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

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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

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44 [1]. The disadvantages are the high cost, the low efficiency of the refinery/production process and
45 the use of food to produce fuels (for example, corn-based methanol); the last point could be morally
46 unacceptable [6].

47 Meanwhile, energy systems are moving to distributed generation, improving electrical
48 transmission efficiency and infrastructure [1]. One solution for household applications is micro-
49 cogeneration, which allows a better match between energy demand and production as well as lower
50 transmission losses with respect to a traditional electrical system. Different cogeneration systems
51 have been proposed, analyzed and studied, such as internal combustions engines, Stirling engines
52 [7], fuel cells [7]-[13], micro-Rankine and micro-gas turbines [14], and photovoltaic cogeneration
53 modules [14] [15]. In some cases, systems set up with a cogenerator and an integrated heating
54 system have been proposed in order to face both electrical and heat demand in a more effective way
55 [16].

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

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

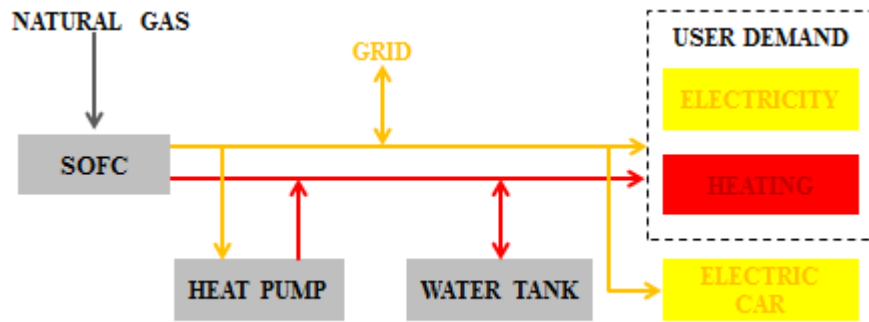
70

71 **2. OVERVIEW OF THE SYSTEM**

72 **2.1 Equipment and design strategy**

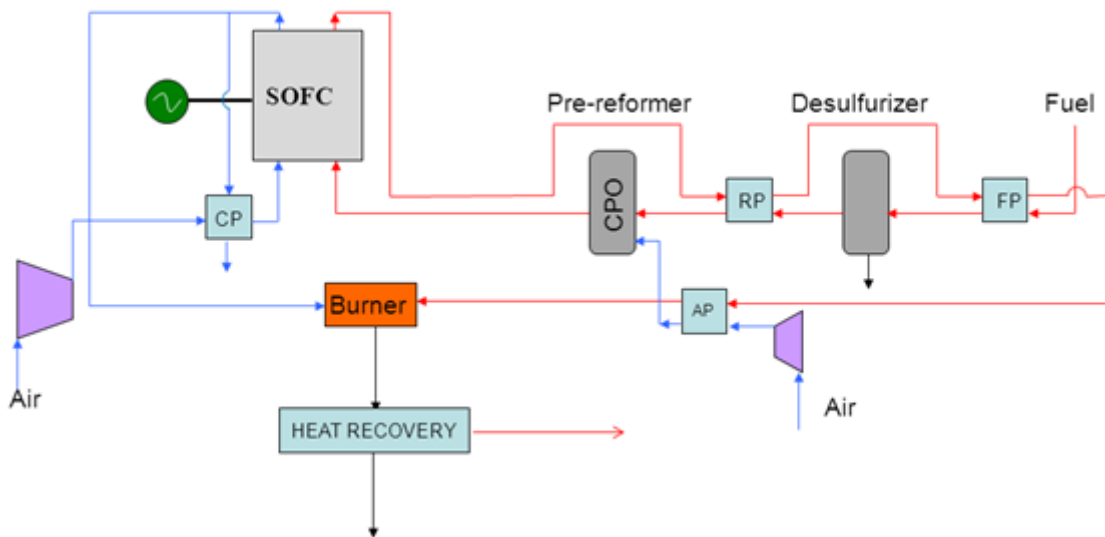
73 The innovative system considered here is based on a previous study by the authors [25]. As
74 proposed, it will satisfy energy demands in terms of electricity, space heating and domestic hot
75 water (DHW) for a residential building located in Denmark. The system is represented in Figure 1,
76 which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

85



86
87 Figure 1 – Representation of system energy fluxes (yellow represents electricity, and red represents
88 heat).
89

90 The main part of the system is the SOFC micro-cogenerator that provides electricity, while its
91 waste heat is used to meet part of the heat demand for the building. Figure 2 shows the main
92 components of the SOFC system, which includes all necessary components, such as an air
93 compressor (to supply air at the correct pressure and to cool the stacks), an inverter (which is used
94 to convert current from direct to alternate current – DC to AC), a catalytic partial fuel reformer (to
95 crack the heavy hydrocarbons), a desulfurizer (to remove sulfur and thus avoid sulfur poisoning for
96 the cells) and a catalytic burner (to burn the unreacted fuels that remain). In this study, a 2 kW
97 nominal electric power SOFC is adopted for covering the electrical demand, while the heat
98 produced by the fuel cell is used to cover space heating and domestic hot water demands as much as
99 possible, thus maximizing the overall system efficiency.
100



101
102 Figure 2 - Schematic of the SOFC system: CP = cathode pre-heater, FP = fuel pre-heater, AP = air
103 pre-heater, RP = reformer pre-heater, and CPO = catalytic partial oxidation [25].
104

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

110 analyzed to cover peak heat demands with the aim of decreasing the nominal power of the heat
111 pump and its purchase cost.

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

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

125

126

Table 1 – Main data and characteristics of the system.

