Integration of the environomic energy services for mobility and household using electric vehicle with a range extender of solid oxide fuel cell

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Abstract. This article studies an innovative concept for vehicle propulsion, considered to deliver mobility services and integrated energy services for a household. An innovative converter – a Solid Oxide Fuel Cell with gas turbines system (SOFC-GT) is powering an electric vehicle. The vehicle architecture is as a serial range extender used to charge the high voltage battery. The range extender vehicle is optimized according to techno-economic and environmental criteria. It is researched to deliver optimal mobility and is integrated to the extended energy system, including the household needs. When the vehicle is unused is considered to be connected to the household and to deliver part of the energy services. In this configuration, the services of extended energy system are optimized. The environomic optimization concerns the extended energy system – vehicle and household and optimal designs for the integrated system are researched. The vehicle integrates energy services for mobility and household and becomes part of the large-scale energy grid for integrated services. The vehicle is sized for both uses. The major advantage of the energy integrated dual system is the reduction of the total global warming potential (GWP) impact with around 30000 kg CO₂ eq. (60%) – from 50590 kg CO₂ eq. to 20338 kg CO₂ in comparison to separate energy services for mobility and household needs.

1. Introduction
The biggest part of the state of the art studies on energy conversion systems for vehicles are concentrated on the on-board energy storage and conversion systems during the phase where the vehicle is used, when this vehicle is driven. The holistic methods might be used to optimize not only the design and the energy systems of the vehicles, but are also enablers to evaluate new energy services of the vehicles propulsion systems, when the vehicles are not used for driving. They are related to the different energy grids – electricity and gas. In this system the vehicles are considered to be related to the energy grids. Their design is as well optimized for the additional energy services and functions in the enlarged energy integrated system.

The environomic optimization method is used in this article to explore the optimal design for vehicles with innovative propulsion system, considering the mobility and also the integrated energy service to the households. The environomic design of vehicles integrated energy systems consists in the systematic and holistic optimization for vehicle energy systems, according to technical, economic and environmental objectives. The method is developed for vehicles applications and is presented for electric vehicles in [1], for hybrid electric vehicles in [2] and for electric vehicles with innovative range extender module with SOFC in [3]. Solid oxyd fuel cells technologies are described in [4] and researched as range extenders for battery electric vehicles in [3] and [5].

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This article presents the application of the environomic design method for an extended energy system, where the vehicle is connected to the household and delivers as well the part of energy services of the household. This is the so-called Vehicle-to-house configuration, part of the Vehicle-to-grid concepts are described in the literature. The idea to use that electric vehicles to supply power to the grid for stabilization and peak time supply is interesting for regions where traditional forms of storage. Vehicle-to-grid scenarios have been proposed in [6]. Prototypes installations proved that the technological means to deliver many of the vehicle-to-grid services are available. Charging electric vehicles can, however, be added to planned demand side management schemes without the need for additional capital investment. Balancing power plants operated with gas serve as stabilizers of the grid in the case of high renewable and variable electricity penetration in power systems. The smart-grid including electric vehicles is playing the grid stabilization role [7]. The results show that even a small share of the fleet of electric vehicles providing load balancing to the grid could lead to important reductions in gas use and energy excess. The integration of renewable energy in the electricity sector and as well the adoption of electric vehicles in the transportation sector have the potential to significantly reduce greenhouse gas emissions with Vehicle-to-Grid technology. The study [8] aims to evaluate the greenhouse gas emission reduction in case of intermittency coming from the introduction of wind power through. The researchers propose in [9] an optimal vehicle to grid planning and scheduling. According to [10], the strategy to reduce CO₂ emissions in the transportation sector is its renewable based electrification. However, the technical option vehicle-to-grid (V2G) requires the vehicle users to temporarily abstain from the usage of their batteries for V2G. 'Range anxiety' and the 'minimum range' are important for the acceptance of the users to participate in V2G. The literature reflects separated optimizations of the vehicles use. Mainly vehicles-to-grid optimizations are done for electric vehicles, to support the electric grid.

This article considers the vehicle as an extended energy system (figure 1), related to the household and proposes optimal design for the energy services for mobility and for the household that the vehicle has to deliver. The optimization of the designs is done by using multi-objective environomic techniques.

