DTU Library

Combined micro-cogeneration and electric vehicle system for household application: An energy and economic analysis in a Northern European climate

Vialetto, Giulio; Noro, Marco; Rokni, Marvin Mikael

Published in:
International Journal of Hydrogen Energy

Link to article, DOI:
10.1016/j.ijhydene.2017.01.035

Publication date:
2017

Document Version
Peer reviewed version

Hydrogen Energy 2017;42:10285 -10297.

Combined micro-cogeneration and electric vehicle system for household application: an energy and economic analysis in a Northern European climate

Giulio Vialetto[a,b], Marco Noro[b,*], Masoud Rokni[a]
[a]Department of Mechanical Engineering - Technical University of Denmark - Nils Koppels Allé, Copenhagen 2800 - Denmark
[b]Department of Management and Engineering - University of Padua - Stradella S. Nicola, 3, 36100 Vicenza - Italy

ABSTRACT

In recent years, Denmark boosted investments in renewable energy and electrification of transportation. The Danish Agenda proposed that all primary energy consumption will be covered by renewable sources such as wind, biomass and solar by 2050. These changes require significant investment and re-thinking of entire energy infrastructures and types of consumption. The Agenda also suggested, among other things, improving the efficiency of energy systems.

In this paper, the interactions between charging an electric car and an innovative cogeneration system for household application (micro-solid oxide fuel cell with an integrated heating system) are investigated. The charge of the electric car by the cogenerator produces waste heat that can be used to partially cover the heat demand of the house. In this way it may be possible to increase overall efficiency and decrease total energy costs. Different innovative strategies are proposed and analyzed to manage charging an electric car and efficiently using the waste heat available. The aims of this study are to make the system grid-independent, to decrease the thermal stress of SOFCs and to determine the nominal power of an integrated heating system. The results show energy efficiency and economic profitability of the system, even if subsidies are not included.

Keywords: SOFC; heat pump; operating strategy; hybrid system; electric car.

1. INTRODUCTION

Electric cars and electrical mobility are open topics of research [1] with the aim of decreasing the environmental impact of transport. For example, traditional cars could be replaced with electric ones, which means that they are powered by electricity instead of chemical energy such as petrol. Different studies show that electrical mobility has an environmental impact that is strictly related to the energy sources used to produce electricity [2]. For example, greenhouse gas emissions can be avoided only if renewable energy sources are used. Electrical mobility has been already studied in relation to the possibility of domestic charging [3]. Also analyzed was the possibility of using electric cars and their batteries as energy storage systems to stabilize electric systems in scenarios where the majority of the total energy demand is supplied by renewable energy [4] [5].

The main problems of electrical mobility are related to energy storage because batteries provide lower energy density storage than hydrocarbon fuels (when comparing, for example, kWh/kg), making the former heavier than the latter. An alternative is proposed between traditional and electrical mobility with the use of bio-fuel. Different types of fuels have been investigated and developed to decrease greenhouse emissions of traditional cars [1]. The main advantages are higher power density and the possibility of using traditional cars with a mixture of fossil fuels and bio-fuel

* Corresponding author. Tel.: +39 0444 998704; Fax: +39 0444 998884 e-mail: marco.noro@unipd.it
mr@mek.dtu.dk

[1]. The disadvantages are the high cost, the low efficiency of the refinery/production process and the use of food to produce fuels (for example, corn-based methanol); the last point could be morally unacceptable [6].

Meanwhile, energy systems are moving to distributed generation, improving electrical transmission efficiency and infrastructure [1]. One solution for household applications is micro-cogeneration, which allows a better match between energy demand and production as well as lower transmission losses with respect to a traditional electrical system. Different cogeneration systems have been proposed, analyzed and studied, such as internal combustions engines, Stirling engines [7], fuel cells [7]-[13], micro-Rankine and micro-gas turbines [14], and photovoltaic cogeneration modules [14] [15]. In some cases, systems set up with a cogenerator and an integrated heating system have been proposed in order to face both electrical and heat demand in a more effective way [16].

Even though electric mobility has been analyzed for years [1], studies on micro-cogeneration combined with electric cars are not so plentiful. In [17] [18] [19] [20], micro-cogeneration systems based on internal combustion engines coupled to natural gas boilers are proposed for household application: the results prove higher efficiencies than those of traditional systems. In [21], a proton exchange membrane fuel cell is proposed as a micro-cogenerator, while in [22] [23], solid oxide fuel cells (SOFCs) are used. Further, [24] proposed instead a PV system. In the authors' opinion, innovative systems require innovative operation strategies. The only example found in the literature is in [21], which proposed an innovative strategy based on multi-linear programming.

In this study, a system composed of an SOFC and a heat pump is presented. In addition, an electric car that is charged from the electricity produced by an SOFC is also considered. An innovative approach is thus followed to boost efficiency of the system, to realize grid independence and to achieve the maximum economic benefit. The aim of the research is to analyze both thermodynamic and economic advantages with respect to a traditional solution for household application.

2. OVERVIEW OF THE SYSTEM

2.1 Equipment and design strategy

The innovative system considered here is based on a previous study by the authors [25]. As proposed, it will satisfy energy demands in terms of electricity, space heating and domestic hot water (DHW) for a residential building located in Denmark. The system is represented in Figure 1, which is a setup consisting of an SOFC system integrated with a ground source heat pump (GSHP). SOFC is the high efficiency micro-cogenerator that provides both electricity and heat, while the GSHP is used to meet part of the heating and DHW demands with a higher efficiency than those of traditional boilers or electric heaters. The electrical energy produced by the SOFC (fueled by natural gas [NG]) is used to cover the user electricity demand, mainly at night, and to charge an electric vehicle (EV). In the case of a mismatch between electrical demand and production, the system exchanges energy with the grid. However, the operation strategies implemented here (section 4) have the aim of maximizing the electrical demand covered by the SOFC in order to be as grid independent as possible.

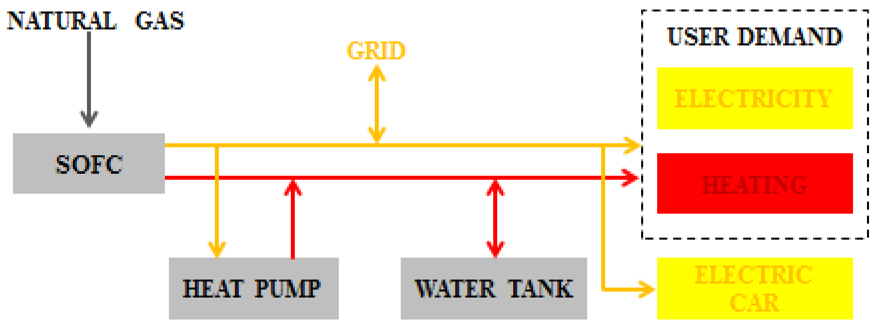

Figure 1 – Representation of system energy fluxes (yellow represents electricity, and red represents heat).

The main part of the system is the SOFC micro-cogenerator that provides electricity, while its waste heat is used to meet part of the heat demand for the building. Figure 2 shows the main components of the SOFC system, which includes all necessary components, such as an air compressor (to supply air at the correct pressure and to cool the stacks), an inverter (which is used to convert current from direct to alternate current – DC to AC), a catalytic partial fuel reformer (to crack the heavy hydrocarbons), a desulfurizer (to remove sulfur and thus avoid sulfur poisoning for the cells) and a catalytic burner (to burn the unreacted fuels that remain). In this study, a 2 kW nominal electric power SOFC is adopted for covering the electrical demand, while the heat produced by the fuel cell is used to cover space heating and domestic hot water demands as much as possible, thus maximizing the overall system efficiency.