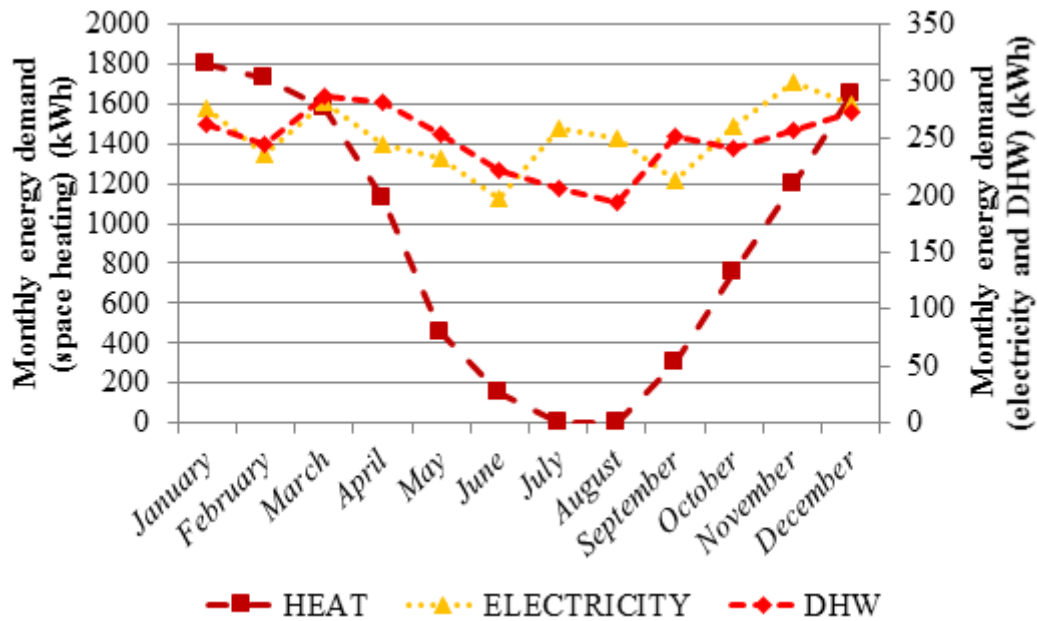
PARAMETERS OF THE SYSTEM	
SOFC – Nominal power	2 kW
SOFC – H/P at full load	0.826
SOFC – Electrical efficiency at full load	0.53
GSHP – Nominal power	7 kW
GSHP – COP at full load at W10/W35	5.1
Water tank – Capacity	140 L

127

128 **2.2 User energy demands**

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

135



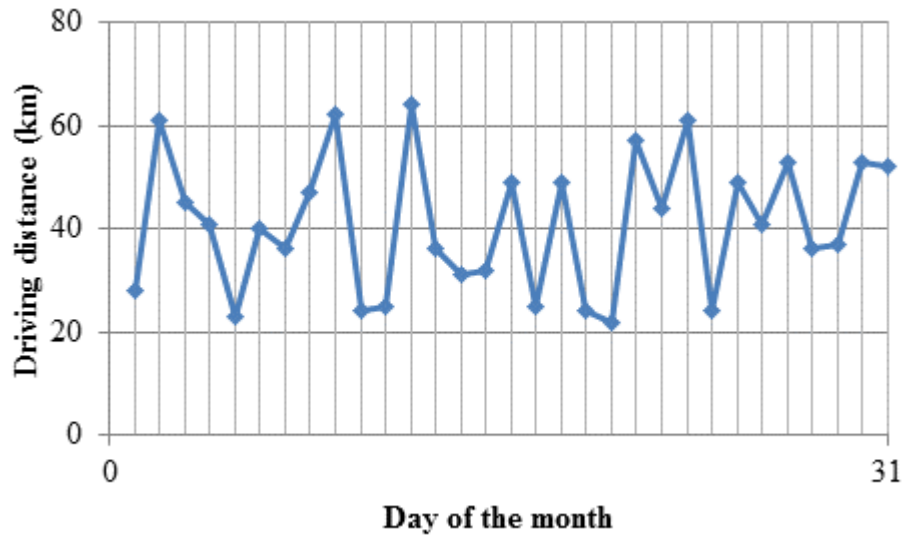
136
 137 Figure 3 - Electrical, DHW (right scale) and heat (left scale) monthly energy demands for the
 138 residential building located in Copenhagen, Denmark [25].
 139

140 **3. MOBILITY MODEL**

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

151
 152 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



154
155 Figure 4 – Daily driving distance for a month for the reference year (January).
156

157 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]		

158
159 The fuel cost increasing index is fixed at 4.56 %, and it is defined as the average annual
160 increasing index of diesel fuel from 2005 to 2014 in Denmark. Since the fuel increasing cost is
161 based on historical data, a sensitivity analysis by varying this index from 0 % to 12 % is useful to
162 examine its impact on the economic results. Even though reference [31] suggests consideration of
163 other costs related to a traditional car (such as the costs of pollution and noise), in this study, it is
164 preferred that such additional costs shall not be considered because the uncertainty related to these
165 values could be high.

166
167 **4. OPERATION STRATEGIES**

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

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

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

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

179 **4.1 ELF strategy**

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

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

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

203
204

Table 4 – Definition of ELF.

Equation	Condition
$ELF = \frac{E_{USER}}{\eta_{trans}} \quad (1)$	This equation is used when SOFC waste heat is available and higher than the user heat request.
$ELF = \frac{1}{\eta_{trans}} * \frac{E_{USER} + \frac{H_{USER}}{COP}}{1 + \frac{H/P}{COP * \eta_{trans}}} \quad (2)$	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).