**Figure 1.** Definition of the extended energy system for the vehicle and the energy services.

### 2. Methodology for environomic design of integrated services for the vehicle energy systems

In the environomic methods and techniques to design, the improvement and the optimizations of energy systems deal simultaneously on the energy consumption, the economics and the environmental impacts.

The modelling of the SOFC GT module and the vehicle simulation models are explained in details in [3]. This article studies the environomic optimization of the extended energy system. The energy integration could be also activated in the superstructure. The energy integration method is presented in additional article [11].

### 3. Study definition

The study researches the dual mode of utilization of the system. This means that the driving and the residential modes are combined. In this mode, the SOFC-GT can be plugged into the house for electricity and heat co-generation.
3.1. Definition of the mobility and the residential needs

The mobility needs are estimated at 15000 km per year – 150000 km during 10 years. For the residential needs it is considered a household composed of 4 persons. The estimation of the needs of electricity consumption of this household is estimated using the average electricity consumption per capita in France in 2012. The mobility and the residential modes are summarized in the table 1.

| Table 1. Definition of mobility and residential needs. |
|------------------------------------------------------|
| **Mobility**                                         |
| Annual distance, km/year                             | 15 000 |
| Total distance during lifetime, km                   | 150000 |
| Household with 4 persons and 120 m² heated surface   |
| Annual electricity needs, kWh                         | 10000  |
| Annual heat needs, kWh                                | 7200   |
| Annual operating hours for heating, h/year            | 2000   |

The vehicle mass characteristics are given in table 2:

| Table 2. Vehicle characteristics.                    |
|------------------------------------------------------|
| Nominal mass, kg                                      | 1000   |
| Mass of the methane tank, kg                          | 25     |
| Specific mass of the SOFC-GT, kg/kW                  | 7.3    |

3.2. Strategy of the SOFC-GT use in dual mode

The optimization study targets the lowest possible investment cost by designing the SOFC-GT power for the vehicle. Due to its lower power, the SOFC-GT when used in residential mode will only provide a small part of the house electricity and heat needs. The rest of this needs are supplied by other energy sources (electricity for light and heat pump powering for heating). The part of the residential electricity provided by the SOFC-GT should be a design variable with the range from 0 to 1. This variable influences the operating cost and the CO2 emissions during the usage.

3.2.1. Economic model and life cycle assessment (LCA) model. The economic and the LCA models of the SOFC-GT technology and the vehicle cost models are explained and presented in details in [3]. The study applies the economic model for SOFC-GT presented in [12].

The annualized investment cost is remained in equation (1).

\[
AIC = IC \frac{i(1+i)^n}{(1+i)^n - 1} \tag{1}
\]

The methane used in the SOFC-GT installation is considered produced from bio mass. We use GWP as indicator for equivalent CO2 emissions and electricity produced in France.

4. Results: Multi-objective optimization for residential needs

4.1. Residential needs – base case scenario

In the base case scenario, electricity is provided from the grid (French electricity mix). Heating is satisfied with a gas boiler using natural gas as fuel.

4.1.1. Economic evaluation of the base case scenario. The investment cost of the energy technologies are annualized using the equation (1). The operating costs are calculated for the vehicle and the residential needs. The results are listed in table 3.
Table 3. Economic evaluation for the base mobility and residential scenario.

|                  | Driving                      |                           |
|------------------|------------------------------|---------------------------|
| Operating cost, €/year | 901.5                        |                           |
| Annualized investment cost, €/year | 2328                        |                           |
| Total driving yearly cost, €/year | 3229.5                      |                           |
| Residential      |                              |                           |
| Heating cost, €/year | 492                          |                           |
| Electricity cost, €/year | 1505                        |                           |
| Annualized boiler cost, €/year | 828                         |                           |
| Total residential cost, €/year | 2825                        |                           |
| Total operating cost, €/year | 2898.5                      |                           |
| Total annualized investment cost, €/year | 3156                      |                           |
| Total yearly cost, €/year | 6054.5                      |                           |

4.2. Residential mode and environmental evaluation of the base case scenario

There are three sources of CO₂ emission in residential mode: methane combustion at boiler during the whole lifetime, eq. CO₂ emission of the fuel production for the total amount of fuel used in the whole lifetime and eq. CO₂ emission for the electricity production phase consumed in the house for 10 years. The CO₂ emission by combustion of methane in the boiler is computed using the CO₂ emission factor and the boiler efficiency. The results are summarized in table 4.

