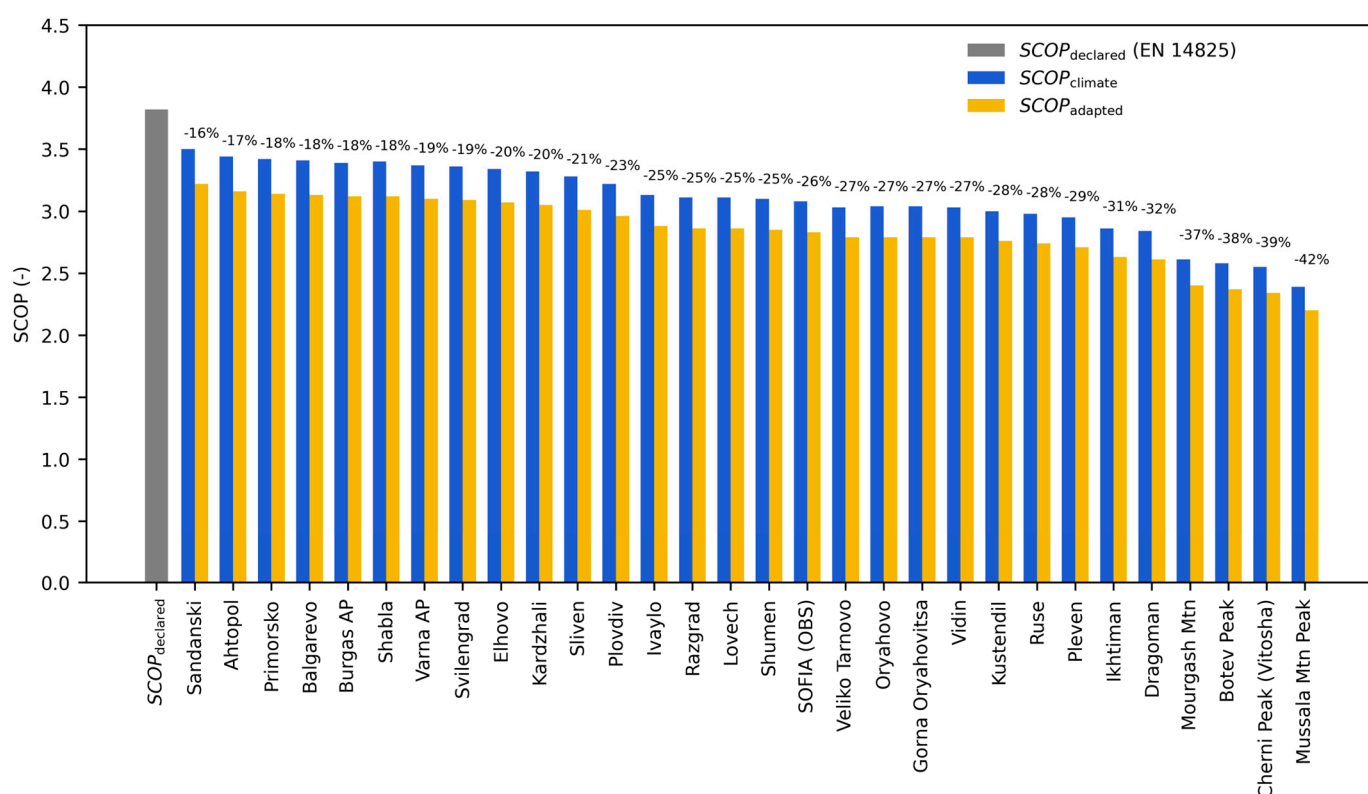


Figure 2. Comparison of the manufacturer-declared seasonal coefficient of performance, $SCOP_{declared}$; the climate-adapted seasonal coefficient of performance, $SCOP_{climate}$; and the climate-adapted and field-corrected seasonal coefficient of performance, $SCOP_{adapted}$.

The combined climate adaptation and field-performance correction reduce the manufacturer-declared seasonal performance from 16 to 42%, depending on the investigated location. This result highlights the importance of accounting for local climatic and actual operating conditions when assessing building energy consumption. The calculation is based on the manufacturer ErP performance data for the W45 application, while the field correction accounts collectively for defrosting, compressor cycling, oversizing, control limitations, and deviations from idealized part-load operation. The resulting $SCOP_{adapted}$ values form the basis for the subsequent hydrogen-consumption analysis.

3.2. Hydrogen Consumption of the Fuel Cell and ICE Pathways

Using the $SCOP_{adapted}$ values obtained in Section 3.1, the annual hydrogen consumption of the two conversion pathways was estimated as a function of the seasonal performance of the heat pump. Figure 3 presents the FC-powered electric heat-pump pathway for three fuel-cell electrical efficiencies, $\eta_{FC} = 0.50$, 0.55, and 0.60, together with the hydrogen ICE-driven heat-pump pathway for three useful heat-recovery fractions, $\eta_{rec,ICE} = 0.35$, 0.45, and 0.50. The values $\eta_{FC} = 0.55$ and $\eta_{rec,ICE} = 0.45$ represent the reference configurations, indicated by solid lines. The FC pathway remains strongly dependent on $SCOP_{adapted}$, as the electricity generated by the fuel cell directly supplies the electrically driven heat pump, whereas the recovered engine heat reduces the sensitivity of the ICE-driven pathway to seasonal heat-pump performance.

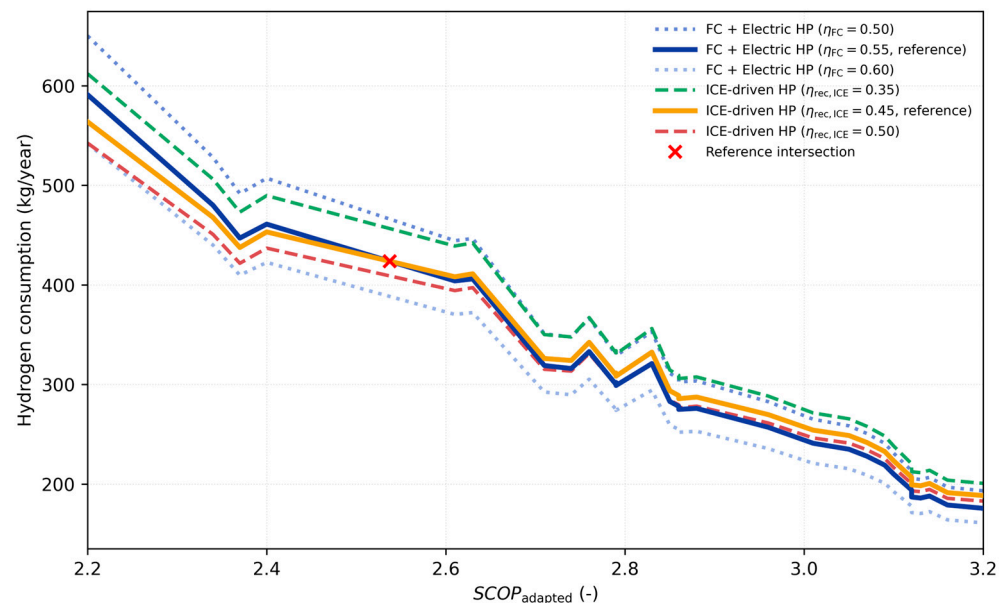


Figure 3. Annual hydrogen consumption as a function of $SCOP_{adapted}$ for the FC-powered electric heat-pump pathway and the ICE-driven heat-pump pathway. Solid lines indicate the reference configurations, and the red cross marks their intersection at $SCOP_{crit} = 2.53$.

