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Integrating a fuel cell with a heat pump: An energy-saving system for residential housing

Tatiana Santos Andrade *, Sindhu Kanya Nalini Ramakrishna, Torbjörn Thiringer

Department of Electrical Engineering Chalmers University of Technology Gothenburg Sweden

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ABSTRACT

Fuel cells are currently pointed out as a promising combined heat and power technology. In this work, the purpose was to investigate the potential to integrate a fuel cell and a heat pump as an energy-saving system for residential houses. We have applied a novel approach by evaluating the system across four European locations with diverse climates, focusing on fuel cell size, energy consumption, and cost. Results have shown that the system composed of the fuel cell and the heat pump can achieve a fuel cell size reduction of at least 40 % and an energy saving of at least 20 % compared to the system without a heat pump. Cost analysis has shown that despite the current high price for heat pumps, the system integrating the fuel cell and the heat pump can be compensated in less than 5 years for locations with a temperature profile similar to Paris or colder.

1. Introduction

Cogeneration of heat and power for residential applications, the so-called combined heat and power (CHP) technologies, can potentially decrease energy consumption and carbon emissions [1]. By providing onsite cogeneration, those systems can reduce transmission losses for heat and electrical energy, reduce grid/district heating dependence, and be even more advantageous during electricity grid or district heating instability or shortages. Among CHP technologies, fuel cell-based systems have the highest electrical/heating efficiency [2,3]. Fuel cells are devices that use hydrogen to deliver high electrical efficiencies, i.e. up to around 60 % for Proton Exchange Membrane (PEM) fuel cells [4] while producing useful heat [5]. Despite the uncertainty about hydrogen production and infrastructure [6], countries worldwide, including European Union nations, the US, and China, have officially adopted strategies to include hydrogen as part of their energy transition targets [7,8]. As a result, fuel cells as CHPs are currently pointed out as economical, efficient, and environmentally friendly solutions for residential applications [9,10]. For instance, projects like CALLUX, with 500 installed units in Germany, and ene.field/PACE, with 3500 installed units in 11 European countries, have proven the functionality and cost-effectiveness of fuel cells as CHPs for residential applications [11,12].

Generally, the high electrical efficiency of fuel cells is a great advantage. However, the high heating requirement in the house, especially during winter, often surpasses the heating provided by the fuel cell. Pointed out as the main reason for housing energy consumption, in 2022, space heating in the residential sector accounted for 64 % of the total building electrical consumption in Europe [13,14]. Thus, despite the high electrical efficiency of fuel cell-based CHPs, they would have to be coupled with additional systems, such as electrical heaters or boilers, especially during cold periods, and produce more electrical energy to be converted into heat to meet both heating demand and electrical consumption [15].

Therefore, one promising alternative to be integrated into the CHP system is a heat pump [16,17]. Heat pumps are devices that efficiently consume electrical energy to provide heating energy. Instead of generating heat directly like electric heaters, heat pumps transfer heat energy from a colder space, e.g. air, or water, to a warmer space enabled by the refrigeration cycle flow. This process provides more thermal energy than the required electrical energy to operate. For instance, the thermal and electrical power ratio, known as the coefficient of performance (COP) of the heat pump, is estimated to be about four at 5 °C for an air-to-water heat pump, i.e. four times more heating power generated per amount of electrical power consumed by the compressor [18]. Thus, integrating a fuel cell with a heat pump is a promising approach to provide a CHP with lower electrical energy consumption, especially for scenarios of high heating demand. However, although combining HPs with FC as CHP has been reported as a potential energy-saving alternative [16,19], this integration has been scarcely addressed.

Some investigations have focused on the selection of the best fuel cell

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* Corresponding author.
E-mail address: tatianas@chalmers.se (T.S. Andrade).

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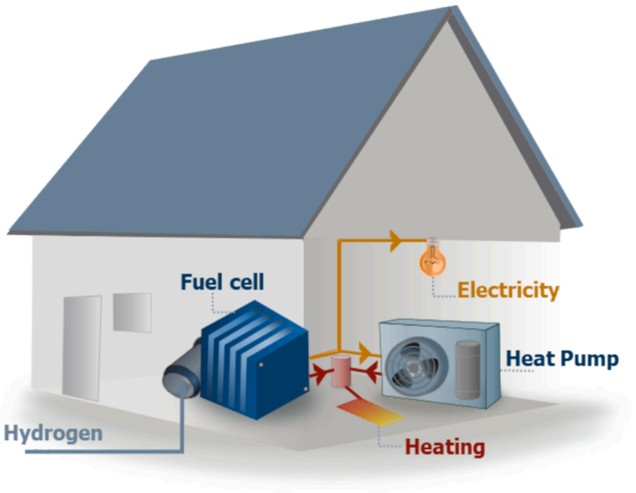