Table 4. Equivalent CO₂ emission for the base case scenario.

|                  | Mobility                                      | Residential                                      |
|------------------|----------------------------------------------|-------------------------------------------------|
| Car production GWP, kg eq. CO₂ | 3740                                         | CO₂ emission by NG boiler, kg eq. CO₂ | 13640 |
| Gasoline production GWP, kg eq. CO₂ | 3775                                         | GWP NG production, kg eq. CO₂ | 3265  |
| Tank-to-Wheels CO₂ emission, kg eq. CO₂ | 17250                                       | GWP electric production, kg eq. CO₂ | 8920  |
| Total GWP / mobility, kg eq. CO₂ | 24765                                        | Total GWP residential, kg eq. CO₂ | 25825  |
| Total GWP, kg eq. CO₂ | 50590                                        |                                                |

The total GWP impact for the base scenario for mobility and residential is 50590 kg eq. CO₂ for the whole life duration (10 years exploitation and 150000 km). The mobility with internal combustion engine vehicle (ICEV) vehicle contributes to the half of the GWP impact. The tank-to-wheels CO₂ emission obtained by gasoline combustion represents 70% of the mobility with 17250 kg eq. CO₂.

In the residential mode the contribution of the different parts is more equilibrated. The electricity contribution based on the French mix is representing around 9000 kg eq. CO₂. This is a favourable case because the French mix is mostly based on nuclear energy. The introduction of other energy mixes majority based on coal will increase the contribution of the GWP impact of the electricity.

4.3. Vehicle as grid related system – mobility and residential mode optimization – optimal scenario

In the dual mode, the SOFC-GT is used for mobility and residential energy needs. The calculation for mobility is done on NEDC and the simulation starts with a fully charged battery. The energy for the battery charge is provided by the house charger and is produced from the solar panels that equip the house. Part of the electricity needs in residential mode is provided by the SOFC-GT module and the remaining part is supplied by the grid (French electricity mix is considered). The complement of heat is
supplied by a heat pump with a coefficient of performance (COP) of 5. The annual saving resulting from the use of SOFC-GT has to be enough to be able to amortize the total investment cost within the lifetime of the system defined at 10 years.

4.3.1. Parameters of the optimization. Two decision variables are added compared to previous optimizations – the SOFC-GT power in residential mode and the part of electricity provided by the SOFC-GT, $\beta_{el,sofcgt}$. The optimizer can decide the size of the SOFC-GT for driving or residential mode. The yearly cost is an effective way to account the cost of both modes. The yearly cost includes:

- The annualized investment cost of the vehicle;
- The operating cost of methane used in driving mode for 150000 km;
- The operating cost of methane used in residential mode for electricity production during 10 years;
- The operating cost of heat production in the house via the heat pump during 10 years;
- Operating cost of pure oxygen needed for the driving and residential mode during 10 years;

The computed GWP includes:

- GWP of the vehicle production phase;
- GWP of the production of methane (wood gasification) needed for mobility and residential mode during 150000 km (driving) and 10 years (residential);
- GWP of the production of the amount of electricity used by the household during 10 years;
- CO$_2$ emission in both driving and residential mode during 150000 km and 10 years.

The amount of CO$_2$ emitted during driving and residential mode is counted in the total GWP to be minimized. The decisions variables are summarized in table 5. The 3 dimension multi-objective optimization function is defined in equation (2):

$$\min (-\text{autonomy}(x), \text{yearly cost}(x), \text{total GWP}(x), x \in (\text{Decisions variables})).$$

### Table 5. Definition of the decision variables for a dual application of the range extender module.

| Decision variables                                      | Range    |
|---------------------------------------------------------|----------|
| Electric machine power, kW                               | [15-50]  |
| Battery capacity $Q_{\text{batt}}$, kWh                  | [5-80]   |
| Power of the SOFC-GT module for driving, kW              | [1-10]   |
| Power of the SOFC-GT module for residential, kW         | [1-10]   |
| Mass of methane, kg                                      | [5-15]   |
| $\beta_{el,sofcgt}$                                      | [0-1]    |