For the ICE-driven pathway, the 7% mechanical-drive performance reduction is applied separately through the correction factor $k_{ICE} = 0.93$, as described in [24], whereas $SCOP_{adapted}$ represents the climate-adapted and field-corrected performance of the reference electrically driven AHP. Nevertheless, the ICE-driven pathway exhibits lower sensitivity to variations in $SCOP_{adapted}$ because the recovered engine heat partially offsets the lower heat-pump contribution resulting from the mechanical-drive performance reduction. Consequently, the difference in hydrogen consumption between the two pathways decreases at lower $SCOP_{adapted}$ values, which are characteristic of colder climatic conditions.

In this study, useful engine heat recovery is represented by the dimensionless parameter $\eta_{rec,ICE}$, defined as the seasonally useful recovered heat delivered to the building relative to the hydrogen LHV input. To evaluate the impact of this parameter, three representative values were considered: $\eta_{rec,ICE} = 0.35$, 0.45, and 0.50, corresponding to the lower-bound, reference, and upper-bound heat-recovery scenarios. The selected range is consistent with experimental GEHP studies reporting waste-heat-recovery rates of approximately 42–61% and 49–78% under different operating conditions [31,32]. Increasing $\eta_{rec,ICE}$ reduces hydrogen consumption by increasing the useful thermal output obtained from each unit of hydrogen input. Therefore, the competitiveness of the ICE-

driven pathway depends strongly on the amount of useful engine heat that can be recovered under seasonal operating conditions. As shown in Figure 3, the FC-driven pathway performs better at higher $SCOP_{adapted}$ values, whereas the ICE-driven pathway becomes increasingly competitive as $SCOP_{adapted}$ decreases. The additional scenario involving useful FC waste-heat recovery is evaluated separately in the sensitivity analysis.

3.3. Thermodynamic Transition and Critical Seasonal Performance ($SCOP_{crit}$)

To summarize the comparison between the two hydrogen conversion pathways for residential heating applications, the relative difference in hydrogen consumption between the ICE-driven heat pump and the FC-driven configuration was evaluated as a function of the seasonal performance of the heat pump. Figure 4 illustrates this relationship for different values of recoverable waste heat efficiency ($\eta_{rec,ICE}$), highlighting the transition between the two pathways. Positive values indicate operating conditions where the fuel cell-powered system will consume less hydrogen, while negative values correspond to conditions favoring the ICE-powered configuration. Therefore, the intersection with the zero line defines a critical operating point at which both systems consume equal amounts of hydrogen throughout the heating period.

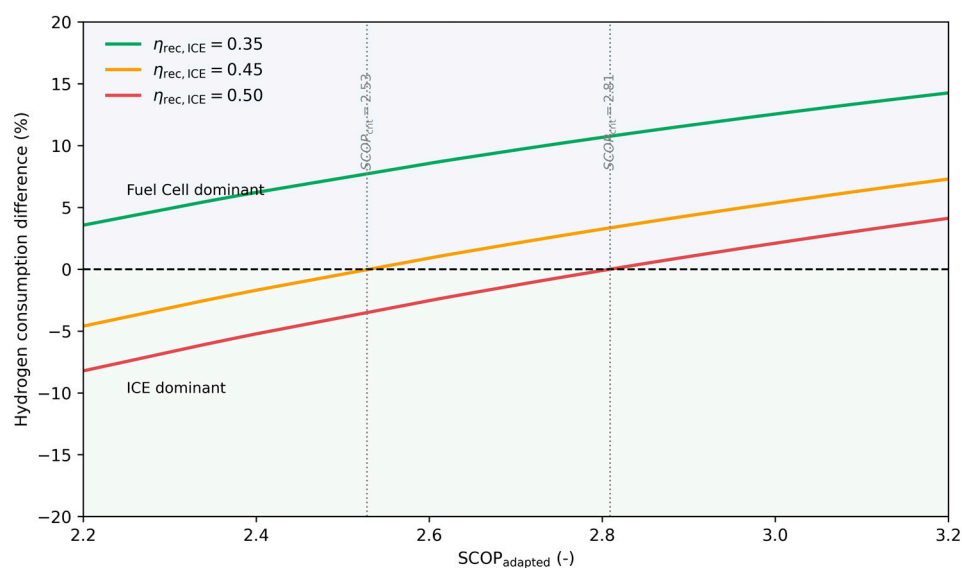


Figure 4. Relative difference in seasonal hydrogen consumption between the ICE-driven and FC-driven pathways as a function of $SCOP_{adapted}$ for different useful ICE heat-recovery fractions.

The transition between the two systems can be expressed analytically by a critical seasonal coefficient of performance, $SCOP_{crit}$, obtained from the balance between the efficiency of electrical conversion in the FC path and heat recovery in the ICE-driven path. For the system parameters studied, the critical values obtained are $SCOP_{crit} = 2.53$ for $\eta_{rec,ICE} = 0.45$ and $SCOP_{crit} = 2.81$ for $\eta_{rec,ICE} = 0.50$. These values represent the thermodynamic boundary separating the operating ranges where FC-driven or ICE-driven heat pump systems become preferable in terms of hydrogen consumption. At $\eta_{rec,ICE} = 0.35$, $SCOP_{crit} = 1.97$, which lies below the investigated $SCOP_{adapted}$ range; consequently, the FC-driven pathway requires less hydrogen for all studied locations. The results show that increasing waste heat recovery shifts the transition to higher SCOP values, effectively expanding the operating area where mechanically driven heat pumps can compete with FC systems. On the other hand, at high seasonal performance levels, the superior electrical efficiency of the FC results in lower hydrogen consumption. Generally, Figure 4 identifies the seasonal performance of the heat pump as the controlling parameter determining technology preferences.