205

206 **4.2 CEV strategy**

207 The aim with the charge electric vehicle (CEV) strategy is to charge the car batteries using
 208 electricity produced by SOFC stacks only, thus avoiding consumption from the grid. Such a
 209 strategy maximizes the efficiency of the system. Electrical and heat demands at night are lower than
 210 those during the daytime. However, if the EV is charged at nominal power from the SOFC during
 211 the nighttime and if there is at the same time a request for electricity (and/or heat) from the
 212 building, then the surplus electricity could be supplied from the grid. It was proposed that the EV be
 213 charged in a way that considers both the nominal power of the SOFC ($SOFC_{nom,power}$), energy

214 consumption of the user (electrical [$E_{demand,user}$], heating [$H_{demand,user}$], and domestic hot water
 215 [$DHW_{demand,user}$]) and the electricity request for charging ($EC_{charge,demand}$). The charging process starts
 216 at 10pm and continues until the battery is fully charged. The duration of the charging process is
 217 related to the previous day's consumption and the EC_{charge} (electricity available for charging)
 218 parameter that varies hour-by-hour:

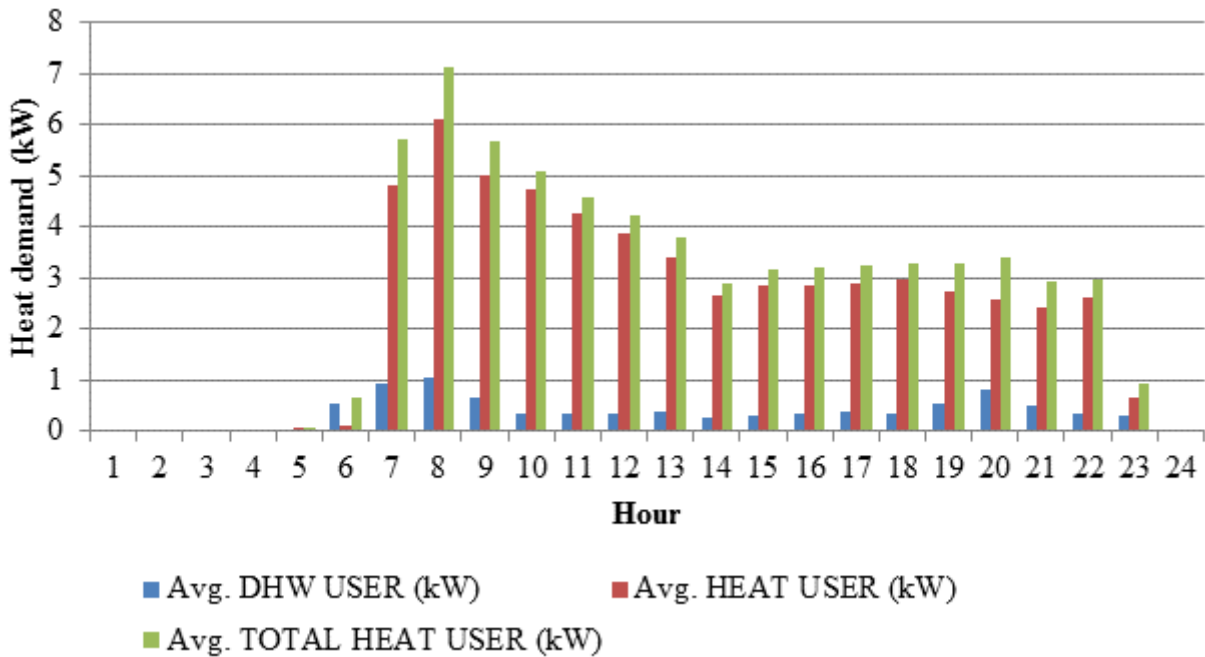
$$219 \quad EC_{charge} = \min \left(SOFC_{nom,power} - \left(E_{demand,user} + \frac{H_{demand,user} + DHW_{demand,user}}{COP_{avg.}} \right); EC_{charge,demand} \right) \quad (3)$$

220

221 4.3 PS strategy

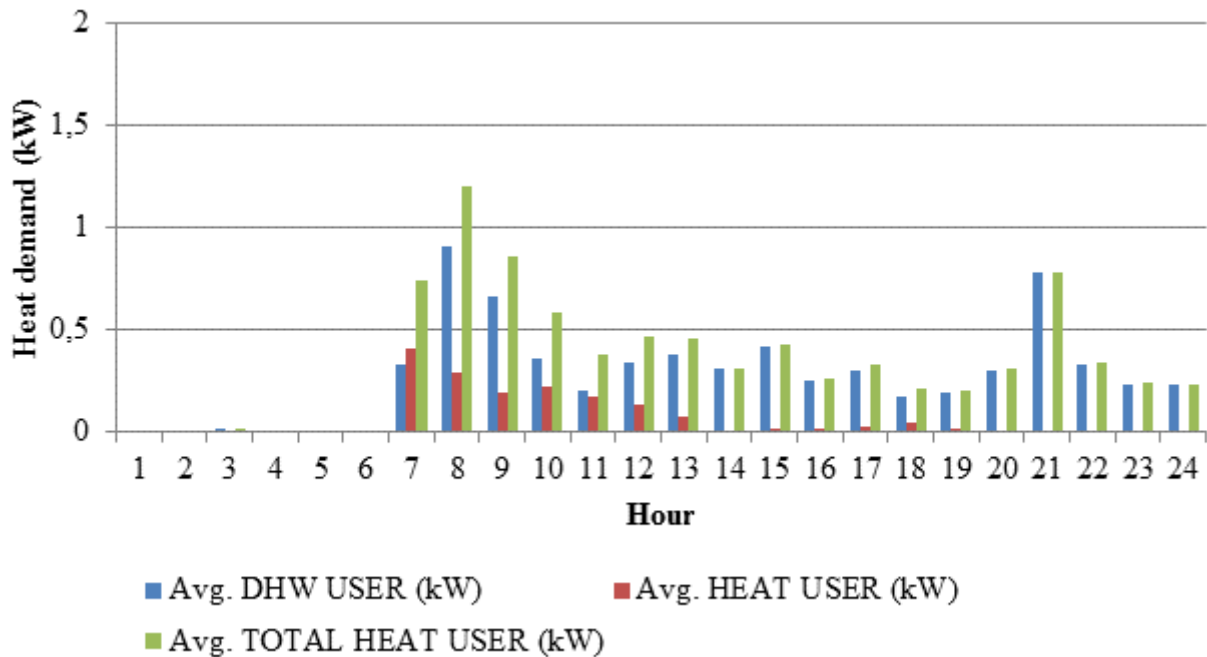
222 The peak shaving (PS) strategy is defined with the aim of smart utilization of waste heat from the
 223 SOFC at night when the electric car is charging, the electricity requested is mainly produced by the
 224 fuel cell (under CEV strategy) and the heat demand is low (both space heating and/or heat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