Fig. 1. Schematic illustration for the residential combined heat and power system composed of a fuel cell and a heat pump. The fuel cell was the source of electricity in the house for all the electrical load including the heat pump, and both the fuel cell and heat pump provided heating energy to meet the house heating demand.

technology, e.g. proton exchange membrane and solid oxide fuel cell [20], the selection of the best heat pump technology, e.g. vapor compression cycle, Peltier device [21,22], or in the heat recovery system [23,24]. However, most works have not focused on the comparison of the impact of CHP with and without heat pumps. In [25], an investigation of a system integrating a PEM fuel cell with a heat pump versus a fuel-cell-based CHP without a heat pump for a house in China was reported. Results have shown that integrating the two technologies was superior in efficiency and cost. Nevertheless, while recent investigations have explored the integration of a fuel cell and a heat pump in residential CHP systems, most studies have assumed a fixed size for the fuel cell and neglected the impact of varying climates/temperature profiles. By addressing these critical factors, this work aimed to contribute to the understanding of the system's suitability across different conditions, thus supporting to bridge a gap in the existing literature.

Therefore, the purpose of this work was to investigate the CHP system composed of a fuel cell and a heat pump compared to a system without a heat pump regarding energy/fuel consumption and fuel cell size considering different European locations with diverse climates. The main novel contributions of this work, concerning other available scientific literature, are:

- Determination of the total heating energy required for residential houses in 4 different locations (Seville, Paris, Gothenburg, and Oulu) based on the average daily outdoor temperature in a year;
- Determination of fuel cell size and electrical energy consumption for the CHP systems composed of a fuel cell and a heat pump and one without a heat pump for the 4 different locations selected;
- Comparison of the system cost estimation feasibility for the fuel cell-based CHP with and without a heat pump in the 4 different locations.

2. Methods

The residential CHP system was designed considering the main components: a PEM fuel cell system, and an air source heat pump, i.e. vapor compression cycle. Thus, the fuel cell was the source of electricity in the house for all the electrical load including the heat pump, and both the fuel cell and heat pump provided heating energy to meet the house heating demand. Thus, the heat pump operates to complement the heat obtained from the fuel cell to fulfill the house's heating demand. Integrated thermal management can benefit heat usage, increasing the system's efficiency.

The system was designed as an independent house not connected to the grid. A system without a heat pump is also considered for comparison purposes. For the system without a heat pump, it was assumed that the fuel cell would provide more electrical energy to be converted into heating energy, when needed, i.e. heating requirement higher than the fuel cell heating "losses" provided, through an electric heater with 100 % efficiency. The scenario of the fuel cell-based CHP with an electric heater was described as Case 1, and the scenario with a heat pump was referred to as Case 2. The system was also composed of a DC-AC converter, between the fuel cell system and the electrical appliances, and a thermal storage for the heating energy from the fuel cell and the heat pump. The schematic representation of the modeled CHP is given in Fig. 1. The electrical and heating load and the component modeling are next described.