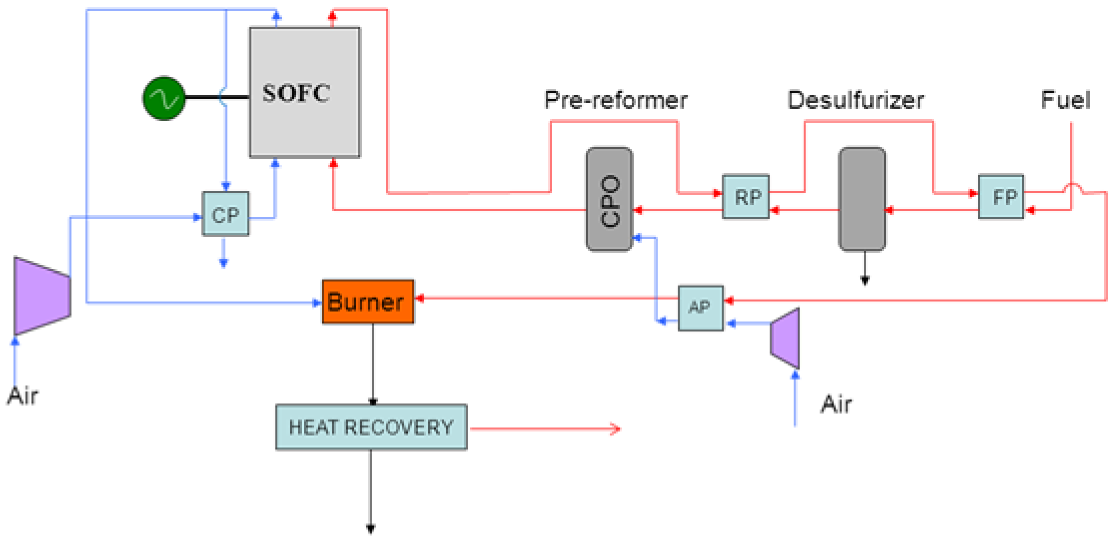

Figure 2 - Schematic of the SOFC system: CP = cathode pre-heater, FP = fuel pre-heater, AP = air pre-heater, RP = reformer pre-heater, and CPO = catalytic partial oxidation [25].

Due to the different heat-to-power ratios of the fuel cell and user demands, the heat recovered by an SOFC is not sufficient to cover the heat demand, and therefore, a ground source heat pump is proposed as an additional integrated heating system. Note that the GSHP nominal power is related to the design strategy, and therefore, no other devices for the heating system will be used. For example, in [16], two different integrated systems (condensing boiler and electric heater) were analyzed to cover peak heat demands with the aim of decreasing the nominal power of the heat pump and its purchase cost.

In the current study, an innovative strategy related to electric car charging is also proposed in which batteries are charged at night when both electrical and heat demands are low. As requested, electricity is covered by the SOFC, and the co-generated heat (SOFC and heat pump) is stored at night and made available to cover heat demand during the day by means of a water storage tank. This strategy has the effect of decreasing the nominal power of the heat pump. To simulate the system as close as possible to a real case, the GSHP is modeled for different working conditions (i.e., both partial load and condenser/evaporator temperatures) using the methods proposed in the technical standards [16] [25] [26] [27].

The size of the water tank mainly depends on the design strategy, as previously mentioned. In the case of nighttime operation, the SOFC produces electricity for the EV when the surplus heat for user demand is low. For this reason, the water tank is sized considering the maximum heat production that can be produced at night in relation to the EV charging. The main parameters of the system are reported in Table 1.

Table 1 – Main data and characteristics of the system.

PARAMETERS OF THE SYSTEM	
SOFC – Nominal power	2 kW
SOFC – H/P at full load	0.826
SOFC – Electrical efficiency at full load	0.53
GSHP – Nominal power	7 kW
GSHP – COP at full load at W10/W35	5.1
Water tank – Capacity	140 L

2.2 User energy demands

To simulate the system it is necessary to collect data for space heating and domestic hot water as well as electrical demands. The aim is to define a reference year containing hourly profiles for each demand. Data from reference [25] were used for this study: the annual energy demand is 10725 kWh for space heating, 2970 kWh for DHW and 3028 kWh for electricity, as displayed in Figure 3. No cooling demand is supposed to exist due to the climate of the Copenhagen area and the type of building (residential).

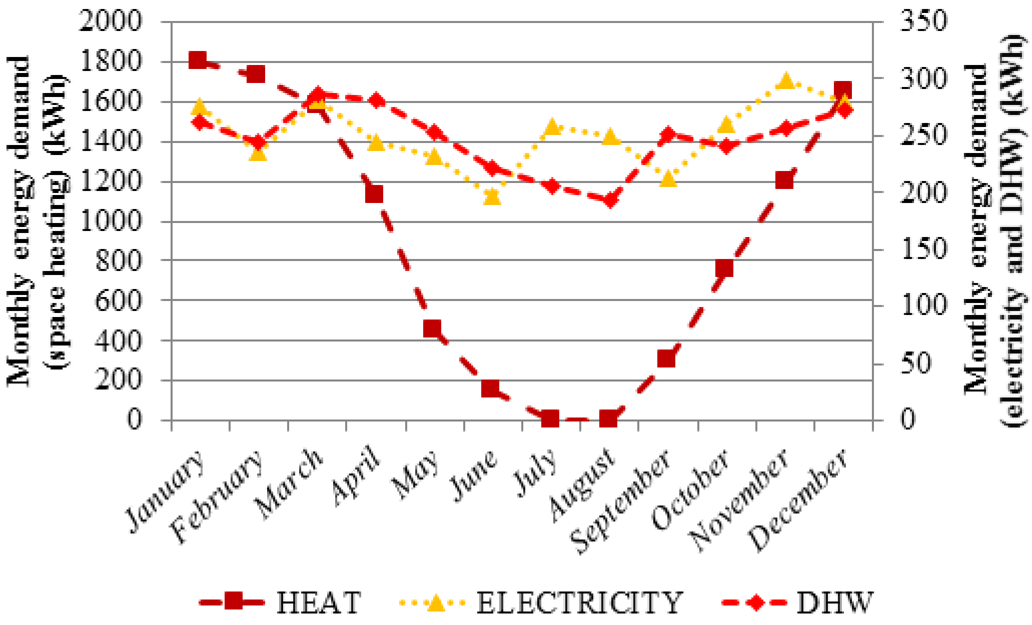

Figure 3 - Electrical, DHW (right scale) and heat (left scale) monthly energy demands for the residential building located in Copenhagen, Denmark [25].

3. MOBILITY MODEL

To complete the data needed for the simulations, a reference year for the daily driving distance of an average Danish car driver should also be provided. An average annual driving distance of approximately 15600 km (42.7 km/day) was proposed [28], but no information regarding a reference year was reported. A dataset of daily driving distance was therefore created using a RANDOM function set to vary between 21.35 and 64.05 km (so that the average of daily driving would be very close to 42.7 km). Table 2 gives a summary of the dataset proposed here, while Figure 4 shows its daily variation. The study investigates both thermodynamic and economic performances of the electric mobility model in comparison with the traditional car. Data on fuel efficiency, purchase costs, fuel costs and the energy scenario (increasing index of fuel cost) are reported in Table 3 [29] [30] [31].

Table 2 – Summary of reference year for daily driving distance.

Driving distance reference year	
Upper limit	64.05 km
Lower limit	21.35 km
Number of values	365
Average	42.72 km
Standard deviation	12.35 km

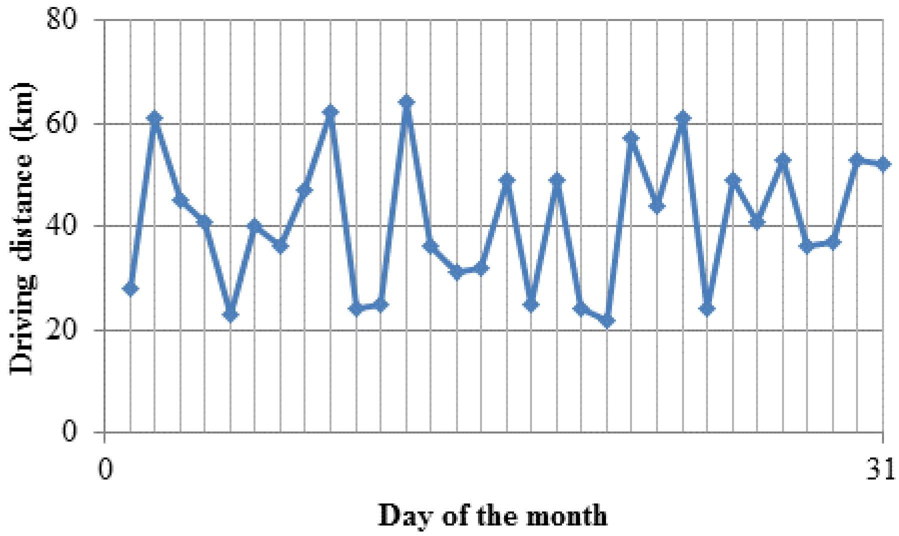

Figure 4 – Daily driving distance for a month for the reference year (January).