238



239

240 Figure 5 - Average heat demand (space heating and domestic hot water) for the winter months of
 241 December, January, and February.
 242

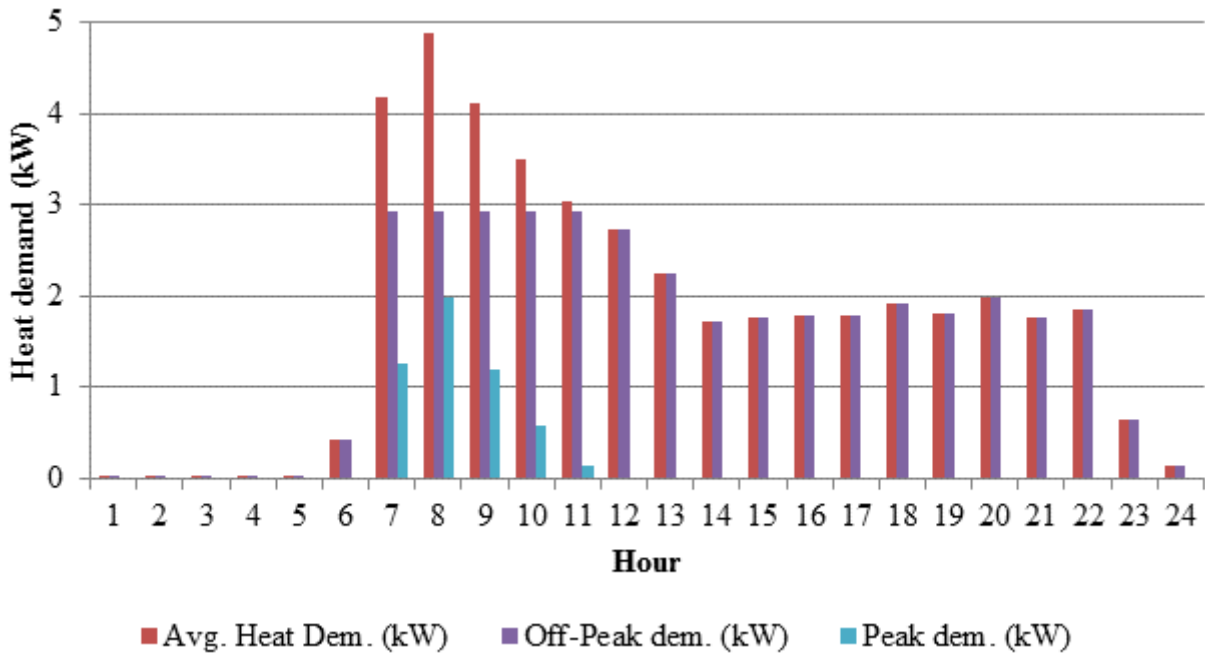


243
 244 Figure 6 – Average heat demand (space heating and domestic hot water) for the summer months of
 245 June, July, and August.
 246

247 The average amount of waste heat that is available after the vehicle charging process is estimated
 248 to be 5.1 kWh, which is calculated using an average daily distance of 42.7 km, a fuel efficiency of
 249 0.15 kWh/km and an H/P ratio equal to 0.8 for the SOFC. To simplify the peak shaving strategy, an
 250 annual average parameter is then created hourly. These values are then used to calculate the
 251 parameter P_{limit} (power limit). If the user heat demand is higher than this parameter (i.e., peak
 252 demand), then stored heat is used to cover the difference in order to shave the peak. This parameter
 253 is calculated by defining a system of 25 equations where 24 equations are related to the hourly user
 254 heat demand ($H^n_{demand,user}$) and one equation correlates the available heat ($H_{tot,available}$) and stored
 255 heat (H^n_{stored}) quantities (see Eq. 4). The parameter $t_{sampling}$ (sampling time) is introduced because
 256 $H^n_{demand,user}$ is the demand power and $H_{tot,available}$ is the available energy. In a case for which the
 257 power is expressed in kW and the energy is expressed in kWh, the value of the $t_{sampling}$ parameter is
 258 1 hour. The system of equations composed here is in non-linear form, and therefore, it was solved
 259 using the Newton-Raphson method from which the result is found to be $P_{limit}=2.92$ kW. If the heat
 260 demand is higher than P_{limit} , the heat stored during car charging is used to decrease the heat demand
 261 required for the SOFC and/or the GSHP (heat demand peak shaving).

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

263 Figure 7 depicts the effect of the strategy in which *Avg. Heat Dem.* is the annual average demand
264 of heat, *Peak dem.* is the peak demand covered by the stored heat during electric car charging, and
265 *Off-Peak dem.* is the heat demand covered by SOFC and/or GSHP. The graph shows that the PS
266 strategy successfully covers the heat demand between 7am and 11am, the time period when there is
267 a peak heat demand.
268



269
270 Figure 7 – Peak shaving of an average day.

