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Natural Gas as a New Prospect in Everyday Use of Electric Vehicles

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Featured Application: This work proposes a home-scale charging station for electric vehicles (EVs), which makes use of the existing grid of natural gas. The station is based on a CH₄-fed solid oxide fuel cell for energy conversion. The feasibility of the wide use of such a system has been also proved in economic terms.

Abstract: We study here the urban use of electric vehicles (EVs), focusing on the electricity production for charging purposes. This work proposes an innovative charging scheme for EVs, by introducing a home-applied power station, consisting of a fuel cell combined with an internal reforming unit, which is fed by natural gas and can thus be directly connected to the already-established natural gas grid. We therefore overcome the barriers posed by hydrogen use (establishment of storage equipment, energy consumption for keeping high pressure, development of supply grid, etc.) while we eliminate the environmental impact, since no fossil fuels are required for electricity production. Furthermore, comparisons against EVs charged by grid and vehicles fueled by petrol, both subjected to urban everyday use, have been carried out here. Precisely, we financially compare the use of an EV charged directly through the national electric grid against our innovative power station. Both options are also compared with the same vehicle, powered by an internal combustion engine fueled by petrol. This study also implements a detailed thermodynamic analysis for this state-of-the-art power station and an additional financial analysis for the everyday use of these vehicles under the three different scenarios. For the sake of equivalence, the new Peugeot 208 was selected as the reference-vehicle, as it is equipped either with a petrol engine or an electric motor, under a roughly identical performance profile. This work also introduces the use of the existing grid of natural gas to produce the necessary electricity for charging EVs, rather than using other renewables (solar, wind, etc.), and could further strengthen the worldwide acceptance of the EVs as a viable and a financially feasible solution for everyday urban transportation.

Keywords: natural gas; zero emissions; renewable energy; electricity; SOFC; electric vehicle

1. Introduction

The unusual increase of technological applications in everyday life inevitably corresponds to an enormous increment of energy consumption. The energizing of the continuously increasing electric vehicle (EV) fleet can prove detrimental for the already-established electric grid, which seems overloaded by the growing human needs. Electrification of vehicles is currently recognized as a feasible option towards an environmental-friendly coverage of these needs, although the automobiles' supply must be independent from the weather and the availability of the grid, if it belongs to the EV fleet. Nowadays, the current energy needs cannot be satisfied by fossil fuels due to strict environmental limitations, mainly for CO₂ emissions and other greenhouse gases, as defined by the

Kyoto Protocol, Paris Agreement, and several other policy guides/agreements. This trend obviously affects transportation as well and, precisely, the design and implementation of passenger cars. During the last few years, electrified vehicles flood the market while many technological options aspects and relative technologies have been proposed. Currently, the marketed electric vehicles are classified into two main groups: the all-electric vehicles (AEVs) and the hybrid electric vehicles (HEVs). The latter combine an internal combustion engine with an electric motor to eliminate the CO₂ emissions [1]. Several reports indicate the penetration of EVs in the automotive market: from a couple of hundred electric vehicles (EVs) in 2010, nowadays the existing EV fleet approaches 6 million, which means an increase of 6000% [2]. Furthermore, market models predicted approximately 100 million EVs on the road by 2030, while this is expected to raise to about 550 million by 2040 [3,4].

Although the above scenario for the future of the automotive market sounds like a very suitable option for addressing environmental issues, there are some major concerns regarding the primary source for electricity supply. Several published works have already underlined that the electrification of the fleet will not drastically improve the planet's situation if electricity is produced by conventional fossil fuels. Therefore, the extensive use of EVs corresponds to increased needs for electric power, which would have a significant environmental impact. Under this perspective, the increasing demand for electric power must inevitably be covered by renewables and other environment-friendly power sources in order to significantly eliminate CO₂ emissions. Specifically, it has been proposed that an EV can be transformed into a reasonable solution to reduce environmental pollution only by using renewable electricity and decreasing CO₂ emissions up to 2000% [5]. Here it must be mentioned that integrating millions of EVs into the grid of the social electric network can impact the load profile and generally its operational characteristics such as phase, voltage, and frequency [6,7]. Moreover, this can cause power losses, stability issues, and overloading of several grid components [8,9].