Table 3 – Parameters for traditional car and electric cars

Traditional car		Electric car	
Fuel efficiency	20 km/l [31]	Fuel efficiency	0.15 kWh/km [30]
Purchase cost	12000 € [31]	Purchase cost	20000 € [31]
Fuel cost	1.454 €/l [29]	Battery cost	10000 € [31]
Fuel cost annual increasing index	4.56 % [29]		

The fuel cost increasing index is fixed at 4.56 %, and it is defined as the average annual increasing index of diesel fuel from 2005 to 2014 in Denmark. Since the fuel increasing cost is based on historical data, a sensitivity analysis by varying this index from 0 % to 12 % is useful to examine its impact on the economic results. Even though reference [31] suggests consideration of other costs related to a traditional car (such as the costs of pollution and noise), in this study, it is preferred that such additional costs shall not be considered because the uncertainty related to these values could be high.

4. OPERATION STRATEGIES

An innovative operation strategy of the system is adopted here in order to

- perform at a high thermodynamic efficiency (by means of increasing as much as possible the utilization of the fuel cell);
- match the system heat-to-power ratio for the user electrical demand, with the aim of maximizing the grid independence of the system.

The innovative operation strategy is derived by the following, which are also implemented simultaneously:

- Electric load following (ELF) to boost the fuel cell utilization factor;
- Charge electric vehicle (CEV) to manage the electric car charge;
- Peak shaving (PS) to manage the heat recovered by the SOFC during the electric car battery charging.

4.1 ELF strategy

ELF (electric load following) is an operation strategy proposed in [32]. It was successfully used by the authors in references [16] and [25]. With this strategy, electricity and heat demands are not followed separately, but they are considered together and simultaneously. An electric equivalent load (EEL) parameter is also defined as the electrical demand for both the user and the heat pump. It assumes that the user heat demand is covered partly by the waste heat from the SOFC and partly by the heat pump. EEL is thus a function of the user electricity demand, the total heat demand (both DHW and space heating), the heat-to-power ratio (H/P), the auxiliary consumption and the heat pump coefficient of performance (COP). With the ELF strategy, the produced electricity is equal to the EEL. The main advantages are as follows:

- The system has a higher thermodynamic efficiency thanks to a higher utilization factor of the fuel cell.
- The system has a higher profitability than those of other strategies as a direct consequence of the previous point. This is therefore related to the higher SOFC utilization factor that in turn yields a higher production of energy and therefore a lower specific cost for the electricity;
- A smaller water tank is required thanks to a better correlation of the heat-to-power ratio between the system and the user.

The equations proposed in [25] require the user electricity demand (E_{USER}), the user heat demand (H_{USER}), and the efficiencies of both the SOFC (η_{trans}) and the GSHP (COP) as input data. The overall transmitted efficiency of the SOFC (η_{trans}) is defined so that both auxiliaries and inverter efficiencies are considered, and it is fixed at 0.9068. The definition for the COP of the heat pump considers the hourly variation as a function of the ground temperature, the tank temperature and the partial load (Table 4). Electrical consumption for the charging EV is not considered in the ELF calculation.

Table 4 – Definition of ELF.

Equation	Condition
$ELF = \dfrac{E_{USER}}{\eta_{trans}}$ (1)	This equation is used when SOFC waste heat is available and higher than the user heat request.
$ELF = \dfrac{1}{\eta_{trans}} * \dfrac{E_{USER} + \dfrac{H_{USER}}{COP}}{1 + \dfrac{H/P}{COP * \eta_{trans}}}$ (2)	This equation is used when waste heat from SOFC is not enough to cover user demand and GSHP is required to cover heat demand (integrated with SOFC system).

4.2 CEV strategy

The aim with the charge electric vehicle (CEV) strategy is to charge the car batteries using electricity produced by SOFC stacks only, thus avoiding consumption from the grid. Such a strategy maximizes the efficiency of the system. Electrical and heat demands at night are lower than those during the daytime. However, if the EV is charged at nominal power from the SOFC during the nighttime and if there is at the same time a request for electricity (and/or heat) from the building, then the surplus electricity could be supplied from the grid. It was proposed that the EV be charged in a way that considers both the nominal power of the SOFC ($SOFC_{nom,power}$), energy consumption of the user (electrical [$E_{demand,user}$], heating [$H_{demand,user}$], and domestic hot water [$DHW_{demand,user}$]) and the electricity request for charging ($EC_{charge,demand}$). The charging process starts at 10pm and continues until the battery is fully charged. The duration of the charging process is related to the previous day's consumption and the EC_{charge} (electricity available for charging) parameter that varies hour-by-hour:

$$EC_{charge} = \min\left(SOFC_{nom,power} - \left(E_{demand,user} + \frac{H_{demand,user} + DHW_{demand,user}}{COP_{avg.}} \right); EC_{charge,demand} \right) \quad (3)$$

4.3 PS strategy

The peak shaving (PS) strategy is defined with the aim of smart utilization of waste heat from the SOFC at night when the electric car is charging, the electricity requested is mainly produced by the fuel cell (under CEV strategy) and the heat demand is low (both space heating and/or heat for the DHW). Heat recovered by the SOFC is stored (in the tank) and used during the day to cover the peak demand. The main effect is the reduction of the maximum heat power required by the heat pump with a double advantage, namely a lower investment cost and operation at a higher partial load ratio for the heat pump. The last point is worth explaining: the GSHP provides heat mainly when heat production of the SOFC is lower than the user demand. As previously stated, the system has no other integrated heating system, and therefore, the heat pump covers the peak demand. The PS strategy shaves peak demand without using any other integrated system but stores the heat that is produced at night (as a consequence of the electric car charging), which will be available during peak hours. The average heat demand is then evaluated hour-by-hour during the year, as shown in Figure 5 (the winter months of December, January and February) and Figure 6 (the summer months of June, July and August). It is possible to appreciate that the maximum request is between 7 am-9 am, when there is high demand for both space heating and domestic heat water. It is also expected that the peak shaving strategy would decrease the heat request during these hours.

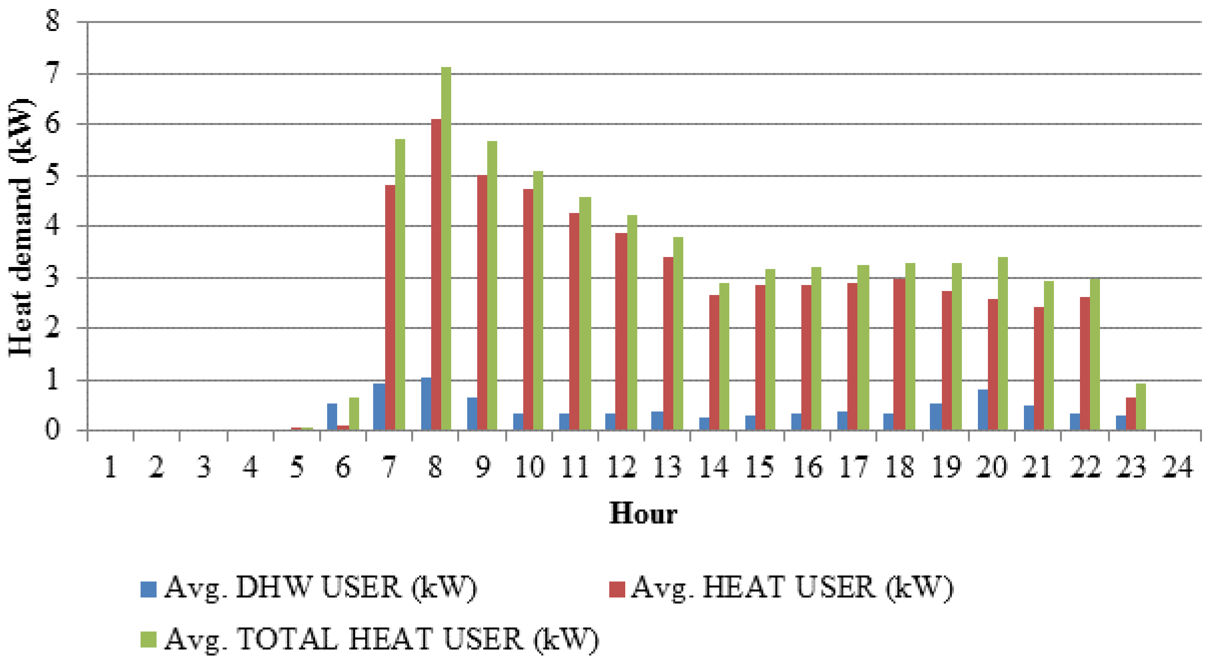

Figure 5 - Average heat demand (space heating and domestic hot water) for the winter months of December, January, and February.