271
272 The parameter P_{limit} is defined using a daily average concept. The daily driving distance (when
273 heat is available from the electric car charging) and heat demand change day by day, and therefore,
274 it would be necessary to solve Eq. (4) for each day of the year. Thus, an alternative method is
275 proposed in which P_{limit} is used as a parameter of peak limit for each day of the year. The results
276 illustrated in Figure 7 are also used to define another parameter, $\%Heat_{available}$, for each hour of the
277 peak demand (7am-11am). This parameter is the percentage of available heat from EV charging
278 used to cover peak demand (see Table 5). For each peak hour of each day of the year, the available
279 heat is calculated from the multiplication of this parameter by the heat available from the EV
280 charging of the previous night. Should the heat be available after 11am (for example, due to a lower

281 user heat request), then it would cover heat demand of the other hours of the day. The aim of this
 282 parameter is to use efficiently the waste heat available in order to decrease peak demand without
 283 using Eq. 4. It will also be possible to achieve peak shaving of the heat demand, as displayed in
 284 Figure 7.

285
 286

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

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

287

288 5. ECONOMIC MODEL

288

289 5.1 Equipment investment costs

289

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

294

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

312 The purchase cost of the electrical car (EV) and the traditional car is estimated using the data
 313 proposed in references [31] and [32]. For the sake of clarification, the results are reported in Table
 314 6.

315

316

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 €

317

318 5.2 Energy costs

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

325

326

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 %

327

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

$$329 C_t = C_0(1 + i_c)^{t-1} \quad (5)$$

330 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
 331 of the first year. Note that $t-1$ is used instead of t because the cost of the first year is given and also
 332 assumed to be constant until the following year.

333

334 5.3 Maintenance costs

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

$$339 C_t = C_0(1 + i_{inf})^{t-1} \quad (6)$$

340 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.

341

342 6. DEFINITION OF BENCHMARKS

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

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

$$352 \quad PE_{trad.sys} = \frac{H_{Demand}}{\eta_{boiler}} + \frac{E_{Demand}}{\eta_{el}} + F_{car} \quad (7)$$

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

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

$$361 \quad PE_{inno.sys,trad.car} = F_{SOFC} + \frac{E_{Grid}}{\eta_{el}} + F_{car} \quad (8)$$

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

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

$$366 \quad PE_{inno.sys,ele.car} = F_{SOFC} + \frac{E_{Grid}}{\eta_{el}} \quad (9)$$

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

$$370 \quad \%PES = 1 - \frac{PE_{inno.,sys.}}{PE_{trad.,sys.}} \quad (10)$$

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

$$374 \quad EAC = \frac{NPV}{A_{t,i}} \quad (11)$$

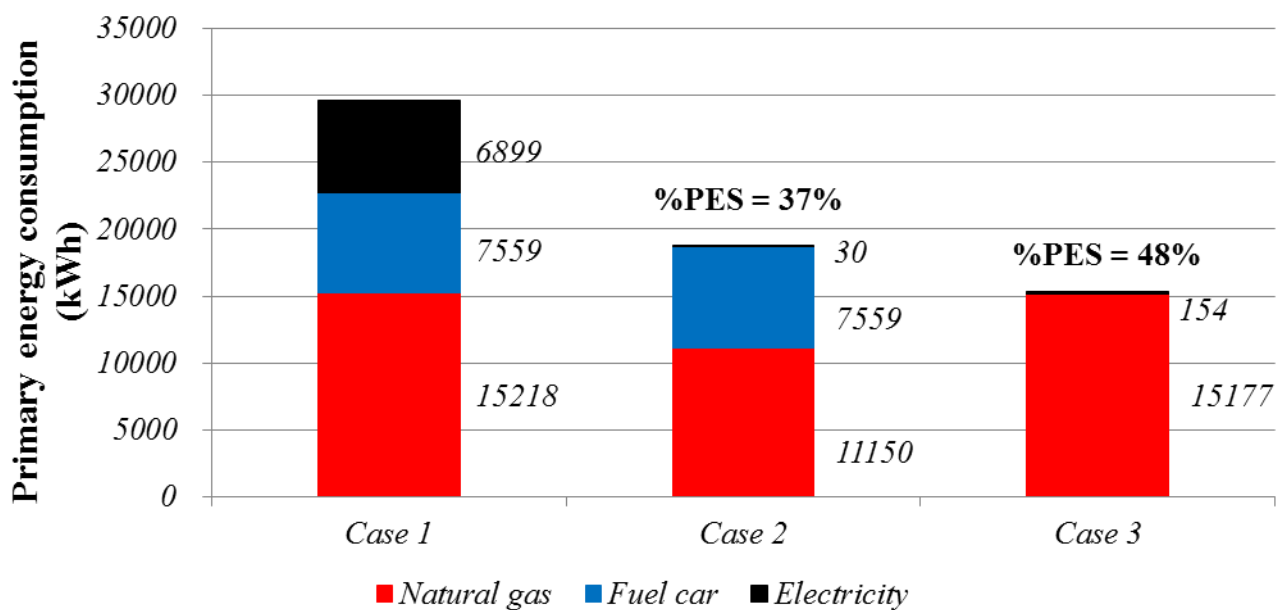
375 NPV depends on investment costs (purchase costs of all components), annual energy
 376 consumption costs (natural gas, electricity and fuel, considering increasing indexes) and annual
 377 maintenance costs (considering inflation rate). The annuity factor ($A_{t,i}$) is defined so that the
 378 expected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