On the other hand, off-grid systems for electric power supply present some negative environmental effects and/or ineffectiveness from a financial point of view [10,11]. Some drawbacks are revealed from the biogas-photovoltaic project implemented in Uttarakhand state in India, where the overall emissions were observed to be elevated [12]. In China, several studies have shown that if there is no combination between the primary, secondary, and tertiary industries, then an off-grid system is not viable [13]. Also, in a survey conducted in a rural area of Bangladesh, the unit cost of electricity from optimal off-grid power supply was much higher than that from the grid [14]. Moreover, standalone hybrid applications used for the electrification of EVs simultaneously use more than one Renewable Energy Source (RES) technology under a complex multiparametric system, which requires a large installation space, being therefore inappropriate for urban networking. Such projects are prohibitively expensive and refer to extensive public use while not being suitable for individual domestic investment [15,16].

By considering all the above issues arising from the use of the widely accepted renewable energy sources when they constitute off-grid electric charging stations, an innovative power supply method is revealed by the use of the inexhaustible deposits of natural gas. The core idea here is to take advantage of the already-established natural gas network in order to use CH₄ not only to produce thermal energy for domestic use but also to electrify a light commercial EV on a daily basis [17]. As is already known, a fuel cell stack fed by hydrogen-rich gases, can constitute the main component of a system for electricity production purposes. The best known and most widely quoted fuel cells (FCs) are the polymer electrolyte membrane (PEM) and Solid Oxide Fuel Cell (SOFC), preferred for portable and stationary applications, accordingly [18,19]. Specifically, PEM FCs are more sensitive to humid conditions and to the purification of the hydrogen. Also, these are significantly influenced by the fuel impurities and by the carbon monoxide produced during the reforming process, while characterized by the high maintenance costs of the membrane's replacement [20,21]. On the other hand, SOFC-stack, which seems more promising for the present project, can be supplied by different mixtures of gases, such as natural gas, without influencing its efficiency, mainly due to the elevated temperatures at which they operate [22,23]. In the present project, an intermediate temperature SOFC (IT-SOFC) is

simulated in order to prevent the additional cost for heat energy demands during the system's operation. These FCs seem to be more profitable under a moderate temperature range of 400–700 °C [24,25].

The core question raised in the discussion of all the above considerations is whether a reliable green energy source exists for everyday use under a domestic establishment, to charge an EV 24 h a day and 7 days a week permanently, without significant issues. At this point, we present an innovative SOFC-based home charging system, fed by natural gas (i.e., directly connected to the national gas supply grid), in order to utilize the methane-rich gas to feed a SOFC-stack for electricity production to cover the needs of a family's EV.

2. Materials and Methods

For the efficient and standard-compliant installation of such a system, it is essential to select the right components to minimize the power loss throughout the total pipeline, from the natural gas flow rate up to the vehicle's charging port. Over the last decade in Europe, the prevailing standards, which deal with the EV charging infrastructure, stem from the International Electrotechnical Commission (IEC) [26,27]. Nowadays, the most prevalent IEC standards are IEC62196 and IEC61851. These relate to the type of power source (DC or AC single/three phase), the operational voltage of the whole system, the maximum current, and the available charging ports and connections. Each one can be used under AC-modes, three available for IEC62196 and two for IEC61851, and DC-mode characterized as fast charge operation by using a power supply path up to 600 V under maximum current load of 400 A and 200–450 V under 80 A for IEC62196 and IEC61851, accordingly [26,28].

More precisely, the innovative simulated electric power station will consist of an innovative IT-SOFC-stack, characterized by 5 kW capacity and operational temperature of 400–700 °C, along with an internal reforming stage to generate the necessary electric power. A heat exchanger unit is also used to raise the inlet ingredients' temperature to the desired operating level of an IT-SOFC while these devices will be accompanied by a high voltage DC-supercharger in order to charge the EV. The above power plant will be supported by a burner unit that will supply the excess thermal energy to reach the desired operating temperatures, as it is presented in Figure 1.