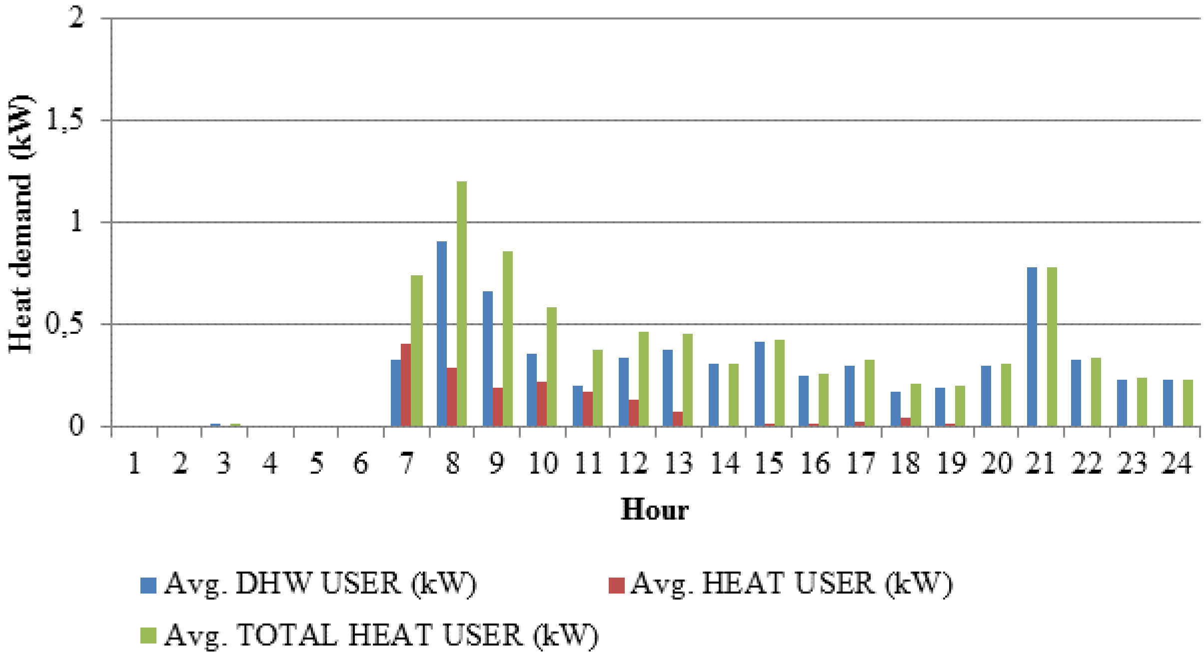

Figure 6 – Average heat demand (space heating and domestic hot water) for the summer months of June, July, and August.

The average amount of waste heat that is available after the vehicle charging process is estimated to be 5.1 kWh, which is calculated using an average daily distance of 42.7 km, a fuel efficiency of 0.15 kWh/km and an H/P ratio equal to 0.8 for the SOFC. To simplify the peak shaving strategy, an annual average parameter is then created hourly. These values are then used to calculate the parameter P_{limit} (power limit). If the user heat demand is higher than this parameter (i.e., peak demand), then stored heat is used to cover the difference in order to shave the peak. This parameter is calculated by defining a system of 25 equations where 24 equations are related to the hourly user heat demand ($H^n_{demand,user}$) and one equation correlates the available heat ($H_{tot,available}$) and stored heat (H^n_{stored}) quantities (see Eq. 4). The parameter $t_{sampling}$ (sampling time) is introduced because $H^n_{demand,user}$ is the demand power and $H_{tot,available}$ is the available energy. In a case for which the power is expressed in kW and the energy is expressed in kWh, the value of the $t_{sampling}$ parameter is 1 hour. The system of equations composed here is in non-linear form, and therefore, it was solved using the Newton-Raphson method from which the result is found to be P_{limit}=2.92 kW. If the heat demand is higher than P_{limit}, the heat stored during car charging is used to decrease the heat demand required for the SOFC and/or the GSHP (heat demand peak shaving).

$$\begin{cases} H^{1}{}_{demand,user} - \min(H^{1}{}_{demand,user}, P_{limit}) = H^{1}_{stored} \\ H^{2}{}_{demand,user} - \min(H^{2}{}_{demand,user}, P_{limit}) = H^{2}_{stored} \\ \quad\quad\quad\quad \ldots \\ H^{n}{}_{demand,user} - \min(H^{n}{}_{demand,user}, P_{limit}) = H^{n}_{stored} \\ \quad\quad\quad\quad \ldots \\ H^{24}{}_{demand,user} - \min(H^{24}{}_{demand,user}, P_{limit}) = H^{24}_{stored} \\ \quad \sum_{n=1}^{24} H^{n}{}_{stored} * t_{sampling} = H_{tot,available} \end{cases} \quad (4)$$

Figure 7 depicts the effect of the strategy in which *Avg. Heat Dem.* is the annual average demand of heat, *Peak dem.* is the peak demand covered by the stored heat during electric car charging, and *Off-Peak dem.* is the heat demand covered by SOFC and/or GSHP. The graph shows that the PS strategy successfully covers the heat demand between 7am and 11am, the time period when there is a peak heat demand.

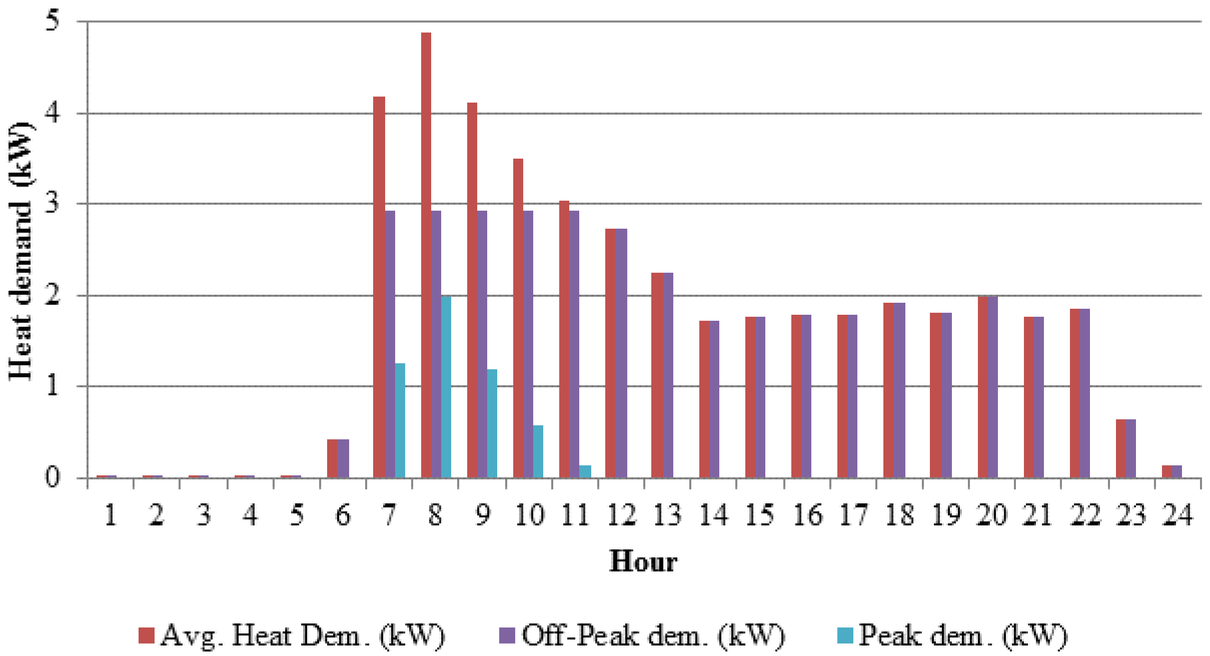

Figure 7 – Peak shaving of an average day.

The parameter P_{limit} is defined using a daily average concept. The daily driving distance (when heat is available from the electric car charging) and heat demand change day by day, and therefore, it would be necessary to solve Eq. (4) for each day of the year. Thus, an alternative method is proposed in which P_{limit} is used as a parameter of peak limit for each day of the year. The results illustrated in Figure 7 are also used to define another parameter, $\%Heat_{available}$, for each hour of the peak demand (7am-11am). This parameter is the percentage of available heat from EV charging used to cover peak demand (see Table 5). For each peak hour of each day of the year, the available heat is calculated from the multiplication of this parameter by the heat available from the EV charging of the previous night. Should the heat be available after 11am (for example, due to a lower user heat request), then it would cover heat demand of the other hours of the day. The aim of this parameter is to use efficiently the waste heat available in order to decrease peak demand without using Eq. 4. It will also be possible to achieve peak shaving of the heat demand, as displayed in Figure 7.