383

384 **7. RESULTS AND DISCUSSION**

385 **7.1 Energy analysis**

386 Figure 8 depicts energy consumption for the different systems. The traditional system with a
 387 traditional car (Case 1) consumes more than 29600 kWh of primary energy based on the previous
 388 cited efficiencies for thermal and electrical energy. Using the innovative system, the primary energy
 389 consumption decreases to 18739 kWh (Case 2). The use of the electric vehicle (Case 3) allows for
 390 further reduction in *PE* consumption to 15322 kWh. The primary energy savings of the innovative
 391 system including the car is approximately 37 % for Case 2 and close to 48 % for Case 3 with
 392 respect to the traditional system. A remarkable energy savings is thus achieved with the innovative
 393 system proposed here (including the electric car) thanks to the SOFC system and the operation
 394 strategies.
 395

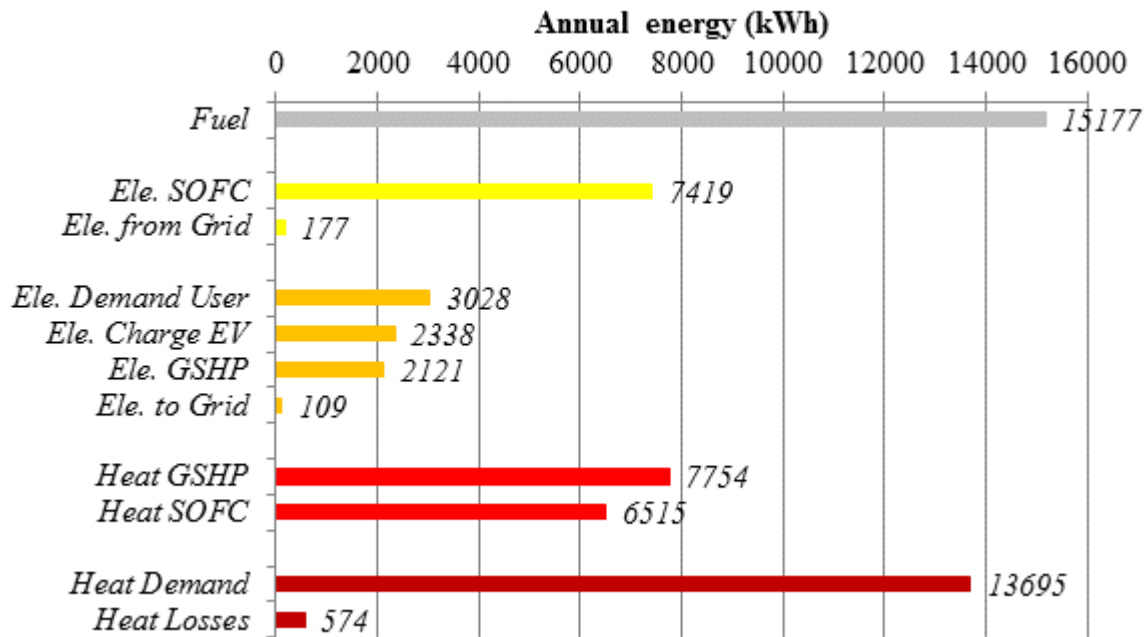


396 Figure 8 – Primary energy consumption divided by sources for each case and Primary Energy
 397 Savings (%*PES*) of innovative systems vs. the traditional one (Case 1 – traditional system with
 398 traditional car; Case 2 – innovative system with traditional car; Case 3 – innovative system with
 399 electric car)
 400
 401

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

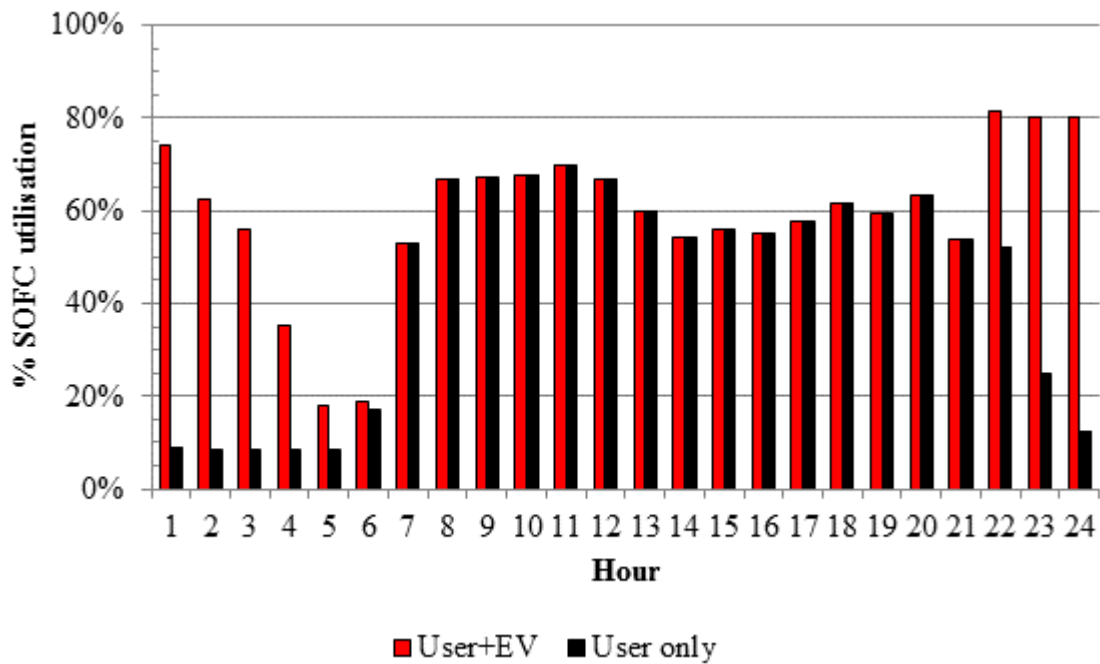
- 408 – The ELF strategy optimizes heat production by considering the heat available from the
 409 SOFC in order to decrease GSHP electricity consumption.
- 410 – The CEV strategy optimizes charging of the EV because when the user electricity demand is
 411 low, then it is not necessary to consume electricity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