The resulting Pareto curve is shown in figure 2. The solutions converge between 6400 €/year and 7800 €/year regarding the yearly cost and between 20000 and 45000 kg CO$_2$ eq. regarding the total GWP during the lifetime. The yearly cost and the total GWP of the base case scenario are 6055 €/year and 50590 kg eq. CO$_2$. The studied integrated system cost more (from 400 to 1800 €/year) than the base case but the GWP impact for all solutions is improved. The families of solutions in the transient autonomy zone, already discussed in the previous section, are also present in this Pareto. They are represented on the figure 2 (b). The variation of the solutions is large. For example, for the autonomy of 200 km, the solutions vary between the 6900 €/year and 7300 €/year. The solutions with less cost and bigger GWP give the lower scatter band. The solutions with bigger cost and lower GWP give the high scatter band. The width of the Pareto curve increases as the autonomy increases.

The evolution of the SOFC-GT designs is plotted on the figure 3. It shows that the autonomy increases when the design power of the range extender increases, as observed in the previous optimizations. In this multi-objective optimization (MOO) the use phase is considered also, and as it contributes to the major impacts and cost, one can observed that the battery design capacity doesn’t
influence a lot the solutions. Figure 4 shows that the battery size between 5 and 15 kWh is selected in the most of the solutions. The efficiency of the converter and the methane production way influence on an important way the use phase CO2 emission.

In order to identify for which application the SOFC-GT is optimally designed, a Boolean variable is created (table 5). This variable is equal to 1 when the range extender is designed for the residential needs and is equal to 0 when the range extender is designed for the mobility needs. Figure 5 shows that in most of the cases the SOFC-GT is optimized to satisfy the mobility needs and to extend the vehicle autonomy. Figure 6 shows that the repartition coefficient $\beta_{el,sofc-gt}$ between the part of electricity provided by the SOFC-GT and the part provided by the electrical grid is related to the cost and the GWP.

![Figure 2. Yearly cost/autonomy Pareto curve in dual mode, GWP in color bar.](image1)

![Figure 3. 3D MOO Pareto curve, SOFC-GT design in colorbar.](image2)

![Figure 4. 3D MOO Pareto curve, battery design in color bar.](image3)
If a low cost is targeted (meaning a high GWP impact), the optimizer choice is that 100% of the energy needs for the household are provided by the SOFC-GT (figure 7). The total GWP is strongly dependent on the variable $\beta_{el,sofcgt}$ and this is logical because most of the GWP comes from the use phase (the electricity use in the residential mode). The electricity needs per year is 10000 kWh and this means 100000 kWh for 10 years. Compared to that and considering a consumption of 11.8 kWh/100 km for the range extender vehicle, as observed in previous optimizations, the amount of energy needed for 150000 km is 17700 kWh. This value represents 18% of the consumption of electricity in residential mode.

The electricity mix production has a determinant impact in the optimizer choice of the $\beta_{el,sofcgt}$ and consequently on the GWP impact. The CO2 contribution for 1 kWh is compared for different production mixes (for different countries) in table 6. The CO2 contribution for the production of 1 kWh of electricity with the SOFC and biomethane is also illustrated. One can see that the electricity produced from SOFC-GT and biomethane has more CO2 contribution than electricity produced in France. For the case of a house supplied with electricity supplied from France, the optimal GWP will be found for solutions supplying the total electricity needs from the grid, the SOFC-GT is used at the minimum. This is the case illustrated on the figure 8.
Table 6. Specific GWP for different sources of electricity.

| Source of electricity | Specific GWP of electrical production, eq. kg CO₂/kWh |
|-----------------------|------------------------------------------------------|
| Mix France            | 0.0892                                               |
| SOFC-GT               | 0.2805                                               |
| Mix Germany           | 0.638                                                |
| Mix Poland            | 1.1                                                  |

If the German or the Polish electricity production mixes were chosen then the optimizer to minimize the GWP, would surely privilege the use of SOFC-GT for the total providing of the residential electricity needs by the SOFC-GT module.