3.4. Climatic Mapping of Hydrogen Pathway Dominance and Mean Heating Temperature Criteria

To provide a practical spatial interpretation of the transition between the two hydrogen conversion pathways for heating, the $SCOP_{adapted}$ values were mapped across

Bulgaria. Figure 5 presents the resulting technology dominance map, illustrating regions where either the fuel-cell-driven or mechanically driven heat pump pathway becomes advantageous in terms of hydrogen consumption. The map was generated using interpolated climate-adapted, field-adjusted $SCOP$ values obtained from the 30 representative climate locations considered in this study. Based on the selected reference heat-recovery fraction, $\eta_{rec,ICE} = 0.45$, the critical seasonal-performance threshold obtained from the thermodynamic analysis was used to classify the operating regions into FC-dominated zones, transition zones in which the two pathways exhibit similar hydrogen consumption, and ICE-dominated zones.

The map was generated by multiquadric radial-basis-function interpolation of the $SCOP_{adapted}$ values for the 30 locations, using a smoothing factor of 0.05; a ± 0.10 band around $SCOP_{crit} = 2.53$ was used to define the transition zone.

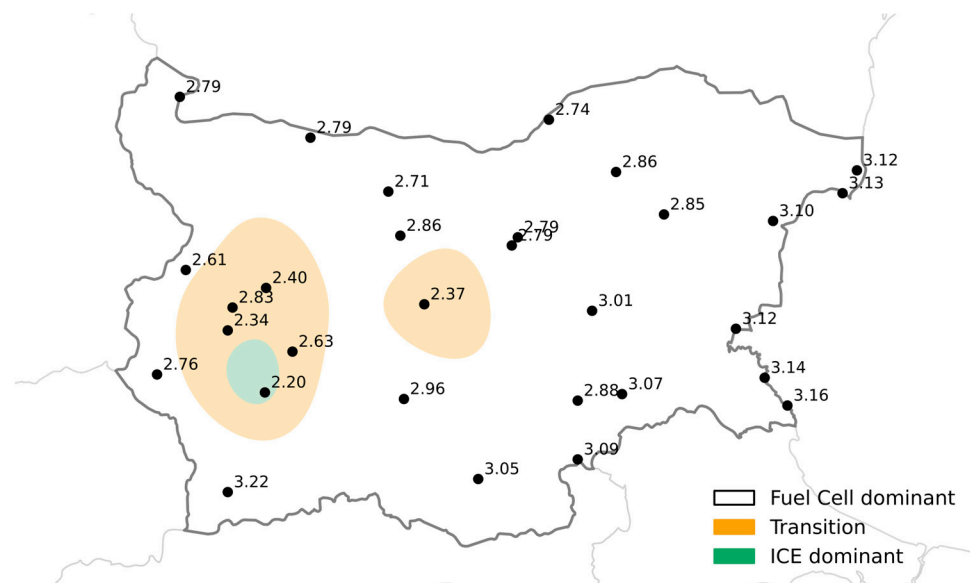


Figure 5. Climatic mapping of hydrogen pathway dominance in Bulgaria using $SCOP_{adapted}$ as an indicator.

The mapping shows a clear climatic pattern. Warmer southern and coastal regions typically show higher seasonal performance values, resulting in lower hydrogen consumption for the FC-powered configuration. In contrast, colder mountainous and continental regions tend to fall below the critical seasonal performance threshold, where the additional heat contribution from engine waste heat improves the competitiveness of the ICE-driven heat-pump pathway. The transition zone occurs mainly in intermediate climate zones, indicating that relatively small variations in seasonal characteristics can shift the preferred hydrogen conversion path. This highlights the strong link between climatic conditions and thermodynamic characteristics at the system level.

To further simplify the interpretation of pathway dominance, the relative hydrogen consumption difference was analyzed as a function of the mean outdoor air temperature during the heating period. Figure 6 illustrates this relationship for the reference waste heat recovery efficiency case, showing a clear correlation between climatic conditions and the preferred hydrogen conversion pathway. A strong linear trend is observed, indicating that pathway dominance can be directly linked to climatic conditions. Warmer climates tend to favor the FC-driven heat-pump configuration because of its higher seasonal performance, whereas colder climates, represented in this study by the four mountainous locations, tend to favor the ICE-driven configuration, in which recovered engine heat compensates for the reduced heat-pump performance. The intersection of the regression

line with the zero-difference axis defines a climatic transition temperature of $t_{\text{trans}} = 2.4\text{ }^{\circ}\text{C}$, corresponding to the condition at which both hydrogen pathways exhibit identical seasonal hydrogen consumption. The high correlation coefficient obtained from the regression analysis ($R^2 = 0.96$) confirms that the mean outdoor temperature during the heating period represents a robust single-parameter indicator for pathway selection.

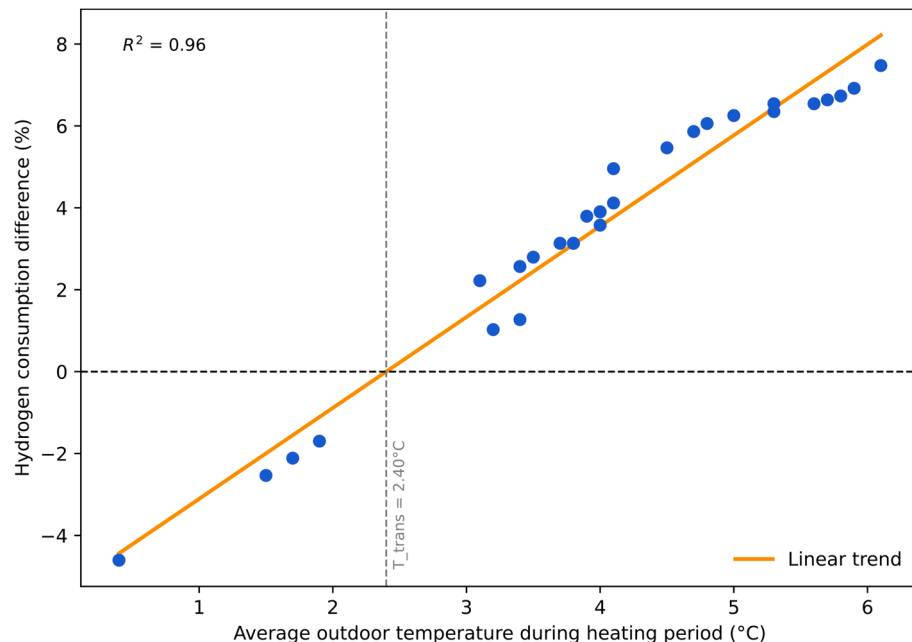


Figure 6. Relationship between the mean outdoor air temperature during the heating period and the hydrogen-consumption difference between the FC-driven and ICE-driven pathways.