For the electrical load, data without heating demand was collected

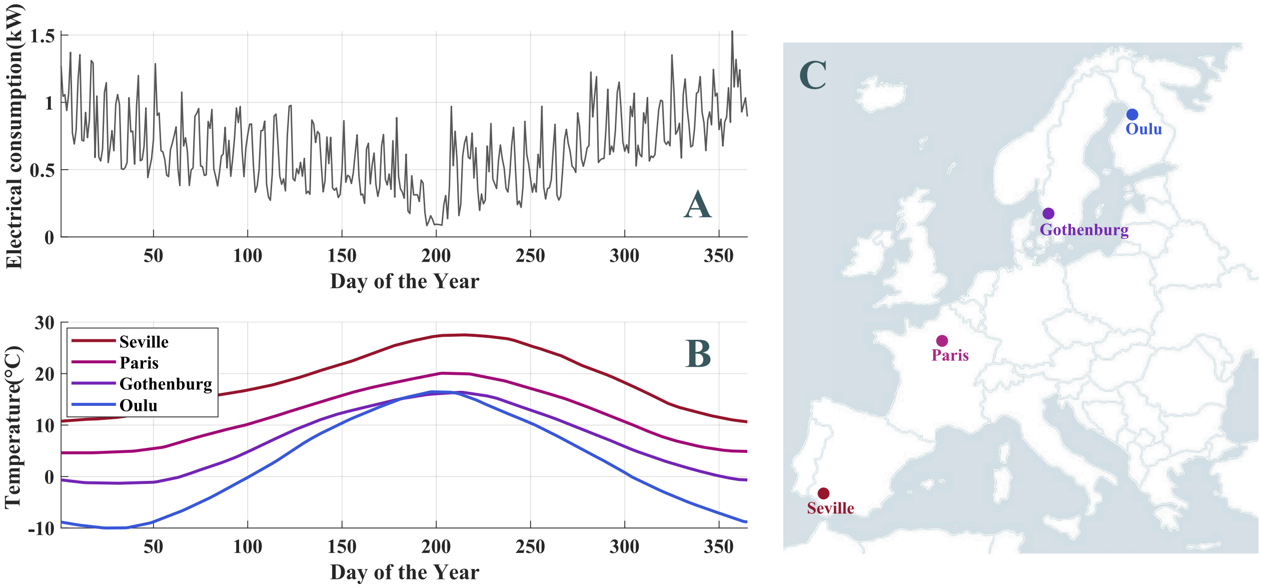

Fig. 2. Electrical load for a single-family house without heating based on collected data (A). Mean daily temperature profile during the year for 4 locations in Europe based on the published database (B). Europe map showing the locations selected (C).

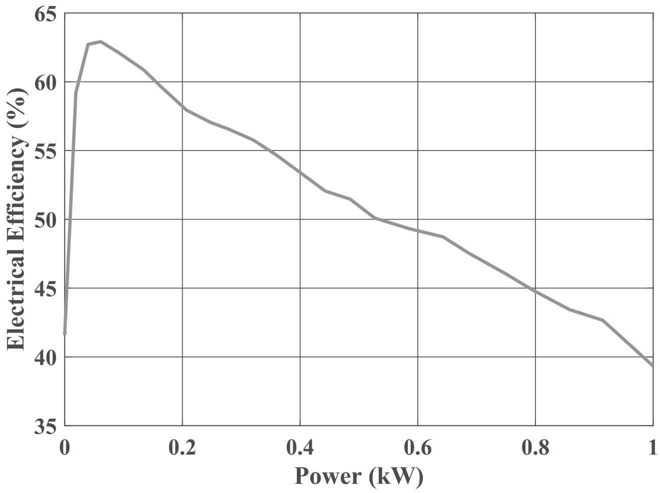

Fig. 3. Fuel cell system power efficiency model per 1 kW maximum power.

from a single-family house with a floor area of about 110 m^2 located in Gothenburg, Sweden. The electrical load data without heating was assumed as the basic electricity consumption for all the scenarios considered. Although there may be regional differences in non-heating electrical consumption, heating is the primary reason for electricity usage. Therefore, variations in electricity consumption excluding heating were considered negligible. This assumption allowed for a generalized consumption pattern across different locations, providing a solid basis for comparison. To address the heating demand difference, the mean daily temperature of 4 different European cities was considered: Seville, Paris, Gothenburg, and Oulu. The location selection aimed at understanding the temperature range effect from south to north Europe thus covering a wide range of climate zones where house heating is of distinct interest. The average daily outdoor temperature was calculated based on the database [26] which provides the minimum and maximum daily average temperature according to historical data from the last decades. Fig. 2 displays the electrical load and the mean outdoor temperature for all the selected locations. A slightly higher basic electrical consumption (excluding heating) can be observed in the winter [27]. This pattern might be associated with factors such as reduced daylight hours, which lead to increased use of artificial lighting, and more time spent indoors. However, the seasonal increase in electric energy consumption was considered to be negligible compared to the heating demand.

MATLAB was used for the CHP system's quasi-steady state time series simulation, i.e. component steady state at a one-day time scale. Quasi-steady state indicates that the system modeled is in a steady state for a given set of input conditions. As the average daily outdoor temperatures are considered for a year period, this method of simulation is deemed to be suitable. From the mean temperature (T_{mean}), the space heating load for a house of floor area A in m^2 was calculated as

$$Q_{heat} = \frac{UA(T_{in} - T_{mean})}{1000} \tag{1}$$

where U is the house heat transfer coefficient that quantifies the heat flow rate through the house structure. The U value indicates the overall heat loss throughout the house including walls, floor, doors, and windows. This value is assumed to be 1 Wm^{-2}K^{-1} as the typical value for European houses [28], while T_{in} is the indoor temperature assumed to be kept at 20 °C, a typical value for the heating temperature within homes in Europe. The hot water energy consumption (Wh/day), considering a heated water temperature difference of 50 °C and the specific heat capacity of water as 1 Wh/L^{o}C, was calculated based on the housing estate hot water consumption linear regression reported in [29] as

Table 1
COP values relative to the outdoor temperature for the heat pump model.