Table 5 – Values of $\%Heat_{available}$ parameter

Hour	**$\%Heat_{available}$**
7	24 %
8	39 %
9	23 %
10	11 %
11	3 %

5. ECONOMIC MODEL

5.1 Equipment investment costs

In this analysis, both economic and thermodynamic benchmarks were used to analyze the results. First, it is necessary to define an economic scenario with both investment and energy costs. The purchase costs of the SOFC (and related auxiliaries), the GSHP and the water tank are estimated using the method proposed in reference [25]:

- The cost of SOFC is related to the number of stacks, the cell geometry and the electrical performance of cells.
- The cost of counterflow plate heat exchangers (an air-water heat exchanger to recover heat from the SOFC and an air-air heat exchanger such as a fuel pre-heater) is related to the heat flow rate, the log mean temperature difference and the heat transfer coefficient.
- The burner cost is estimated from the mass flow of the gases.
- The DC/AC inverter cost is related to the power of the fuel cell.
- The compressor cost is estimated from the compression power.
- The pre-reformer cost is related to its characteristic area and volume.
- The cost of the desulfurizer is related to its annual production volume, fuel mass flow and system power.
- The GSHP cost is related to the nominal heating power based on an algebraic power regression developed here to follow the technical datasheet of the heat pump. It also includes the cost of a ground heat exchanger coupled with the necessary drilling, and it is based on a calculation method that considers the heat absorbed by the GSHP, which in turn is related to the nominal heating power as well as the electric consumption of the heat pump.
- For the water tank (storage), a power regression is developed to follow the technical datasheet of the tank, relating the cost estimation to the capacity of the tank.

The purchase cost of the electrical car (EV) and the traditional car is estimated using the data proposed in references [31] and [32]. For the sake of clarification, the results are reported in Table 6.

Table 6 – Estimated purchase costs of the main equipment.

Component	**Purchase cost**
SOFC system [25]	5067 €

GSHP [25]	12347 €
Water tank [25]	685 €
Electric car [32]	30000 €
Traditional car [32]	12000 €

5.2 Energy costs

To calculate the operating cost of the system, it is essential to know the costs of electricity, natural gas and fuel (for the traditional car). Energy prices are not constant, varying every year, so it is worthwhile to take into account an increasing index of electricity, natural gas and fuel prices per year (Table 7 based on [25] and [29]). In addition, a sensitivity analysis is also performed by varying the increasing indexes between 0 % and 12 % in order to make the analysis more comprehensive and therefore analyze different energy scenarios.

Table 7 – Energy prices and increasing index

Energy cost	**Value**
Natural gas [25]	0.1083 €/kWh
Natural gas increasing index [25]	3.75 %
Electricity [25]	0.2972 €/kWh
Electricity increasing index [25]	3.84 %
Fuel [29]	1.454 €/l
Fuel increasing index [29]	4.56 %

Equation (5) defines how annual increasing indexes affect the energy costs:

$$C_{\mathrm{t}} = C_0 \left(1 + i_c\right)^{t-1} \tag{5}$$

where C_t is the cost at period t (time), i_c is the relative increasing index and C_0 is the cost at the end of the first year. Note that t–1 is used instead of t because the cost of the first year is given and also assumed to be constant until the following year.

5.3 Maintenance costs

Maintenance costs are defined for both SOFC and GSHP, as suggested in [33] and [34]. For the SOFC, it is proposed to be 46.46 €/year, considering two stacks of 1 kW each [33]. For the GSHP, it is proposed to be 72.62 €/year, that is, 1 % of the purchase cost [34]. These costs are assumed to be affected by the inflation, which is assumed to be 2 % for all periods:

$$C_{\mathrm{t}} = C_0 \left(1 + i_{\mathrm{inf}}\right)^{t-1} \tag{6}$$

where C_t is the cost at period t, i_{inf} is the inflation rate and C_0 is the cost at the end of the first year.

6. DEFINITION OF BENCHMARKS

As mentioned above, a comparison will also be made among a traditional system (Case 1), the innovative system proposed here but coupled with a traditional car (Case 2), and the innovative system coupled with an electric car (Case 3). Note that we considered the traditional system defined as a natural gas boiler for thermal energy demand and the distributor grid for electrical demand. In the traditional system, a traditional car is also used. Both thermodynamic and economic points of view will be discussed (see section 7). For this reason, definitions of both thermodynamic and economic benchmarks are useful.

For thermodynamic benchmarks, the total primary energy consumption (*PE*) of each system will be evaluated first. For the traditional system, the primary energy $PE_{trad.sys}$ is estimated as:

$$PE_{trad.sys} = \frac{H_{Demand}}{\eta_{boiler}} + \frac{E_{Demand}}{\eta_{el}} + F_{car} \tag{7}$$

where H_{demand} is the user heat demand and η_{boiler} is the efficiency of a traditional natural gas fired boiler used in the traditional system to cover heating and DHW demands (its efficiency is assumed to be 0.9). E_{demand} is the user electricity demand, and η_{el} is the efficiency of electric energy supply from the grid (considering generation with both a traditional power plant and grid efficiency, which is fixed at 43.9 %). F_{car} is the fuel consumption of a traditional car (a lower heating value of 9.7 kWh/l was considered).

The primary energy consumption for the innovative system considering a traditional car ($PE_{inno.sys,trad.car}$) was calculated as:

$$PE_{inno.sys,trad.car} = F_{SOFC} + \frac{E_{Grid}}{\eta_{el}} + F_{car} \tag{8}$$

where F_{SOFC} is the natural gas consumption of the SOFC, E_{Grid} is the electricity net consumption from the grid and F_{car} is the fuel consumption of the traditional car.

The primary energy consumption for the innovative system with an electric car ($PE_{inno.sys,ele.car}$) is calculated as:

$$PE_{inno.sys,ele.car} = F_{SOFC} + \frac{E_{Grid}}{\eta_{el}} \tag{9}$$

Here, a second benchmark related to the energy analysis is *%PES* (percentage of primary energy savings), which compares the energy demands of the traditional system and the other two systems. This parameter is defined as:

$$\%PES = 1 - \frac{PE_{inno.,sys.}}{PE_{trad.,sys.}} \tag{10}$$

Finally, the energy flux distribution for the innovative system proposed in this study (Case 3) is analyzed. Concerning the economic analysis, the EAC (equivalent annual cost) criterion is used as the benchmark. It is defined by both the net present value (NPV) and the annuity factor ($A_{t,i}$):

$$EAC = \frac{NPV}{A_{t,i}} \tag{11}$$

NPV depends on investment costs (purchase costs of all components), annual energy consumption costs (natural gas, electricity and fuel, considering increasing indexes) and annual maintenance costs (considering inflation rate). The annuity factor ($A_{t,i}$) is defined so that the expected lifetime of the system is 20 years and the interest rate is fixed at 3 %. The inflation rate is considered to be 2 %. A sensitivity analysis of purchase costs of the components and the energy increasing indexes is useful in order to show their weight on EAC. The analysis is performed by varying purchasing costs between -50 % and +100 % and the energy increasing index between 0 % and +12 %.

7. RESULTS AND DISCUSSION

7.1 Energy analysis

Figure 8 depicts energy consumption for the different systems. The traditional system with a traditional car (Case 1) consumes more than 29600 kWh of primary energy based on the previous cited efficiencies for thermal and electrical energy. Using the innovative system, the primary energy consumption decreases to 18739 kWh (Case 2). The use of the electric vehicle (Case 3) allows for further reduction in *PE* consumption to 15322 kWh. The primary energy savings of the innovative system including the car is approximately 37 % for Case 2 and close to 48 % for Case 3 with respect to the traditional system. A remarkable energy savings is thus achieved with the innovative system proposed here (including the electric car) thanks to the SOFC system and the operation strategies.