The linear regression relationship can be expressed as:

$$\Delta_{H2} = 2.22 \cdot t_{\text{average}} - 5.33 \quad (14)$$

where $\Delta_{H2} = ((m_{H2,ICE} - m_{H2,FC})/m_{H2,FC}) \times 100$ is the relative hydrogen-consumption difference (%) and t_{average} is the average outdoor air temperature during the heating period (°C). Setting $\Delta_{H2} = 0$ shows that the climatic transition temperature is $2.40\text{ }^{\circ}\text{C}$.

The overall efficiency of both hydrogen conversion pathways was evaluated by combining the seasonal heat pump performance with the efficiencies of the main conversion components. The fuel-cell-driven configuration exhibits an overall efficiency proportional to the seasonal coefficient of performance, while the mechanically driven system benefits from both mechanical conversion and recoverable engine waste heat. Across the investigated operating range above ($SCOP_{\text{adapted}} = 2.2 \div 3.2$), both systems achieve overall efficiencies significantly above unity on an LHV basis, ranging approximately from 1.2 to 1.8. These values clearly exceed the typical efficiency of direct hydrogen combustion technologies, which are generally limited to about 0.95. This confirms that integrating hydrogen conversion technologies with heat pumps provides substantially higher useful heat output per unit hydrogen input, making such systems more suitable for low- and medium-temperature heating applications.

The comparison of overall efficiencies reveals a distinct transition point at which both systems exhibit identical performance. By equating the overall efficiency expressions for the fuel-cell-driven and mechanically driven heat pump pathways, a critical seasonal coefficient of performance of $SCOP_{\text{crit}} = 2.53$ was obtained for the reference waste heat recovery efficiency ($\eta_{\text{rec,ICE}} = 0.45$). Above this value, the higher electrical efficiency of the fuel cell leads to lower hydrogen consumption, whereas below this threshold the additional thermal contribution from engine waste heat makes the mechanically driven

configuration more advantageous. This efficiency crossover represents the thermodynamic transition identified throughout the analysis and provides a clear physical explanation for the pathway dominance observed in both the climatic mapping and temperature-based transition criteria.

3.5. Sensitivity Analysis

The sensitivity analysis evaluates the influence of the FC electrical efficiency, ICE brake efficiency, ICE useful heat-recovery fraction, and the additional FC heat-recovery scenario on the transition between the two hydrogen pathways. Each parameter was varied individually while the remaining parameters were maintained at their reference values given in Table 1.

The results are presented in Figure 7.

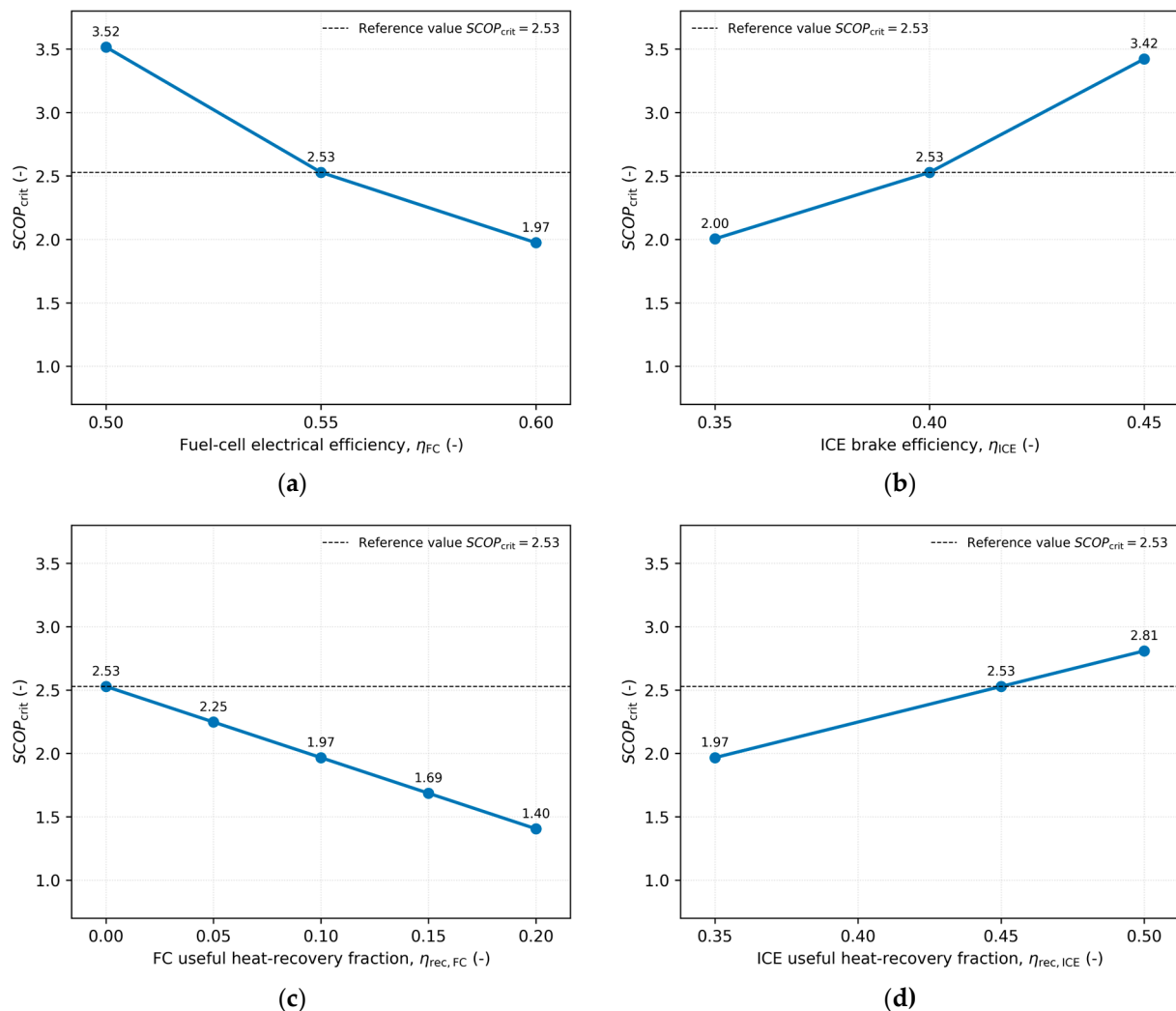


Figure 7. Sensitivity of the critical seasonal coefficient of performance, $SCOP_{crit}$, to the investigated parameters: **(a)** Effect of fuel-cell electrical efficiency, η_{FC} ; **(b)** effect of ICE brake efficiency, η_{ICE} ; **(c)** effect of the useful FC heat-recovery fraction, $\eta_{rec,FC}$; **(d)** effect of the useful ICE heat-recovery fraction, $\eta_{rec,ICE}$. In each panel, only the indicated parameter is varied, while the remaining parameters are maintained at their reference values. The dashed horizontal line indicates the reference value $SCOP_{crit} = 2.53$.