T_{mean}	−10	−5	0	5	10	15
COP	2.37	2.89	3.41	4.0	4.66	5.39

$$HW = 5100 - 47T_{mean} \tag{2}$$

All heat losses in the fuel cell, i.e. based on its electrical efficiency, are assumed possible to use as "useful" heat in the house considering the PEM temperature operation of 60–85 °C. In contrast, the losses from the electrical appliances and the converter are neglected as heating energy in the house. However, these also serve as small heating sources. The fuel cell system model, power-efficiency per maximum kW shown in Fig. 3, was based on reported data of a commercialized PEM fuel cell system, i.e. including pumps and compressor, [30] rescaling for the fuel size selected as proposed in [10] considering each system and location requirements as further explained.

The fuel cell size for the systems was calculated according to each system's energy requirements as the sum of the maximum electrical/heating consumption further oversizing the selected size. Thus, the fuel cell size, i.e. its maximum power, was calculated as the sum of the maximum electrical power load without heating, EC, added to 1) the maximum heating power, HD, or 2) the maximum heat pump electrical consumption, EC_{HP}, for the system without and with a heat pump respectively. The maximum fuel cell power determined ($\mathrm{FC}_{\mathrm{det,\ size}}$) was considered to be 70 % of the fuel cell's actual power ($\mathrm{FC}_{\mathrm{size}}$):

CHP without heat pump,

$$FC_{det,size} = \max(EC) + \max(HD) \tag{3}$$

CHP with heat pump,

$$FC_{det,size} = \max(EC) + \max(EC_{HP}) \tag{4}$$

$$FC_{size} = \frac{100}{70} FC_{det,size} \tag{5}$$

The oversizing of the fuel cell system is justified both to prevent the fuel cell size from operating at its maximum power accelerating degradation and to prevent power insufficiency in cases of unexpectedly higher electrical/heating loads. Since operating fuel cells at power levels higher than 80 % of the total load can accelerate degradation [31,32], limiting the maximum power to 70 % should be reasonable for the current purposes. For the converter, a 95 % efficiency was assumed as a typical value for the DC/AC converter connected to the CHP fuel cell [33]. The air-to-water heat pump with a vapor compression cycle was designed as previously reported [18] as a function of the outdoor temperature, T_{mean} for a water sink temperature in the range of 30–55 °C. Copeland Emerson's variable speed ZPV030 scroll compressor having 'R410a' as the working fluid refrigerant was assumed for the heat pump design. The variable-speed heat pump adjusts the speed according to the heating demand thus, a fixed nominal size was assumed for the heat pump for a conservative approach. Detailed information about the heat pump model can be found in [18]. The values of the coefficient of performance (COP) for the modeled heat pump along with the outside temperature are presented in Table 1. The electrical consumption for the heat pump is calculated as the ratio of the heating load and the COP.

To evaluate the economic aspects of the two fuel cell-based CHPs, i.e. with and without a heat pump, the investment cost of the main devices and the fuel consumption cost were investigated for correlation. The current installation cost of a fuel cell as CHP is not accurate due to its limited commercialization. A cost range of 4000 to 9000 € per kW of maximum electrical power can be found in the literature, however, the forecast for broader dissemination of this technology for residential applications expects it to be 2000 €/kW in the next years/decade [20,34,35]. Therefore, the fuel cell price was assumed as 2000 € per kW

Table 2
Prices for the devices and fuel.

	Fuel cell	Heat pump	Electric Heater	Hydrogen
Price	2000 €/kWe	10,000 €	1500 €	5 €/kg

of maximum electrical power. For the heat pump price a fixed price of 10,000 € was assumed for this technology. This is the current average price for a high-quality air-to-water heat pump and due to the maturity of the heat pump technology, its price has remained constant over decades [36–38]. Further, a 4 % yearly maintenance cost related to the initial investment cost and a 15-year lifetime were assumed for the systems. Regarding the fuel cost, the current price for the hydrogen produced from natural gas is in the range of 1–5 € per kg. Meanwhile,