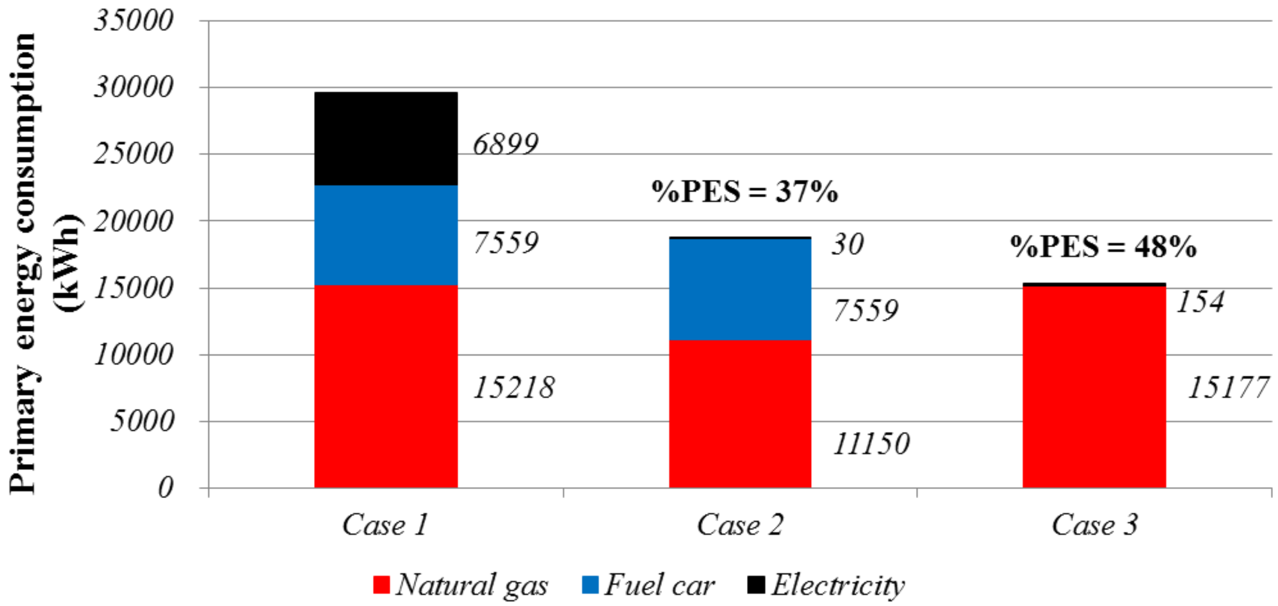

Figure 8 – Primary energy consumption divided by sources for each case and Primary Energy Savings (*%PES*) of innovative systems vs. the traditional one (Case 1 – traditional system with traditional car; Case 2 – innovative system with traditional car; Case 3 – innovative system with electric car)

Figure 9 shows the energy balance for the innovative system (Case 3). SOFC has to cover both the electrical demand from the user and the electricity required for charging the car and operating the heat pump. The electricity exchanged with the grid is very low: 177 kWh is imported from the grid when total electricity demand is higher than SOFC production; and 109 kWh is delivered to the grid when SOFC production is higher than the electrical demand. This is the consequence of the proposed operation strategies, which are as follows:

- The ELF strategy optimizes heat production by considering the heat available from the SOFC in order to decrease GSHP electricity consumption.
- The CEV strategy optimizes charging of the EV because when the user electricity demand is low, then it is not necessary to consume electricity from the grid. Then, the SOFC nominal power is suitable to meet the charging energy demand. Thanks to the higher electricity

production from the SOFC, more waste heat from the SOFC is available to cover both space heating and DHW demands (approximately 50 % of the total heat demand).

– The PS strategy decreases the peak heat demand, thus lowering the required nominal power for the GSHP (7 kW instead of 8 kW, as discussed in [25], which is 12.5 % lower). The consequence is that the heat pump operates at a higher mean partial load ratio – with a higher COP and a lower purchase cost.

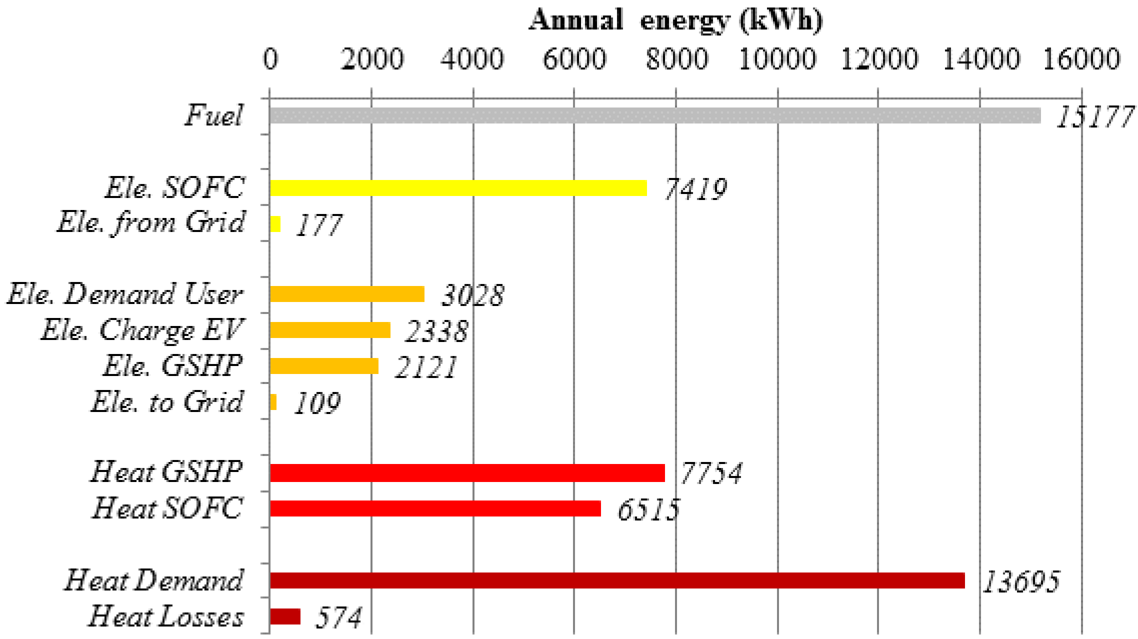

Figure 9 – Energy balance of the system (Case 3)

Another advantage of EV charging during the nighttime is that the SOFC works more continuously, thus avoiding frequent shutdown and startup of the stacks and consequent thermal stresses. If there is a variation in SOFC system utilization between daytime and nighttime, failure and/or breakdowns may occur. Figure 10 shows that when EV charging is required (at night), system utilization is more persistent. During the daytime, system utilization is approximately 60 %, while during the night hours, it falls under 20 % if no EV charging is made. It is above 60 % if EV charging is considered.

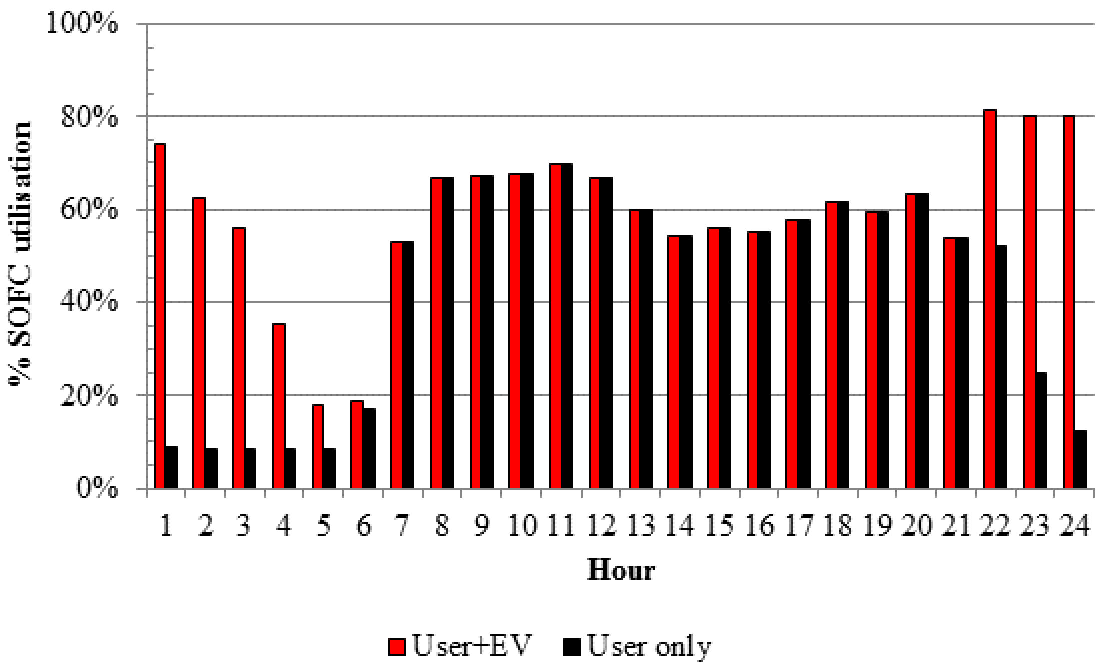

Figure 10 – Utilization factor of SOFC for user demand only (User only) and for user demand and EV charging request (User+EV)

7.2 Economic analysis

The equivalent annual cost of the system proposed here (Case 3, with the assumptions taken above) is calculated to be 5739 €, which is 6.7 % lower than the traditional system with a traditional car (Case 1). In fact, according to [25], the EAC of the traditional system is 6151 €, considering also purchase cost of the car and annual fuel consumption. The EAC demonstrates that the innovative system with the electric car is cheaper than the traditional system (including car) even though subsidies are not considered. Sensitivity analyses are performed to study different scenarios and therefore make the analysis more comprehensive.