Variation in the FC electrical efficiency from $\eta_{FC} = 0.50$ to 0.60 changed $SCOP_{crit}$ from 3.52 to 1.97 . At $\eta_{FC} = 0.50$, the transition lies above the investigated $SCOP_{adapted}$ range, indicating lower hydrogen consumption for the ICE-driven pathway throughout the

studied locations. Conversely, at $\eta_{FC} = 0.60$, the transition lies below the investigated range, and the FC pathway becomes preferable for all locations.

The ICE brake efficiency produced an opposite effect. Increasing η_{ICE} from 0.35 to 0.45 increased $SCOP_{crit}$ from 2.00 to 3.42. Thus, higher ICE conversion efficiency expands the range in which the mechanically driven pathway requires less hydrogen.

Variation in $\eta_{rec,ICE}$ from 0.35 to 0.50 shifted $SCOP_{crit}$ from 1.97 to 2.81. The reference value $\eta_{rec,ICE} = 0.45$ resulted in $SCOP_{crit} = 2.53$, as discussed in Section 3.3. These results confirm that the competitiveness of the ICE-driven pathway depends strongly on both engine efficiency and the amount of useful heat recovered from the cooling and exhaust systems.

As an additional scenario, useful FC waste-heat recovery was included using Equation (9). Increasing $\eta_{rec,FC}$ from 0.00 to 0.20 reduced the transition value from 2.53 to 1.40. At $\eta_{rec,FC} = 0.05$, $SCOP_{crit}$ decreased to 2.25, leaving only locations with the lowest seasonal performance potentially suitable for the ICE-driven pathway. For $\eta_{rec,FC} \geq 0.10$, the transition falls below the investigated $SCOP_{adapted}$ range, and the FC pathway with useful heat recovery requires less hydrogen for all studied locations.

Relative to the reference value $\eta_{FC} = 0.55$, reducing the FC electrical efficiency to 0.50 increases the calculated FC-pathway hydrogen consumption by 10.0%, whereas increasing it to 0.60 reduces consumption by 8.3%. Across the investigated $SCOP_{adapted}$ range of 2.2–3.2, reducing η_{ICE} from 0.40 to 0.35 increases ICE-pathway hydrogen consumption by 8.8–10.0%, whereas increasing it to 0.45 reduces consumption by 7.5–8.3%. Reducing $\eta_{rec,ICE}$ from 0.45 to 0.35 increases consumption by 6.5–8.6%, whereas increasing it to 0.50 reduces consumption by 3.0–3.8%. These values represent a sensitivity-based uncertainty envelope associated with the constant-efficiency assumption rather than a formal statistical measurement uncertainty.

4. Discussion

The results demonstrate that the seasonal performance of the heat pumps represents the dominant parameter responsible for the effective hydrogen usage as a source of primary energy in both conversion pathways. The determined thermodynamic transition point between both pathways, expressed through the critical seasonal coefficient of performance ($SCOP_{crit}$), provides a clear physical explanation for the observed system behavior. While the fuel-cell-driven configuration benefits from high electrical conversion efficiency, its performance scales directly with $SCOP_{adapted}$, making it more sensitive to climatic conditions. On the other hand, the mechanically driven pathway is less dependent on seasonal performance of the heat pump due to the additional contribution of recoverable engine waste heat. This behavior explains the reduced sensitivity of the ICE-driven system observed in Figure 3 and the appearance of a well-defined crossover at $SCOP_{crit} = 2.53$ for the reference heat recovery scenario ($\eta_{rec,ICE} = 0.45$). The existence of such a transition confirms that technology preference cannot be defined independently of seasonal operating conditions.

Similar observations have been reported for integrated fuel-cell and heat-pump systems. Kwan et al. [19] demonstrated that the hydrogen utilization efficiency of fuel-cell-assisted heat pumps is strongly dependent on the seasonal performance of the heat pump, while Andrade et al. [20] reported substantial reductions in hydrogen demand when high-efficiency air-to-water heat pumps were integrated with residential fuel-cell systems. The present study extends these findings by identifying a quantitative thermodynamic transition threshold ($SCOP_{crit}$), which establishes the operating boundary between electrochemical and thermomechanical hydrogen conversion pathways.

The climatic mapping of the hydrogen pathway dominance in Bulgaria reveals a systematic shift from fuel-cell dominance in warmer coastal and southern regions toward

mechanically driven dominance in colder and mountainous areas. The strong correlation between hydrogen consumption difference and the mean outdoor temperature during the heating period ($R^2 = 0.96$) suggests that this parameter may serve as a simplified design indicator for pathway selection. The identified transition temperature of approximately 2.4 °C effectively represents a practical equivalent of the $SCOP_{crit}$ threshold. This dual interpretation, combining thermodynamic and climatic perspectives, provides a useful framework for preliminary system selection without requiring detailed seasonal simulations at early design stages. The identified climatic transition temperature is specific to the adopted reference building, W45 heat-pump model, Bulgarian TMY datasets, and reference conversion parameters; application to other buildings or regions therefore requires recalculation.

The strong dependence on climatic conditions is consistent with previous field investigations of residential heat pumps. Miara et al. [37] reported considerable variation in seasonal performance between different climatic regions, highlighting the importance of local weather conditions when assessing heat-pump-based heating systems. Similar conclusions are presented in the IEA report *The Future of Heat Pumps* [38], which identifies climate adaptation and operational conditions as key determinants of real-world seasonal efficiency. The high correlation obtained in the present study ($R^2 = 0.96$) confirms that climatic conditions play an equally important role when hydrogen conversion pathways are combined with heat pump technologies.

Regarding overall system efficiency, both hydrogen conversion pathways achieve values substantially higher than those of direct hydrogen-combustion boilers on an LHV basis because the heat-pump cycle extracts additional heat from the ambient environment. Across the investigated $SCOP_{adapted}$ range, overall system efficiencies of 1.2 to 1.8 were obtained, exceeding the typical efficiency of direct hydrogen-combustion systems, which is generally limited to approximately 0.90–0.95. This finding indicates that hydrogen can be used more effectively as an energy carrier in heat-pump-based conversion pathways than through direct combustion for low- and medium-temperature heating applications. This interpretation is also consistent with the broader energy-system perspective which identified hydrogen as a strategic energy carrier for balancing renewable generation and supporting sector coupling rather than serving as a direct substitute for highly efficient electrification technologies [11,39,40].