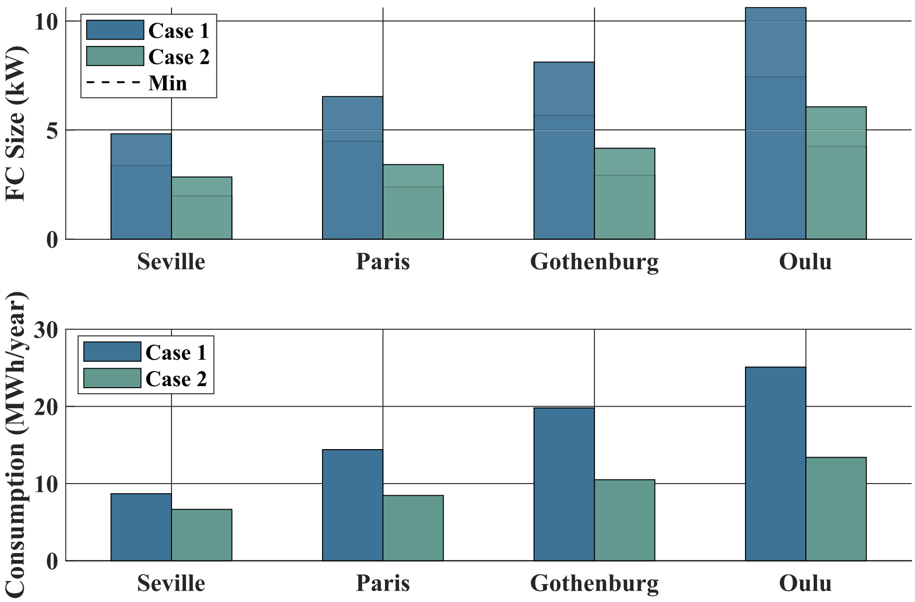

Fig. 4. Fuel cell size and electric energy consumption calculated for the 4 locations: Seville, Paris, Gothenburg, and Oulu for a fuel-cell-based CHP system with an electric heater (Case 1) and with a heat pump (Case 2).

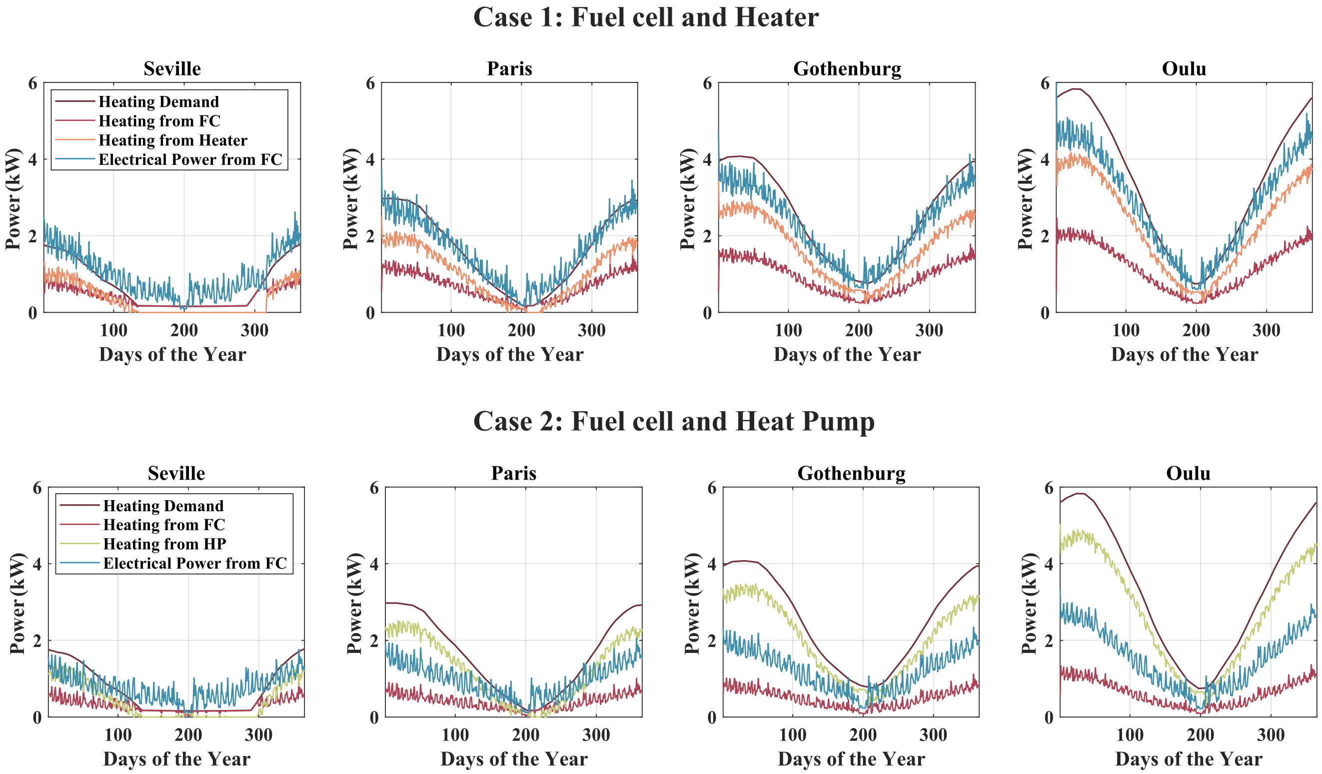

Fig. 5. Electrical and heating power profile along with the source of power for the fuel-cell-based CHP systems: with an electric heater (Case 1) and with a heat pump (Case 2).