413 production from the SOFC, more waste heat from the SOFC is available to cover both space
 414 heating and DHW demands (approximately 50 % of the total heat demand).
 415 – The PS strategy decreases the peak heat demand, thus lowering the required nominal power
 416 for the GSHP (7 kW instead of 8 kW, as discussed in [25], which is 12.5 % lower). The
 417 consequence is that the heat pump operates at a higher mean partial load ratio – with a
 418 higher COP and a lower purchase cost.
 419



420
 421 Figure 9 – Energy balance of the system (Case 3)
 422

423 Another advantage of EV charging during the nighttime is that the SOFC works more
 424 continuously, thus avoiding frequent shutdown and startup of the stacks and consequent thermal
 425 stresses. If there is a variation in SOFC system utilization between daytime and nighttime, failure
 426 and/or breakdowns may occur. Figure 10 shows that when EV charging is required (at night),
 427 system utilization is more persistent. During the daytime, system utilization is approximately 60 %,
 428 while during the night hours, it falls under 20 % if no EV charging is made. It is above 60 % if EV
 429 charging is considered.
 430



431

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

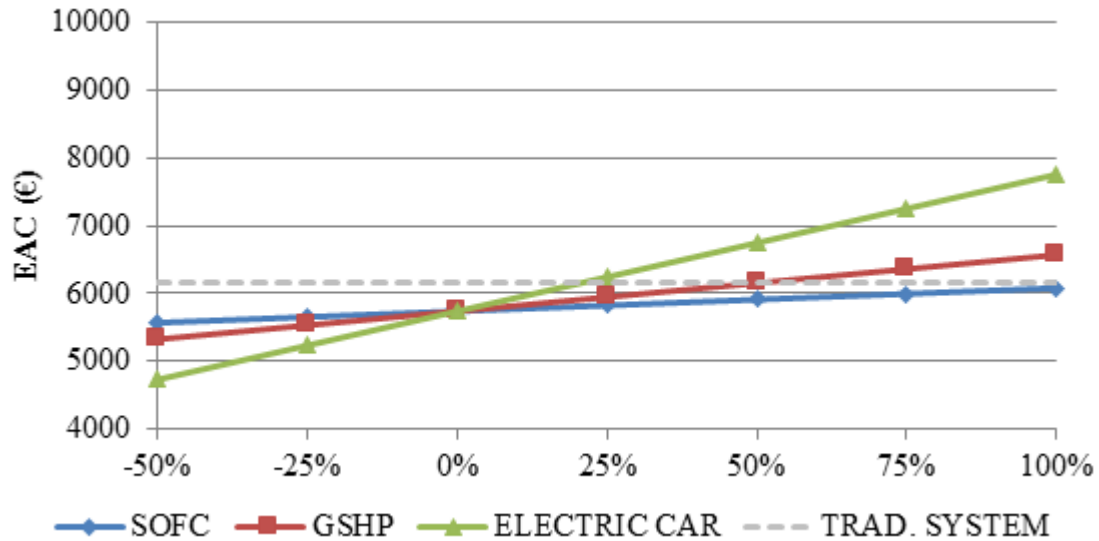
434

435 **7.2 Economic analysis**

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

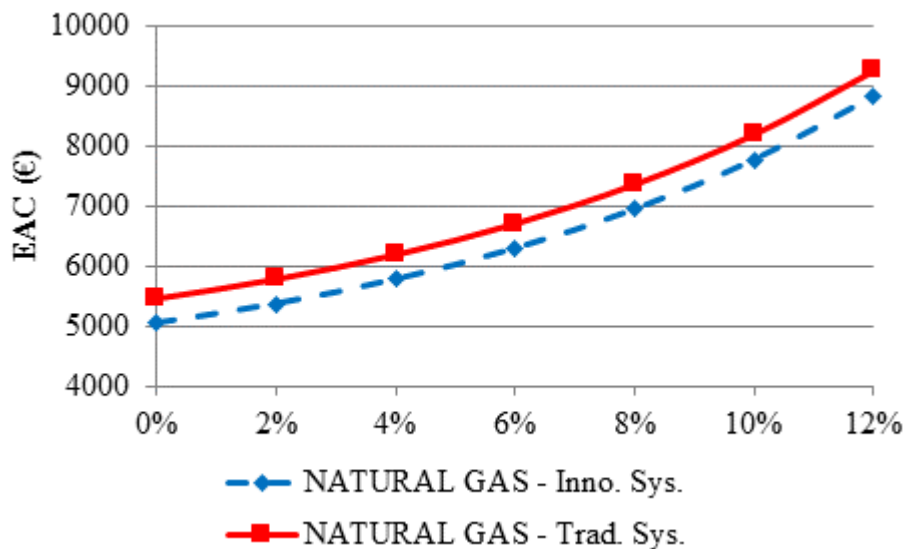
443 Figure 11 shows how the EAC changes when varying purchase costs of the SOFC, the GSHP
 444 and the electric car. The electric car has the highest weight on profitability; thus, its purchase
 445 variation cost corresponds to a higher variation for the system EAC. The results show that even if
 446 the total investment cost of all the components (fuel cell, heat pump and electric car) are increased
 447 by 20 %, then the system is still profitable. The maximum increase in purchase cost of the heat
 448 pump is approximately 50 %, and still, the proposed system has an economic advantage. Another
 449 interesting result is that the SOFC has the lowest sensitivity, and thus, its cost may be increased by
 450 100 % (doubled). Still, the EAC would be lower than 6000 €.