This conclusion is consistent with broader assessments of hydrogen utilization pathways. Ueckerdt et al. [41] demonstrated that direct hydrogen use often results in lower overall system efficiency than pathways utilizing hydrogen for higher-value energy conversion processes. Similarly, the International Renewable Energy Agency (IRENA) [42] highlighted that the efficient utilization of renewable hydrogen will become increasingly important as hydrogen production scales up to support future decarbonization targets. The overall efficiencies obtained in the present work therefore support the concept that hydrogen should be combined with highly efficient heat pump technologies whenever low-temperature heating applications are considered.

From a technological perspective, the mechanically driven hydrogen pathway can be interpreted as a near-future extension of existing gas engine heat pump (GEHP) technology. Previous studies have demonstrated the feasibility of mechanically driven heat pumps with waste heat recovery under varying climatic and part-load conditions. The present work extends this concept by evaluating the thermodynamic implications of replacing natural gas with hydrogen and demonstrates that useful engine heat recovery can provide an important performance advantage for this type of system. These observations are also supported by the review of Pawela and Jaszczur [25], who identified waste heat recovery as one of the principal advantages of gas-engine-driven heat pumps. The results obtained in the present study suggest that the same thermodynamic benefit

can be retained when natural gas is replaced by hydrogen, enabling a gradual transition toward zero-emission mechanically driven heat pump systems. At the same time, fuel-cell-driven configurations remain attractive under moderate climates and high seasonal efficiencies due to their superior electrical conversion performance. This suggests that future zero-emission heating strategies may not rely on a single universal solution but rather on climate-dependent technology selection.

The transition criterion may also be interpreted as the minimum ICE brake efficiency required for the mechanically driven pathway to achieve lower hydrogen consumption than the FC-powered configuration. Under the reference system heat-recovery assumptions, the required ICE efficiency increases from approximately 0.37 at $SCOP_{adapted} = 2.2$ to 0.44 at $SCOP_{adapted} = 3.2$. When useful FC heat recovery is included, the requirement becomes more demanding; for example, at $\eta_{rec,FC} = 0.10$, the minimum ICE efficiency increases from 0.42 to 0.47 over the investigated seasonal-performance range. This indicates that the ICE-driven pathway remains technically competitive primarily under lower seasonal heat-pump performance, effective engine heat recovery, and sufficiently high engine brake efficiency.

Several limitations of the present study should be acknowledged. The analysis is based on seasonal performance indicators and simplified energy balances without detailed transient modelling or control optimization. The FC electrical efficiency, ICE brake efficiency, and useful heat-recovery fractions are represented by constant seasonal values, whereas real systems exhibit load-dependent behaviour. The sensitivity analysis indicates that this simplification may change the calculated hydrogen consumption by approximately -8% to $+10\%$ for the FC pathway and by approximately -8% to $+10\%$ for the ICE-driven pathway when each principal efficiency parameter is varied individually within the investigated ranges. These values should be interpreted as an expected sensitivity envelope rather than a formal prediction error. A more precise uncertainty assessment would require experimentally validated part-load performance maps, hourly system simulation, and dynamic modelling of the FC, ICE, heat-recovery circuits, thermal storage, and control strategies.

5. Conclusions

This study investigated two hydrogen conversion pathways for residential heating in Bulgaria based on heat pump technologies: a fuel-cell-driven electric heat pump and a mechanically driven heat pump powered by a hydrogen internal combustion engine. By combining climate-adapted seasonal performance modeling with thermodynamic analysis, the following main conclusions can be drawn:

- Seasonal heat-pump performance is the key parameter governing the effective utilization of hydrogen as a primary energy source. Climate adaptation and field-performance correction reduced the manufacturer-declared SCOP values by approximately 16–42%, demonstrating the necessity of accounting for local climatic and actual operating conditions when comparing hydrogen-based heating pathways.
- A thermodynamic transition between the pathways exists, defined by a critical seasonal coefficient of performance, $SCOP_{crit}$. For the reference ICE heat-recovery fraction ($\eta_{rec,ICE} = 0.45$) and without direct FC heat recovery ($\eta_{rec,FC} = 0$), the transition occurs at $SCOP_{crit} = 2.53$, separating the operating regions in which either the FC-driven or ICE-driven pathway achieves lower hydrogen consumption.
- Climatic conditions directly influence technology preference. Climatic mapping and regression analysis revealed a strong correlation between pathway dominance and the mean outdoor air temperature during the heating period ($R^2 = 0.96$), with the transition occurring at a mean outdoor temperature of approximately $2.4\text{ }^{\circ}\text{C}$.

- Both hydrogen-to-heat-pump pathways significantly outperform direct hydrogen combustion for low- and medium-temperature heating applications. Overall system efficiencies of approximately 1.2–1.8 on an LHV basis were obtained across the investigated range, exceeding the typical efficiency of direct hydrogen-combustion systems and highlighting the advantage of combining hydrogen conversion with heat-pump technology. An additional benefit of both pathways is the elimination of on-site CO₂ emissions.
- The sensitivity analysis demonstrated that the transition between the pathways depended strongly on the FC electrical efficiency, ICE brake efficiency, and useful heat-recovery fractions. Across the investigated parameter ranges, $SCOP_{crit}$ varied from 1.40 to 3.52. The constant-efficiency assumption produced an estimated hydrogen-consumption sensitivity envelope of approximately −8% to +10%; therefore, these results should be interpreted as a comparative thermodynamic assessment rather than as exact predictions of system operation.
- Mechanically driven hydrogen heat pumps represent a near-future extension of existing gas-engine heat-pump concepts, whereas FC-driven systems remain favorable at higher seasonal heat-pump performance levels. The inclusion of useful FC heat recovery further strengthens the FC-driven pathway and can shift the transition toward lower $SCOP_{adapted}$ values. Therefore, future zero-emission heating strategies may require climate- and configuration-dependent technology selection rather than a single universal solution.

The developed framework demonstrates that thermodynamic performance and climatic conditions are strongly interdependent when evaluating hydrogen-based residential heating systems. The proposed methodology provides practical guidance for early-stage technology selection and supports the development of climate-adapted hydrogen utilization strategies for zero-emission buildings.