hydrogen from renewables is in the range of 3–11 € per kg, predicted to drop as renewable energy price goes down [39–41]. Thus, a fixed price of 5 € per kg of hydrogen is assumed as a reasonable cost for the green hydrogen in the current/near future scenario. The energy content of hydrogen is 33 kWh per kg. The assumed prices are summarized in Table 2, and the implications of possible different prices are discussed in the further section. Since the scenario is unsettled, the economic analysis was focused on capital and maintenance costs to maintain clarity with fewer uncertain parameters; its limitations are further discussed. Thus, to correlate the total lifetime cost and the energy consumption concerning cases 1 and 2, the number of years, that the fuel savings take to compensate for the extra system cost, was calculated as

$$Yearstorecover = \frac{\Delta TotalSystemCost_{Case1,2}}{\Delta FuelCostperYear_{Case1,2}} \quad (6)$$

3. Results and discussion

3.1. System's heating and electrical profile

The calculated fuel cell size and total electric energy consumption for the fuel cell-based CHP with a heat pump (Case 2) were lower for all selected locations, as shown in Fig. 4. This indicates a possible promising integration of a fuel cell and a heat pump for a residential CHP system. As expected, both fuel size and energy consumption increase with a colder location, due to its higher heating energy requirement. Thus, for Oulu where lower temperatures are reached, larger fuel cells and more electrical energy are needed compared to all the other locations. The fuel cell size and energy consumption were at least double for Oulu compared to Seville demonstrating the significant impact of heating energy in the residential system, based on location. Furthermore, despite the lower electric energy consumption in the systems with a heat pump, for Seville with a lower heating energy requirement, the energy saving of about 20 % is not so significant compared to the other locations. Places with a temperature profile like Gothenburg and Oulu can potentially reduce their electric energy consumption by about 50 % with a fuel cell-based CHP integrated with a heat pump instead of an electric heater. This result supports a better suitability of such a system for locations with colder climates, achieving higher electric energy savings. The electrical and heating power along the year with the corresponding heating energy source are shown in Fig. 5 and further discussed.

When analyzing the fuel cell contribution to the heating power of both systems, it makes the relevance of using the fuel cell heat "losses" for the CHP system clear. For instance, in case 1, the fuel cell heat "losses" can provide at least one-third of the heating requirement in the house in Oulu, about half in Paris and Gothenburg in the winter, and up to the total heating requirement for most of the year in Seville. Once again, the result questions the need for the heat pump in cases of warmer temperature profiles similar to Seville. In case 2, where the fuel cell has a lower heating contribution due to the limited electrical power needed, it can still support at least around 20 % of the heating power in Oulu in the colder period. These outcomes support the suitability of fuel cell technologies for residential CHP systems. Regarding the contribution of the electric heater and the heat pump, the power curves in Fig. 5 emphasize the advantages of the fuel cell with a heat pump as a CHP system compared to the system with an electric heater in heat generating and electrical consumption. In case 2, for all locations, the heating contribution of the heat pump is higher than the heating power from the electric heater, however, a significantly lower electrical power profile from the fuel cell is required. Furthermore, since the fuel cell heat contribution does not increase with the same proportion as of the total heating requirements, in locations with a colder temperature profile, such as Gothenburg and Oulu, the heat pump can have a higher contribution, thus better justifying the system coupled with a heat pump. The economic impact of the two different cases is discussed next.

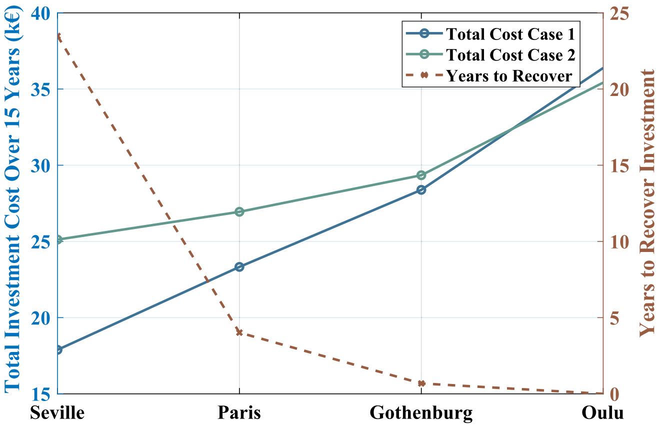

Fig. 6. The total investment cost (with maintenance, without fuel) for the fuel-cell-based CHP systems: with an electric heater (Case 1) and with a heat pump (Case 2), and years to compensate the investment difference for Case 2 to Case 1 considering the energy-saving provided.