451



452
 453 Figure 11 – Sensitivity analysis on purchase costs of SOFC, GSHP and electric car. For
 454 comparison, the equivalent annual cost of the traditional system is also included.
 455

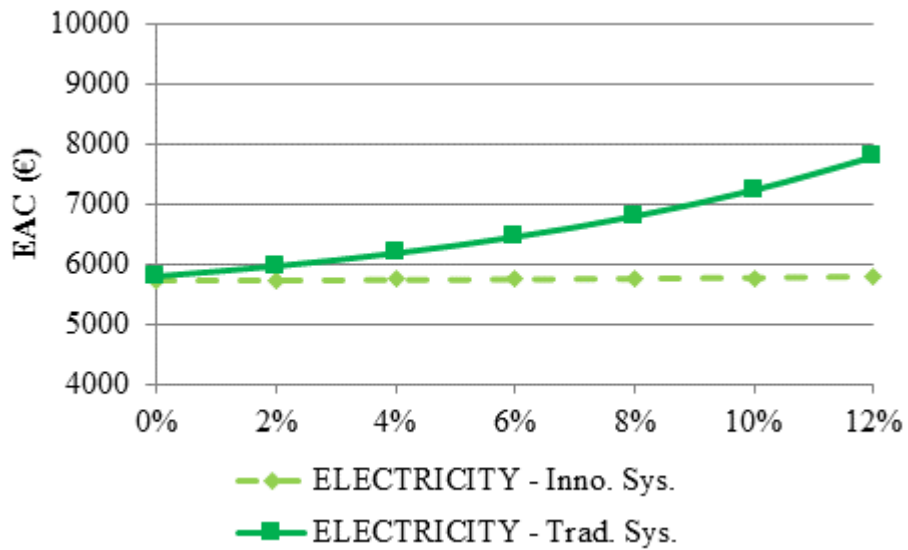
456 Figure 12 shows how the EAC changes with the natural gas cost rate. When the difference
 457 between the two curves (innovative system vs. traditional system) is negative, then there will be a
 458 cost savings. Natural gas consumption is similar for the traditional system (Case 1) and the
 459 innovative system (Case 3) – 15218 kWh and 15177 kWh, respectively (see Figure 8). This means
 460 that the profitability of the latter is not affected by the natural gas increasing cost rate (the distance
 461 between the two curves in Figure 12 is constant).
 462



463
 464 Figure 12 – Sensitivity analysis on natural gas cost.
 465

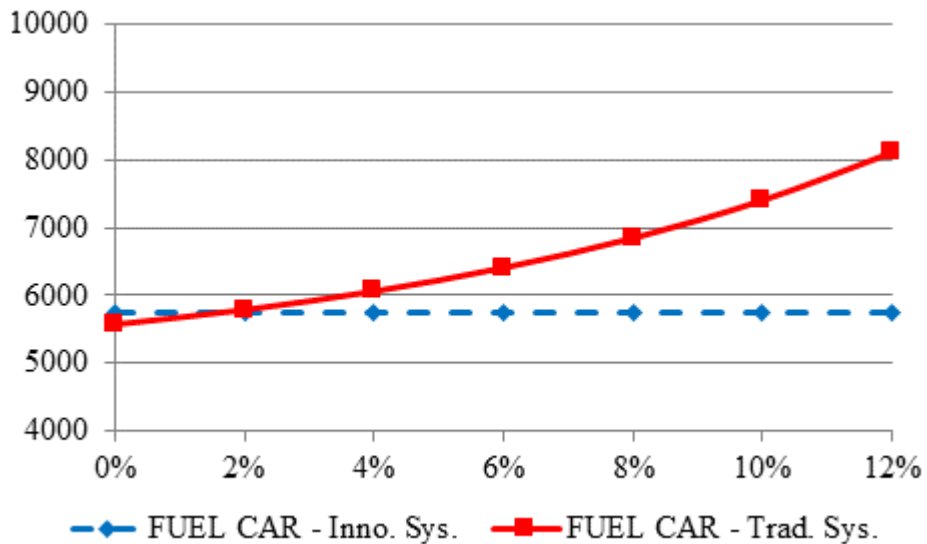
466 Figure 13 shows the weight of the electricity increasing price rate on EAC. The higher the
 467 increasing rate, the higher the profitability of the innovative system. As displayed in Figure 9, the
 468 electricity consumption from the grid is low (177 kWh), and therefore, increasing this rate does not
 469 affect the EAC of the innovative system. The traditional system, instead, covers all the electrical

470 demand by the energy taken from the grid, and therefore, its EAC increases with increasing
 471 electricity cost index.
 472



473
 474 Figure 13 – Sensitivity analysis on electricity cost
 475

476 Figure 14 shows the profitability of the system by increasing the fuel price rate for the car. The
 477 proposed system here has no fuel consumption due to the use of an electric car, and therefore, its
 478 increasing index only needs to be higher than 1.5 % to have profitability compared to the traditional
 479 system. Note that a 1.5 % increasing index is very low, and no subsidies/discounts (such as a fossil
 480 fuel tax and a CO₂ tax) are taken into account.
 481



482
 483 Figure 14 – Sensitivity analysis on fuel cost
 484

485 **8. CONCLUSIONS**

486 In this study, an innovative cogeneration system coupled with an electric car is proposed and
 487 analyzed. The results proved a high efficiency for the proposed system and its economic viability.
 488 Innovative strategies are also analyzed with different aims, such as efficiently managing energy

489 production to cover user demands, smartly handling electric car charging by minimizing electrical
490 consumption from the grid, and elegantly using the heat available to shave heat demand during peak
491 time.

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

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

502

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