Author Contributions: Conceptualization, I.D., A.T. and P.Z.; Methodology, I.D. and P.Z.; Software, I.D.; Validation, I.D. and P.Z.; Formal Analysis, I.D., A.T. and P.Z.; Investigation, I.D. and A.T.; Resources, I.D.; Data Curation, I.D.; Writing—Original Draft Preparation, I.D., P.Z. and A.T.; Writing—Review & Editing, P.Z. and A.T.; Visualization, I.D.; Supervision, A.T.; Project Administration, A.T.; Funding Acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This study is financed by the European Union—NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No. BG-RRP-2.004-0005.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AWHP	Air-to-Water Heat Pump
CHP	Combined Heat and Power
COP	Coefficient of Performance
EPBD	Energy Performance of Buildings Directive
ErP	Energy-related Products

FC	Fuel Cell
GEHP	Gas Engine Heat Pump
HP	Heat Pump
HT-PEMFC	High-Temperature Proton Exchange Membrane Fuel Cell
ICE	Internal Combustion Engine
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LHV	Lower Heating Value
PEMFC	Proton Exchange Membrane Fuel Cell
SCOP	Seasonal Coefficient of Performance
TMY	Typical Meteorological Year

References

- European Commission. Zero-Emission Buildings Under the Energy Performance of Buildings Directive (EPBD). Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/energy-performance-buildings-directive/zero-emission-buildings_en (accessed on 5 June 2026).
- European Parliament and Council of the European Union. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings (Recast). *Off. J. Eur. Union* **2024**, L 1275, 1–68. Available online: <https://eur-lex.europa.eu/eli/dir/2024/1275/oj> (accessed on 5 June 2026).
- Jesper, M.; Schlosser, F.; Pag, F.; Walmsley, T.G.; Schmitt, B.; Vajen, K. Large-Scale Heat Pumps: Uptake and Performance Modelling of Market-Available Devices. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110646. <https://doi.org/10.1016/j.rser.2020.110646>.
- Wang, Z.; Luther, M.B.; Amirkhani, M.; Liu, C.; Horan, P. State of the Art on Heat Pumps for Residential Buildings. *Buildings* **2021**, *11*, 350. <https://doi.org/10.3390/buildings11080350>.
- Thomaßen, G.; Kavvadias, K.; Jiménez Navarro, J.P. The Decarbonisation of the EU Heating Sector through Electrification: A Parametric Analysis. *Energy Policy* **2021**, *148*, 111929. <https://doi.org/10.1016/j.enpol.2020.111929>.
- Dimchev, I.; Borisov, I.; Stankov, B.; Pitchurov, G. Evaluating the Seasonal Performance of Air-to-Water Heat Pumps Using Field Data. In Proceedings of the 12th International Conference on Energy and Environment (CIEM 2025), Bucharest, Romania, 23–24 October 2025; pp. 1–5. <https://doi.org/10.1109/CIEM67454.2025.11284579>.
- Dimchev, I.; Vlahov, P.; Ivanov, M.; Ivanov, S. Field-Based Performance Analysis of R32 Split-Type Air-to-Water Heat Pumps. In Proceedings of the 2025 10th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE 2025), Stara Zagora, Bulgaria, 5–7 November 2025; pp. 1–5. <https://doi.org/10.1109/EEAE65901.2025.11273625>.
- Żelazna, A.; Pawłowski, A. Review of the Role of Heat Pumps in Decarbonization of the Building Sector. *Energies* **2025**, *18*, 3255. <https://doi.org/10.3390/en18133255>.
- European Commission. Hydrogen Strategy for a Climate-Neutral Europe. Available online: https://energy.ec.europa.eu/system/files/2020-07/hydrogen_strategy_0.pdf (accessed on 5 June 2026).
- Kurniawati, H.; Broersma, S.; Itard, L.; Mohammadi, S. Integrated Hydrogen in Buildings: Energy Performance Comparisons of Green Hydrogen Solutions in the Built Environment. *Buildings* **2025**, *15*, 3232. <https://doi.org/10.3390/buildings15173232>.
- Staffell, I.; Scamman, D.; Velazquez Abad, A.; Balcombe, P.; Dodds, P.E.; Ekins, P.; Shah, N.; Ward, K.R. The Role of Hydrogen and Fuel Cells in the Global Energy System. *Energy Environ. Sci.* **2019**, *12*, 463–491. <https://doi.org/10.1039/C8EE01157E>.
- Huckebrink, D.; Bertsch, V. Decarbonising the Residential Heating Sector: A Techno-Economic Assessment of Selected Technologies. *Energy* **2022**, *257*, 124605. <https://doi.org/10.1016/j.energy.2022.124605>.
- Glenk, G.; Reichelstein, S. Economics of Converting Renewable Power to Hydrogen. *Nat. Energy* **2019**, *4*, 216–222. <https://doi.org/10.1038/s41560-019-0326-1>.
- Staffell, I.; Green, R. The Cost of Domestic Fuel Cell Micro-CHP Systems. *Int. J. Hydrogen Energy* **2013**, *38*, 1088–1102. <https://doi.org/10.1016/j.ijhydene.2012.10.090>.
- Dodds, P.E.; Staffell, I.; Hawkes, A.D.; Li, F.; Grünewald, P.; McDowall, W.; Ekins, P. Hydrogen and fuel cell technologies for heating: A review. *Int. J. Hydrogen Energy* **2015**, *40*, 2065–2083. <https://doi.org/10.1016/j.ijhydene.2014.11.059>.
- Baroutaji, A.; Arjunan, A.; Robinson, J.; Wilberforce, T.; Abdelkareem, M.A.; Olabi, A.G. PEMFC Poly-Generation Systems: Developments, Merits, and Challenges. *Sustainability* **2021**, *13*, 11696. <https://doi.org/10.3390/su132111696>.
- Boait, P.J.; Greenough, R. Can fuel cell micro-CHP justify the hydrogen gas grid? Operating experience from a UK domestic retrofit. *Energy Build.* **2019**, *194*, 75–84. <https://doi.org/10.1016/j.enbuild.2019.04.021>.