The optimal solution for a system with integrated energy services is chosen in ID 16 (figure 7). ID 16 presents autonomy of 200 km, which is the targeted autonomy for current electric vehicles. Globally, all integrated solutions present higher yearly cost than the base case. This is due to the high investment cost for the SOFC-GT installation. But all obtained solutions for the integrated services have lower total GWP impact than the base case separated house and mobility energy services. Therefore choosing a high autonomy vehicle for competitiveness with the ICEV would end up not economically competitive at all considering the high yearly cost. The vehicle with 200 km of autonomy integrated to the house energy services gives a balanced solution between cost and GWP. This solution is with integrated energy services for residential and driving mode. The details of the ID16 are presented in table 7. The comparison with the base energy scenario is also done.

The detailed contribution of the cost and the GWP of the ID 16 are compared to the base scenario. One can observe that with the chosen solution, the main outcomes are: the yearly cost 1000 € higher for the integrated solution and the GWP is with around 30000 kg CO₂ eq. smaller than in the base case.

Table 7. Comparison between ID16 at 200 km of autonomy and the base case scenario.

|                        | ID 16  | Base case |
|------------------------|--------|-----------|
| Power Electric machine, kW | 32.28   |           |
| Capacity of the battery, kWh | 6.28    |           |
| SOFC-GT power for driving, kW | 2.80    |           |
| SOFC-GT power for residential, kW | 1.60    |           |
| Mass of methane, kg    | 10.2   |           |
| \( \beta_{el,sofc,gt} \), \( - \) | 0.33    |           |
| Range/Autonomy, km    | 206    | 1000      |
| Vehicle cost, €        | 28430  | 20900     |

Mobility

|                        | ID 16  | Base case |
|------------------------|--------|-----------|
| Operating costs, €/year| 127    | 900       |
| Annualized investment costs, €/year | 3681 | 2328 |
| Total driving yearly costs, €/year | 3808 | 3229 |
| Car production GWP, kg eq. CO₂ | 6596 | 3740 |
| Fuel production GWP, kg eq. CO₂ | 768  | 3775 |
| T-t-W CO₂ emission, kg eq. CO₂ | 3594 | 17250 |
| Total GWP driving, kg eq. CO₂ | 10958 | 24765 |

Residential

|                        | ID 16  | Base case |
|------------------------|--------|-----------|
| Total residential yearly costs, €/year | 3258 | 2825 |
| Total GWP residential, kg eq. CO₂ | 9380 | 25825 |
| Total operating costs, €/year | 1660 | 2898.5 |
| Total annualized investment costs, €/year | 5406 | 3156 |
| Total yearly costs, €/year | 7066 | 6054.5 |
| Total GWP, kg eq. CO₂ | 20338 | 50590 |
5. Conclusions
In the study, the vehicle is considered as grid related to the house and this means that its energy service of mobility and comfort is related to the energy services for the family house. The study contributes to consider in an integrated scale mobility and energy services for a household and introduces the use of the vehicle in dual mode. SOFC-GT module is introduced as a range extender of the autonomy of the electric vehicle. A base energy scenario for the house is also defined. The total GWP impact of the base case scenario is estimated to 50590 kg CO₂ eq. The multi-objective optimization for environomic design of the new vehicle-house system is performed for the definition of the environomic design of the driving and the residential mode. In the case of the energy supplied in France the optimization sizes the SOFC-GT module for the mobility needs. The rest of the energy needs of the house are covered by the grid supply. Optimal design of the range extender vehicle in dual mode is proposed for 200 km of autonomy, investment cost of 28430 € and 3808 €/year of total driving yearly cost. The base case scenario has lower investment (20900 €) and total driving yearly cost (3229 €/year).

The total yearly cost for the integrated system in dual mode stays still higher (1000 €/year) than the base case separately delivered energy services. This is due to the high investment cost of the equipment in the vehicle and the house. The major advantage of the energy integrated dual system is the reduction of the total GWP impact with around 30000 kg CO₂ eq. (60%). – from 50590 kg CO₂ eq. to 20338 kg CO₂ eq. This study illustrates large scale economic and environmental benefits opportunities by integration of the energy services for mobility and household.

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