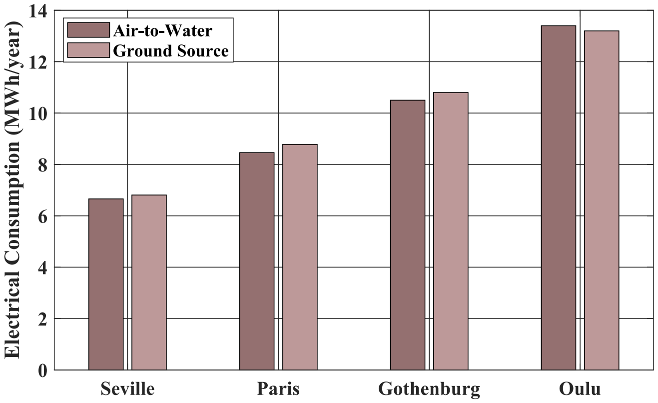

Fig. 7. Electrical consumption for a fuel cell-based CHP combined with an air-to-water or a ground source heat pump considering a temperature profile of Seville, Paris, Gothenburg, and Oulu.

3.2. Economic impact and sensitivity analysis

The total cost over 15 years (capital investment and maintenance) for the CHP comprising a heat pump was higher for all the cities, except for Oulu, despite the smaller fuel cell size requirements in the systems compared to those without a heat pump. Thus, in the Oulu scenario, the fuel size reduction, as shown in Fig. 4 calculated from Eqs. (4) and (5), was already significant to favor the total investment cost for Case 2, in Eq. (6). The exception for Oulu indicates a higher advantage of the CHP system integrating both the fuel cell and the heat pump where the heating energy required is more pronounced. For the cities of Paris and Gothenburg despite the higher investment cost, the energy saving provided by the integration of a heat pump in the fuel cell-based CHP can be compensated for in less than 5 years, supporting the suitability of the proposed system for temperature range profile similar to Paris or colder. The system is not justified for a temperature profile similar to Seville, taking decades to compensate for the increased investment cost. The total investment cost for the two cases and the years to recover the case with a heat pump in contrast to the case without a heat pump are shown in Fig. 6. The impact of how other parameter values could affect this analysis is further discussed.

Despite the uncertain scenario around the hydrogen economy, heat pumps are considered to be a more mature technology. Nevertheless, other heat pump technologies might be associated with different electrical consumption for the systems analyzed. For instance, ground

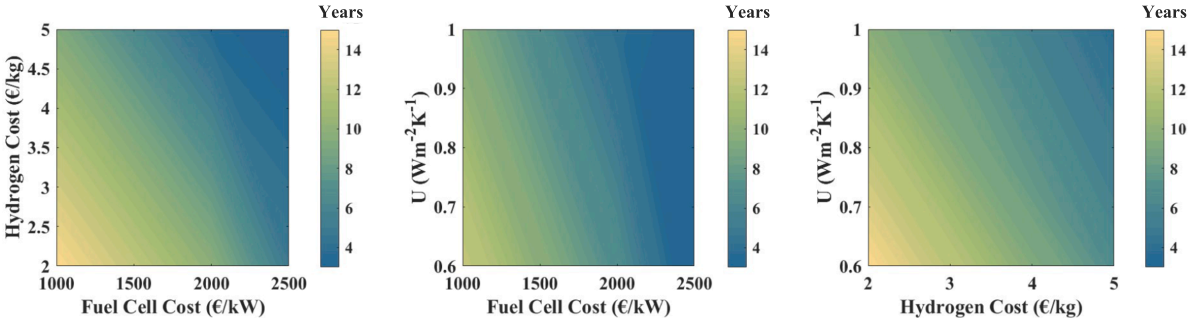

Fig. 8. Years to compensate for the fuel cell based-CHP coupled with a heat pump with reference to the fuel cell based-CHP without a heat pump for a house in Paris considering fuel cell cost, hydrogen cost, and U value. Each graph has one of the variables fixed as the base case, i.e. fuel cell cost, hydrogen cost, and U value as 2000 €/kW, 5€/kg, and 1 Wm^{-2}K^{-1}.