18. Bachmann, T.M.; Carnicelli, F.; Preiss, P. Life cycle assessment of domestic fuel cell micro combined heat and power generation: Exploring influential factors. *Int. J. Hydrogen Energy* **2019**, *44*, 3891–3905. <https://doi.org/10.1016/j.ijhydene.2018.12.076>.
19. Kwan, T.H.; Wu, X.; Yao, Q. Performance Comparison of Several Heat Pump Technologies for Fuel Cell Micro-CHP Integration Using a Multi-Objective Optimisation Approach. *Appl. Therm. Eng.* **2019**, *160*, 114002. <https://doi.org/10.1016/j.applthermaleng.2019.114002>.
20. Andrade, T.S.; Ramakrishna, S.K.N.; Thiringer, T. Integrating a Fuel Cell with a Heat Pump: An Energy-Saving System for Residential Housing. *Energy Convers. Manag.* **2025**, *326*, 119509. <https://doi.org/10.1016/j.enconman.2025.119509>.
21. Boretti, A. Hydrogen Internal Combustion Engines to 2030. *Int. J. Hydrogen Energy* **2020**, *45*, 23692–23703. <https://doi.org/10.1016/j.ijhydene.2020.06.022>.
22. Durkin, K.; Khanafer, A.; Liseau, P.; Stjernström-Eriksson, A.; Svahn, A.; Tobiasson, L.; Andrade, T.S.; Ehnberg, J. Hydrogen-Powered Vehicles: Comparing the Powertrain Efficiency and Sustainability of Fuel Cell versus Internal Combustion Engine Cars. *Energies* **2024**, *17*, 1085. <https://doi.org/10.3390/en17051085>.
23. Sari, R.L.; Robles, A.F.; Serrano, J.M.; Cleary, D. Techno-Economic Assessment of Hydrogen as a Fuel for Internal Combustion Engines and Proton Exchange Membrane Fuel Cells. *Energy Convers. Manag.* **2024**, *311*, 118522. <https://doi.org/10.1016/j.enconman.2024.118522>.
24. Busato, F.; Lazzarin, R.M.; Noro, M. Energy and Economic Analysis of Different Heat Pump Systems for Space Heating. *Int. J. Low-Carbon Technol.* **2012**, *7*, 104–112. <https://doi.org/10.1093/ijlct/cts016>.
25. Pawela, B.; Jaszczur, M. Review of Gas Engine Heat Pumps. *Energies* **2022**, *15*, 4874. <https://doi.org/10.3390/en15134874>.
26. Crystal. Crystal Aqua Aura II 19S Air-to-Water Heat Pump—Product Fiche (35 °C/55 °C); Manufacturer Documentation. Available online: https://bgr.bg/wp-content/uploads/product-fiche/crystal-aqua-aura-2/termopompa-crystal-aqua-aura-II-19S-product-fiche-35%E2%84%83,55%E2%84%83_bg.pdf (accessed on 5 June 2026).
27. Briguglio, N.; Ferraro, M.; Brunaccini, G.; Antonucci, V. Evaluation of a Low Temperature Fuel Cell System for Residential CHP. *Int. J. Hydrogen Energy* **2011**, *36*, 8023–8029. <https://doi.org/10.1016/j.ijhydene.2011.01.050>.
28. Gandiglio, M.; Lanzini, A.; Santarelli, M.; Leone, P. Design and Optimization of a Proton Exchange Membrane Fuel Cell CHP System for Residential Use. *Energy Build.* **2014**, *69*, 381–393. <https://doi.org/10.1016/j.enbuild.2013.11.022>.
29. Arsalis, A.; Kær, S.K.; Nielsen, M.P. Modeling and Optimization of a Heat-Pump-Assisted High Temperature Proton Exchange Membrane Fuel Cell Micro-Combined-Heat-and-Power System for Residential Applications. *Appl. Energy* **2015**, *147*, 569–581. <https://doi.org/10.1016/j.apenergy.2015.03.031>.
30. Sorace, M.; Gandiglio, M.; Santarelli, M. Modeling and Techno-Economic Analysis of the Integration of a FC-Based Micro-CHP System for Residential Application with a Heat Pump. *Energy* **2017**, *120*, 262–275. <https://doi.org/10.1016/j.energy.2016.11.082>.
31. Hu, Y.; Lv, J.; Huang, C.; Song, W.; Feng, Z. Experimental Investigation on Heating Performance of a Gas Engine-Driven Heat Pump System with R410A. *Appl. Therm. Eng.* **2022**, *215*, 118863. <https://doi.org/10.1016/j.applthermaleng.2022.118863>.
32. Hu, Y.; Feng, Z.; Song, W. Study on Performance of a Gas Engine-Driven Heat Pump System with R410A for Heating and Domestic Hot Water Applications. *Appl. Therm. Eng.* **2023**, *228*, 120538. <https://doi.org/10.1016/j.applthermaleng.2023.120538>.
33. Ministry of Regional Development and Public Works (MRDPW). *Regulation No. RD-02-20-3 of 9 November 2022 on the Technical Requirements for the Energy Performance of Buildings*; Ministry of Regional Development and Public Works: Sofia, Bulgaria, 2022.
34. ASHRAE. *International Weather for Energy Calculations (IWEC), Version 2.0*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2012.
35. Lawrie, L.K.; Crawley, D.B. Development of Global Typical Meteorological Years (TMYx). OneBuilding. Available online: <https://climate.onebuilding.org> (accessed on 5 June 2026).
36. Dimchev, I.; Terziev, A.; Ivanov, M. Estimation of the seasonal coefficient of performance of air-to-water heat pumps in temperate climate. In Proceedings of the 2024 9th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE 2024), Ruse, Bulgaria, 27–29 June 2024; pp. 1–6. <https://doi.org/10.1109/EEAE60309.2024.10600630>.
37. Miara, M.; Günther, D.; Langner, R.; Helmling, S.; Wapler, J. 10 Years of Heat Pumps Monitoring in Germany: Outcomes of Several Monitoring Campaigns, from Low-Energy Houses to Un-Retrofitted Single-Family Dwellings. In Proceedings of the 12th IEA Heat Pump Conference, Rotterdam, The Netherlands, 15–18 May 2017; pp. 1–11.
38. International Energy Agency (IEA). *The Future of Heat Pumps*; IEA: Paris, France, 2022. Available online: <https://www.iea.org/reports/the-future-of-heat-pumps> (accessed on 5 June 2026).
39. Fischer, D.; Madani, H. On Heat Pumps in Smart Grids: A Review. *Renew. Sustain. Energy Rev.* **2017**, *70*, 342–357. <https://doi.org/10.1016/j.rser.2016.11.182>.

40. Ajanovic, A.; Sayer, M.; Haas, R. The Economics and the Environmental Benignity of Different Colors of Hydrogen. *Int. J. Hydrogen Energy* **2022**, *47*, 24136–24154. <https://doi.org/10.1016/j.ijhydene.2022.02.094>.
41. Ueckerdt, F.; Bauer, C.; Dirnaichner, A.; Overall, J.; Sacchi, R.; Luderer, G. Potential and Risks of Hydrogen-Based e-Fuels in Climate Change Mitigation. *Nat. Clim. Change* **2021**, *11*, 384–393. <https://doi.org/10.1038/s41558-021-01032-7>.
42. International Renewable Energy Agency (IRENA). *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal*; IRENA: Abu Dhabi, United Arab Emirates, 2020. Available online: <https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction> (accessed on 5 June 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.