Figure 11 shows how the EAC changes when varying purchase costs of the SOFC, the GSHP and the electric car. The electric car has the highest weight on profitability; thus, its purchase variation cost corresponds to a higher variation for the system EAC. The results show that even if the total investment cost of all the components (fuel cell, heat pump and electric car) are increased by 20 %, then the system is still profitable. The maximum increase in purchase cost of the heat pump is approximately 50 %, and still, the proposed system has an economic advantage. Another interesting result is that the SOFC has the lowest sensitivity, and thus, its cost may be increased by 100 % (doubled). Still, the EAC would be lower than 6000 €.

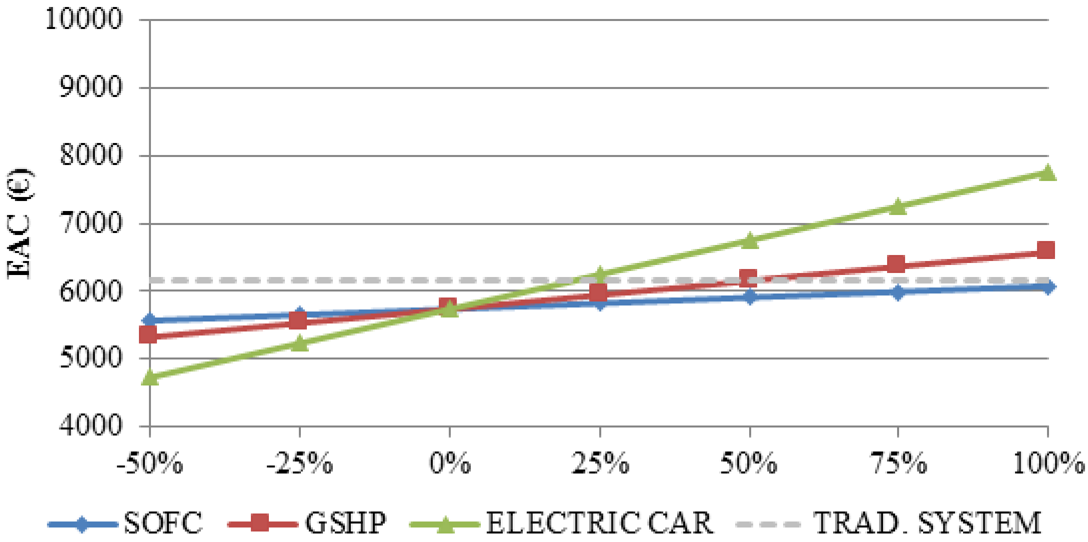

Figure 11 – Sensitivity analysis on purchase costs of SOFC, GSHP and electric car. For comparison, the equivalent annual cost of the traditional system is also included.

Figure 12 shows how the EAC changes with the natural gas cost rate. When the difference between the two curves (innovative system vs. traditional system) is negative, then there will be a cost savings. Natural gas consumption is similar for the traditional system (Case 1) and the innovative system (Case 3) – 15218 kWh and 15177 kWh, respectively (see Figure 8). This means that the profitability of the latter is not affected by the natural gas increasing cost rate (the distance between the two curves in Figure 12 is constant).

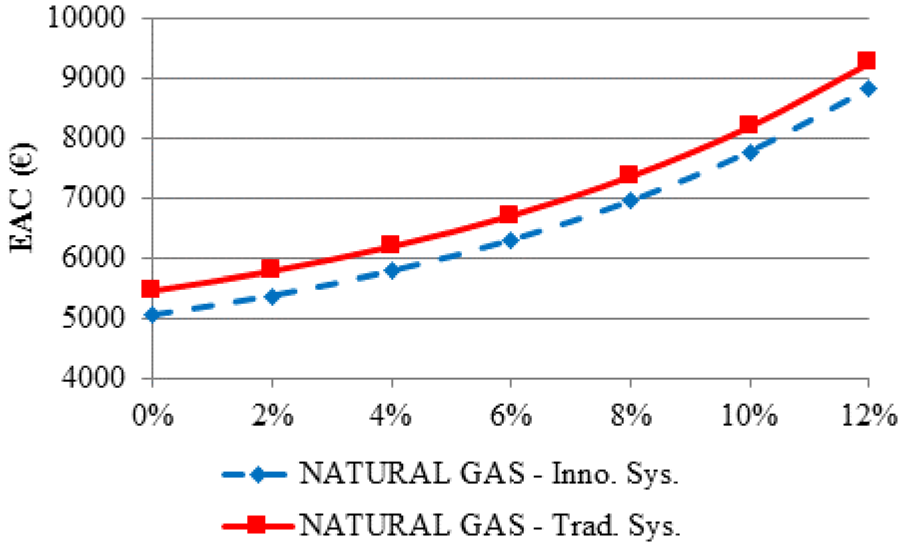

Figure 12 – Sensitivity analysis on natural gas cost.

Figure 13 shows the weight of the electricity increasing price rate on EAC. The higher the increasing rate, the higher the profitability of the innovative system. As displayed in Figure 9, the electricity consumption from the grid is low (177 kWh), and therefore, increasing this rate does not affect the EAC of the innovative system. The traditional system, instead, covers all the electrical demand by the energy taken from the grid, and therefore, its EAC increases with increasing electricity cost index.

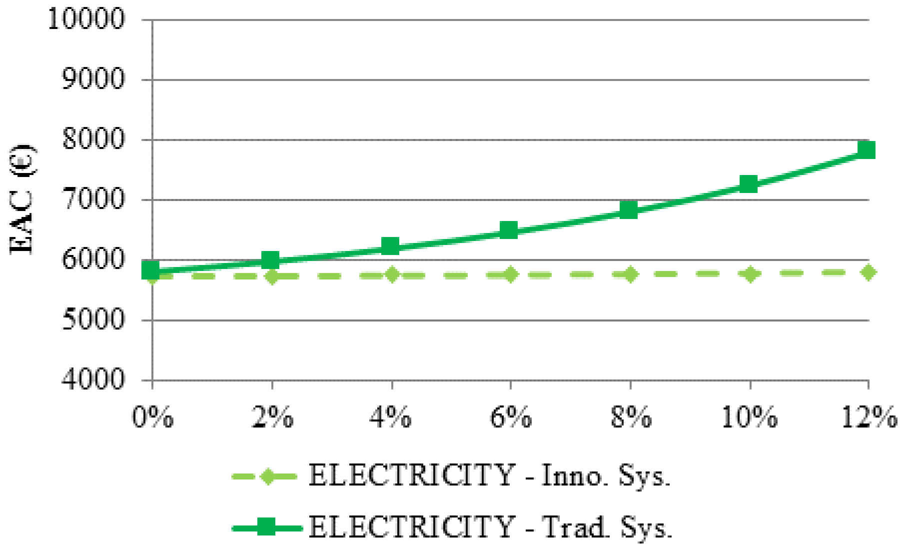

Figure 13 – Sensitivity analysis on electricity cost

Figure 14 shows the profitability of the system by increasing the fuel price rate for the car. The proposed system here has no fuel consumption due to the use of an electric car, and therefore, its increasing index only needs to be higher than 1.5 % to have profitability compared to the traditional system. Note that a 1.5 % increasing index is very low, and no subsidies/discounts (such as a fossil fuel tax and a CO_2 tax) are taken into account.