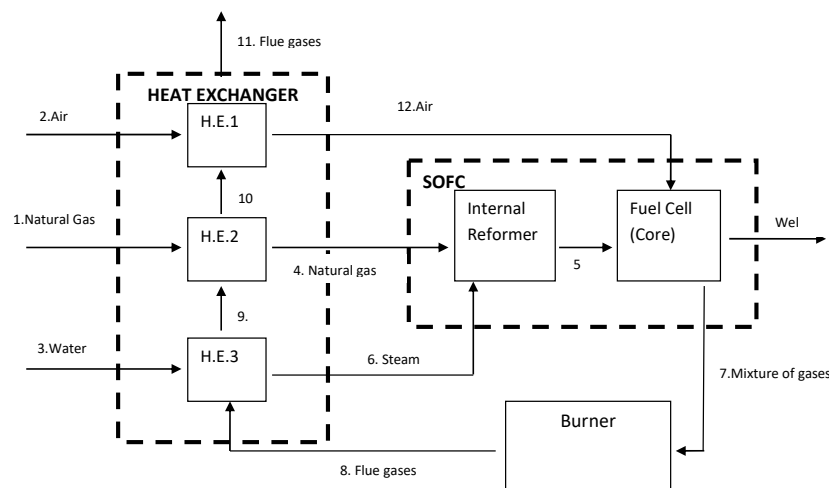


Figure 1. Flow chart of the innovative Solid Oxide Fuel Cell (SOFC) based Electric Vehicles (EV) charge station.

Natural gas will be considered as the unique provided power source for the presented innovative charging station. To calculate the mass and energy balances, we assumed that the system is in steady-state conditions, being fed by a certain amount of 0.64 kg CH₄, 10.11 kg air, and 1.8 kg H₂O. These values are the optimal ones that may assure approximately 18000 KJ (i.e., approx. 5 kWh) at the output, which is the normal demand for a typical EV charger. Also, at the entrance of our apparatus, we introduce air and water, needed for the reactions occurring in the reformer and FC. We assume that

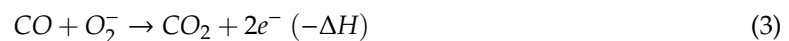
methane is the main component of natural gas at a level of 91.2%. Initially, the moles of the substances (namely CH₄, CO₂, N₂, O₂, and H₂O) involved in the reactions that take place in the reformer and the cell, were calculated. Then, mass balances were produced and solved in a linear system. To control the reforming process, we introduced the extend-of-reforming, ϵ ; thus, the mass balances for each device as well as for the whole apparatus can be calculated easily. Regarding the relative energy balances, we made use of enthalpy (ΔH) of each reaction we considered, in accordance with known thermodynamic formulas for the heat transport and specific heat capacity involved [29,30].

In order to simulate and optimize the IT-SOFC-based system, the energy aspect of the present research study was based on the previously presented simulation tool THERMAS [29,30]. This model incorporates extensively the energy balances over each simulated device and can be described through the following expression [29,30]:

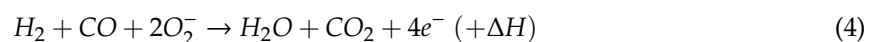
$$\begin{aligned} & \left\{ \sum_i \left[(\Delta H_f^0)_i + \int_{T_0}^{T_{in}} m_i(\tilde{C}_p)_i dT \right] + Q + \sum_r |\Delta H|_{ex} \right\}_{in} \\ = & \left\{ \sum_i \left[(\Delta H_f^0)_i + \int_{T_0}^{T_{out}} m_i(\tilde{C}_p)_i dT \right] + Q + \sum_r \Delta H_{end} \right\}_{out} \end{aligned} \quad (1)$$

where ΔH_f^0 is the enthalpy of formation in the reference state, and \tilde{C}_p is the mean molar specific heat capacity. Symbol ΔH refers to the enthalpy changes of the exothermic or endothermic reactions according to each process. Also, Q describes either the essential thermal energy for a specific process or thermal losses. As reference state for the above process, we considered $T_0 = 298$ K and $P_0 = 1$ atm.

The optimal value for the air excess at the inlet was found to be 100% (i.e., stoichiometric requirement), while the extent of reforming was set to 80%. In the fuel cell, we considered the reactions



that can be summarized as



which produces electricity and heat. This reaction is supposed to take place in an extent of 80%.