source heat pumps are more efficient at lower temperatures compared to air-to-water heat pumps, due to the warmer temperature of the ground compared to the air during the winter, reaching higher COPs, e.g. 3 at −10 °C. However, the efficiency is lower than the air-to-water at moderate temperatures, e.g. 4 at 10 °C [28]. As a result, when the ground source heat pump is adopted for the fuel cell-based CHP instead of the air-to-water heat pump, similar electrical consumption was obtained for all the cities considered, as shown in Fig. 7. For Oulu, the coldest city considered, the electrical consumption was slightly lower when using the ground-source reflecting the advantage of the adoption of this kind of heat pump for cold climates due to its higher COP at lower temperatures. Nevertheless, since similar electrical consumption values were obtained and higher installation costs are related to the ground source heat pump [36], the air-to-water heat pump was adopted and considered representative of the fuel cell-based CHP with a heat pump. Regarding the fuel cell type selection, PEM fuel cells, used in this work, are potentially a more practical and cost-effective choice for residential applications due to their lower operating temperatures, and faster start-up times compared to other fuel cell types [20,42]. However, given the high efficiency of SOFCs, further investigation and diverse climate comparisons could be valuable as a future study topic. The impact of hydrogen and fuel cell prices is further discussed.

The fuel cell and hydrogen prices currently face an uncertain scenario attributed to the technology dissemination and renewable electricity source costs. Thus, the fuel cell price drop is strongly related to the prospect of the technology mass production while the green hydrogen price is dependent on renewable energy cost and hydrogen upscale production. The fuel cell price assumed for the base case, i.e. 2000 € per max kW, already lies in an optimistic forecast. Nevertheless, the higher the fuel cell price, the more advantageous it is to combine a fuel cell with a heat pump in comparison to a system that uses just a fuel cell with an electric heater regarding both cost and energy consumption reduction. A similar relation applies to hydrogen prices. Since the fuel cell-based CHP with a heat pump reduces electric energy consumption, the higher the fuel price, the more advantageous is this setup. The relation between fuel cells and hydrogen price is illustrated in Fig. 8, for the Paris temperature profile case, indicating fewer years to compensate for higher prices. However, naturally, the higher the fuel cell and hydrogen price the less interesting it is to adopt this technology either alone or in combination with other devices. On the other hand, considering the same hydrogen price, if the fuel cell is cheaper than the assumed price, the system will take longer to compensate for the extra cost associated with the integration of a heat pump, as shown in Fig. 8. Still, if the price decreases by half, this system compensates for locations like Paris or colder in less than 7 years. A cheaper hydrogen price would also favor the system without a heat pump. Nevertheless, if the hydrogen price goes as low as 2 €/kg, the system with a heat pump in Paris would compensate in 10 years due to its lower energy consumption, as shown in Fig. 8 at a hydrogen cost of 2 €/kg and a fuel cell cost of 2000 €/kW. The economic evaluation can be more accurate when broader mass production of the technologies occurs and a clear situation about the hydrogen infrastructure and renewable production takes place. By then, a more detailed economic evaluation could be beneficial by incorporating additional parameters, such as net present worth and discounted payback period which are challenging to estimate at this point. Besides the hydrogen and fuel cell price, another parameter that might change in modern house construction is the heat transfer coefficient, i.e. U value in Eq. (1). This value can be 40 % lower in modern constructions in cold climates reducing the heating energy requirements for the house [28]. Still, considering the same systems, for a $U = 0.6$ Wm^{-2}K^{-1}, the energy savings provided by the fuel cell and heat pump CHP in Paris compensate for the extra cost in the first decade, as shown in Fig. 8. Different scenarios' impact in the total years to compensate for a fuel cell-based CHP combined with a heat pump is illustrated in Fig. 8 considering Paris' temperature profile. Thus, concerning the outcomes of this work, the results support the integration of a fuel cell and a heat pump for a residential CHP system providing energy savings and cost reduction, especially for colder temperature profile regions.

4. Conclusion

In this work, a residential fuel cell-based CHP system coupled with a heat pump was investigated across various European locations, focusing on fuel cell size, energy consumption, and cost. Results have demonstrated that, compared to a system without a heat pump, the integrated system can require significantly smaller fuel cells with an energy saving of at least 40 % for locations with similar temperature profiles of Paris or colder. Despite the higher investment cost for the system, cost analysis has shown that in less than 5 years the energy savings compensate for the total investment for cities like Paris, Gothenburg, and Oulu. The results emphasize the long-term advantage of this integrated system, which becomes increasingly beneficial as the temperature profile becomes colder.

CRediT authorship contribution statement

Tatiana Santos Andrade: Writing – review & editing. **Sindhu Kanya Nalini Ramakrishna:** Writing – review & editing, Investigation. **Torbjörn Thiringer:** Writing – review & editing, Supervision, Funding acquisition.

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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Data availability

Data will be made available on request.

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