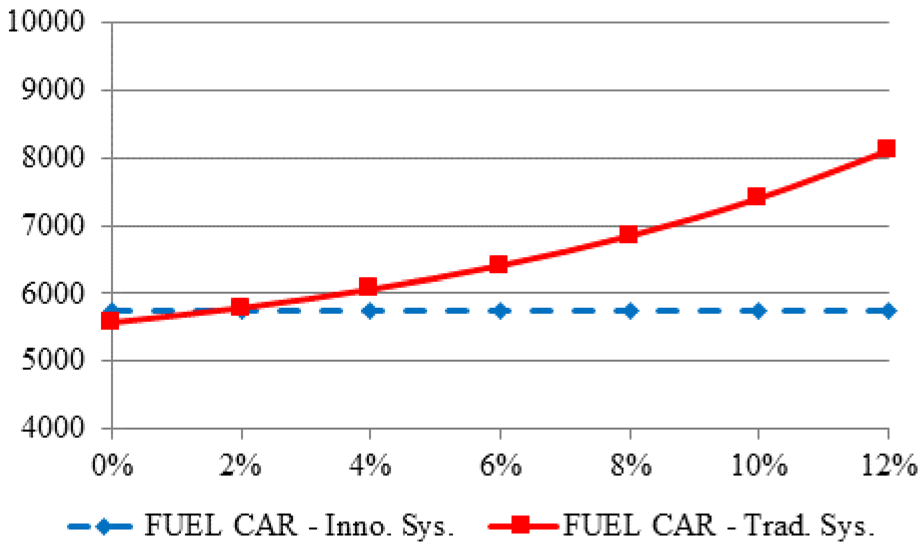

Figure 14 – Sensitivity analysis on fuel cost

8. CONCLUSIONS

In this study, an innovative cogeneration system coupled with an electric car is proposed and analyzed. The results proved a high efficiency for the proposed system and its economic viability. Innovative strategies are also analyzed with different aims, such as efficiently managing energy production to cover user demands, smartly handling electric car charging by minimizing electrical consumption from the grid, and elegantly using the heat available to shave heat demand during peak time.

The thermodynamic analysis demonstrated that primary energy savings are obtained not only with respect to a traditional system (natural gas boiler and electric grid) but also with respect to the proposed innovative system coupled to a traditional car. The advantages of considering the charging of the electric car at night are related to a constant utilization factor of the SOFC and to the lower peak heat demand.

An economic analysis is also developed under different economic scenarios, such as various investment and energy costs. Results showed that an electric car coupled with the system proposed here is an economically valuable alternative, even if subsidies are not considered. The sensitivity analysis showed that the higher weight on profitability of the system is due to the purchase cost of the electric car and to the increasing price index of fuel for the traditional car.

REFERENCES

[1] DTU Energy Report 2012: Energy efficiency improvements Technical University of Denmark Energy ISBN 978-87-550-3965-0

[2] Faria R. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renewable and Sustainable Energy Reviews 2013;24:271–287

[3] Amirioun M. H. A new model based on optimal scheduling of combined energy exchange modes for aggregation of electric vehicles in a residential complex. Energy 2014;69;186-198

[4] Metz M., Electric vehicles as flexible loads – A simulation approach using empirical mobility data. Energy 2012;48;369-374

[5] Samweber F. Electric Mobility as a Functional Energy Storage in Comparison to On-Site Storage Systems for Grid Integration Energy Procedia 2015;73;94-102

[6] Koizumi T. Biofuels and food security Food and Agricultural Organization of the United Nations (FAO). Renewable and Sustainable Energy Reviews 2015;52:829–841

[7] Rokni M. Thermodynamic analysis of SOFC (solid oxide fuel cell) - Stirling hybrid plants using alternative fuels. Energy 2013;61:87–97

[8] Cooper SJG, Hammond GP, McManus MC, Ramallo-Gonzlez A, Rogers JG. Effect of operating conditions on performance of domestic heating systems with heat pumps and fuel cell micro-cogeneration. Energy Build 2014;70:52–60.

[9] Bompard E, Napoli R, Wan B, Orsello G. Economics evaluation of a 5kW SOFC power system for residential use. Hydrogen Energy 2008;33:3243–7.

[10] Farhad S, Hamdullahpur F, Yoo Y. Performance evaluation of different configurations of biogas-fuelled SOFC micro-CHP systems for residential applications. Hydrogen Energy 2010;35:3758–68.

[11] Liso V, Brandon N, Zhao Y, Nielsen MP, Koer SK. Analysis of the impact of heat-to-power ratio for a SOFC-based mCHP system for residential application under different climate regions in Europe. Hydrogen Energy 2011;36:13715–26.

[12] Lamas J, Shimizu H, Matsumura E, Senda J. Fuel consumption analysis of a residential cogeneration system using a solid oxide fuel cell with regulation of heat to power ratio. Hydrogen Energy 2013;38:16338–43.

[13] Kuhn V, Klemes J, Bulatov I. MicroCHP: overview of selected technologies, products and field test results. Appl Therm Eng 2008;28(18):2039–48.
[14] Maghanki M, Ghobadian B, Najafi G, Galogah JR. Micro combined heat and power (MCHP) technologies and application. Renew Sustain Energy Rev 2013;28:510–24.
[15] Busato F, Lazzarin R, Noro M. Experimental analysis of photovoltaic cogeneration modules. Int J Low Carbon Technol 2008;3(4):221–44.
[16] Vialetto G, Noro M, Rokni M. Innovative household systems based on solid oxide fuel cells for the Mediterranean climate. International Journal of Hydrogen Energy 2015;40(41):14378-14391.
[17] Angrisani G, Canelli M, Roselli C, Sasso M. Integration between electric vehicle charging and micro-cogeneration system. Energy Conversion and Management 2015;98:115-126.
[18] Rosato A, Sibilio S, Scorpio M. Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part I: Energy analysis. Energy Conversion and Management 2014;79:731-748.
[19] Rosato A, Sibilio S, Scorpio M. Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part II: Environmental and economic analyses. Energy Conversion and Management 2014;79:749-770.
[20] Ribberink H, Entchev E. Exploring the potential synergy between micro-cogeneration and electric vehicle charging. Applied Thermal Engineering 2014;71:677-685.
[21] Wakui T, Wada N, Yokoyama R. Energy-saving effect of a residential polymer electrolyte fuel cell cogeneration system combined with a plug-in hybrid electric vehicle. Energy Conversion and Management 2014;77:40-51.
[22] Wakui T, Wada N, Yokoyama R. Feasibility study on combined use of residential SOFC cogeneration system and plug-in hybrid electric vehicle from energy-saving viewpoint. Energy Conversion and Management 2012;60:170-179.
[23] Tanaka T, Kamiko H, Bando T, Zaffirah A, Kakimoto N, Inui Y, Maeda T. Energetic analysis of SOFC co-generation system integrated with EV charging station installed in multifamily apartment. International Journal of Hydrogen Energy 2014;39:5097-5104.
[24] Zhang Q, Tezuka T, Ishihara KN, Mclellan BC. Integration of PV power into future low-carbon smart electricity systems with EV and HP in Kansai Area, Japan. Renewable Energy 2012;44:99-108.
[25] Vialetto G, Rokni M. Innovative household systems based on solid oxide fuel cells for a northern European climate. Renewable Energy 2015;78:146-156.
[26] EN 14825. Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - testing and rating at part load conditions and calculation of seasonal performance. European Committee for Standardisation; 2008.
[27] Busato F, Lazzarin R, Noro M. Energy and economic analysis of different heat pump systems for space heating. Low-Carbon Technol 2012;7:104–12.
[28] Standardv rider for traffic data til OSPM modellen, Tetraplan A/S, 2001.
[29] Weekly Oil Bulletin, European Commission (http://ec.europa.eu/energy/en/statistics/weekly-oil-bulletin), Accessed 18/04/2015, Last update 13/04/2015.
[30] Wu Q, Nielsen A H, Østergaard J, Cha, ST, Marra F, Andersen PB. Modeling of Electric Vehicles (EVs) for EV Grid Integration Study, 2 European Conference Smart Grids & E-Mobility, 2010.

[31] Prud'homme R, Koning M. Electric vehicles: A tentative economic and environmental evaluation. Transport Policy 2012;23:60–69

[32] Kavvadias KC, Tosios AP, Maroulis ZB. Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis. Energy Conversion and Management 2010; 51(4):833–845.

[33] Hawkes AD, Aguiar P, Hernandez-Aramburo CA, Leach MA, Brandon NP, Green TC, Adjiman CS. Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power. Power Sources 2006;156(2):321–333.

[34] Dickinson J, Jackson T, Matthews M, Cripps A. The economic and environmental optimisation of integrating ground source energy system into building. Energy 2009;34(12): 2215–22.