The performance analysis of such an innovative charge station in terms of energy efficiency sounds insufficient if not performed along with financial feasibility over time. Note that the initial costs of a SOFC-based project are quite high, while the maintenance and the operational costs are lower than those of internal combustion engine (ICE) technology. The overall comparison between the several simulated projects will be based on the optimisation of the Net Present Cost (NPC), expressed as

$$NPC = |CAPC + \sum ADICFL| \quad (5)$$

where $CAPC$ is the capital cost of each project in the initial (zero) year, and $ADICFL$ refers to the annual discounted cash flows per year summed over the 5 years of the project's lifetime. In order to calculate $ADICFL$, it is necessary to estimate the discounted factor (FD), which is used to calculate the present value of a future cash flow varying throughout the whole project's lifetime, as the following expression indicates:

$$FD = \frac{1}{\left(1 + \left(\frac{i}{100}\right)\right)^N} \quad (6)$$

where N is the year of calculation, and i is the real discount rate using it in the above expression as a percentage. For the scope of the present research study, the $ADICFL$ (see Equation (5)) incorporates the discounted cost of emissions per year calculated as follows:

$$DTCEMI = -FD \frac{0.606 \cdot TPCON}{1000} CEMI \tag{7}$$

where 0.606 is the mass of CO₂ emissions in kilogram per produced kWh of electric energy, as announced by the Greek government, the $TPCON$ is the total power consumption in kWh, and $CEMI$ represents the cost of a produced CO₂ ton, as specified by EU (30 €/ton) [31].

3. Results & Discussion

The overall performance of the system, defined as the percentage ratio of the produced electricity W_{el} ($= 17.8 \times 10^6$ J) over the sum of energy at the input of the apparatus ($E1 + E2 + E3$), was found to be as high as 65.96%, while the thermal wastes of the fuel cell and of the burner were calculated to be 12.84% and to 21.78%, respectively. In compliance with the notation introduced by Figure 1, the following Table 1 depicts the temperatures, the mass fluxes, and the energy at any branch of the system.

Table 1. Typical results for the optimized system.

Branch	Temperature (K)	Mass Flux (Kg/s)	Energy ($\times 10^6$ J)
1	298	0.64	2.89
2	298	10.11	0.00
3	298	1.80	24.2
4	680	0.64	1.11
5	675	2.44	2.82
6	780	1.80	2.00
7	675	12.50	6.86
8	800	12.50	9.38
9	704	12.50	7.38
10	649	12.50	6.27
11	415	12.50	1.98
12	675	10.11	4.29

For the purpose of the present research study, three different simulated scenarios were chosen for an everyday transportation in an urban area: (a) use of a conventional, ICE technology vehicle, (b) use of an EV charged by grid, and (c) use of an EV charged by the innovative FC-based power station as Figure 1 presents. The comparison of the above scenarios is performed in terms of NPC after a period of 5 years of use. In all the above scenarios, the vehicle is of the same performance and is assumed to be used in the same way. We have chosen here the new Peugeot 208 as reference vehicle due to the fact that it is a chassis in the automotive industry that can be sold either as AEV (all-electric vehicle) or with a traditional petrol engine technology, as Table 2 shows. Both electric and conventional vehicles are identical; thus, a direct comparison can be feasible for safe results.

Table 2. Vehicle specifications and costs.

Performance Specs	Peugeot e208	Internal Combustion Engine (ICE) Peugeot 208
Maximum power output (kW)	100	97
Gearbox	Continuous transmission	8-speed automatic
* Fuel consumption	5.44 (km/kWh)	7 (lt/100 km)
* Emissions (gr CO ₂ /km)	-	130
Salvage Value (SAL) (%)	70	50
** CAPC (€)	35,000	22,000

* According to the Protocol WLTP (Worldwide Harmonized Vehicle Test Procedure), ** Under the same gadget equipment; CAPC is the Capital Cost of Each Project.

Moreover, it is important to mention here that after a 5-year period, the salvage value (SAL) of an AEV is higher than that of an ICE vehicle due to the durable construction of the electric motor and the absence of moving parts in the transmission. On top of the above-presented costs resulting from the ownership of each vehicle, there are several more annual operational and maintenance costs arising from an everyday use for each simulated scenario, as Table 3 reveals. Also, the appropriate annual mileage was designated at 20,000 km, a value that is the annual average in Greece, in order to calculate the fuel and the electric load costs of the traditional vehicle and the AEV, accordingly. Finally, for the purpose of this research work, the emission costs of the simulated grid-connected AEV and the ICE car will be embodied in the financial study because these will play a crucial role in the final calculation of the NPC, which will reveal the viability of such a project.

Table 3. Nominal cash flows.

Costs	Petrol Engine 208	Grid Connected e208	FC-Based 208
CAPC (€)	-	-	-
RC (€)	-	-	-
OPMAC	ENVTX (€/year)	156	-
-	INSUC (€/year)	350	500
-	SERVC (€/year)	150	60
-	TYREC (€)	400	400
FUC	PETRC (€/year)	2100	-
-	ELLDC (€/year)	-	369.36
-	STLGE (€/year)	-	91.43
-	CEMI (€/year)	78	66.84
SAL	-	-	-

RC is the replacement cost, OPMAC is the operational and maintenance cost and FUC is the fuel cost.

Nowadays, regarding the investment cost of the FC-based project, it seems that the global market has already reached the estimated cost target for 2020 [32] of 500 €/kW for a small scale SOFC-stack for domestic use, such as those by Elcogen, the world's most advanced manufacturer of ceramic anode-supported SO (solid oxide) cells and stacks. The extra costs for auxiliary components during the system installation almost treble the establishment cost of such a SOFC-based project, being as high as 1500–2000 €/kW approximately [32]. More precisely, the capital investment contains the FC-stack, fuel and water valves, pumps, flow meters and pressure regulators, power electronics in combination with FC-ECU (electronic control unit), heat exchangers and burners, assembly and final components for plant's balance such as DC/DC converters, wirings, and connectors, system controller, bus bar, fuses, and several sensors all over the paths. All the above assumptions have been incorporated in Table 3, for a 5-kW FC-stack that supports the innovative natural-gas-fed power station for the AEV's charging needs.

Now, regarding the above presented costs, it is important to note that a grid-connected power station is encumbered with the STLGE (special tax for low gas emissions), which is calculated by multiplying the consumed electric load measured in kWh by 0.02487 €/kWh. For each project, the CO₂ emissions, presented as CEMI in Table 3, have been quantified as cash flow according to the European Union by calculating the pollutant emissions in CO₂. Finally, the salvage value constitutes a positive feedback for the innovative FC-based power station at the end of the project lifetime specified at 5 years, which is calculated by excluding the operating hours of the FC-stack from its lifetime (more than 40,000 h of continuous operation), and the remaining percentage can be translated as a positive cash flow. For the already-presented costs and cash flows, as Tables 2 and 3 show, it is important to estimate the discounted prices for a detailed calculation of NPC (see Table 4), which will judge the financial feasibility of the presented project.

Table 4. Discounted cash flows and Net Present Cost (NPC).

No of Year	Petrol Engine 208	Grid Connected e208	FC-Based 208
0	-22,506.00	-35,500.00	-44,250.00
1	-2715.58	-1027.40	-1084.16
2	-2603.08	-971.14	-1026.02
3	-2857.66	-1280.07	-1333.13
4	-2394.42	-869.37	-920.66
5	7326.64	20,202.63	26,807.03
Total	-25,750.10	-19,445.35	-21,806.94
NPC	25,750.10	19,445.35	21,806.94

At this point, it is appropriate to mention that the initial investment (zero year) to own an electric car is excessively increased regardless of the chosen charging case, compared to a traditional ICE technology vehicle. On the other hand, the total annual costs for an AEV project are diminished up to 70% by using the innovative FC-based power station fed by natural gas (Figure 1), while the salvage value of such an innovative project at the end of the fifth year is raised up to 350% compared to that of owning a petrol engine vehicle. Finally, it is important to note that the assessment of the environmental footprint in annual cash flows is almost at zero level by using the FC-based charging station.

4. Conclusions

In this work, we compare a conventional ICE technology vehicle with an EV of the same characteristics and performance, charged either by being plugged in the grid or by an innovative energy conversion system proposed here, which produces electricity when supplied with natural gas (i.e., CH₄). It was found that the annual cashflow for oil/petrol is high compared to electricity, while the difference between the EV and the conventional vehicle increases with the increment of project lifetime. In this context, an EV using the grid for charging purposes is not a good option for “green” transportation, given that the costs of CO₂ emissions are lower only by 15% in comparison with a new technology petrol vehicle. Obviously, the scenario with the innovative charger involves really zero emissions, thus highlighting the trend and the potential of our system. This option is further strengthened by the low costs of installation, operation, and use, which are almost equivalent to those of the grid-connected EV and 75% lower than those of the ICE vehicle. The solution presented here might also help to decrease emissions of greenhouse gases, as there is no need for developing a specific network of charging stations, while the optimized energy efficiency can assure low needs of extra electricity production. The forthcoming legislation regarding the financing of the EV market is expected to further decrease the NPC value of such an advanced project, thus leading to an extensive electrification of the automotive market.

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