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Impacts assessment and trade-offs of fuel cell-based auxiliary power units Part I: System performance and cost modeling

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Abstract

Auxiliary power units (APUs) are devices that can provide all or part of the non-propulsion power of a vehicle. They do not replace the main internal combustion engine, but they complement it offering low consumption, high comfort and low emissions during the idling periods of the vehicle. This work presents an integrated framework to evaluate the trade-offs between cost effectiveness, efficiency and health and environmental impacts of fuel cell power systems considering various stages of the life cycle of the device. The integrated framework has six main components, namely system level modeling, cost modeling, environmental impact assessment, health impact assessment, life cycle assessment and multi-objective optimization. In part I of these two papers, concerning the integrated framework, the first two components are described and applied to a solid oxide fuel cell-based auxiliary power unit. All the results are validated with experimental data or other published models.

Keywords: Integrated framework; Auxiliary power units; Fuel cell; System level modeling; Cost modeling

1. Introduction

Since the late 1980s, there has been a strong push to develop fuel cells for use in light-duty and heavy-duty vehicle applications. In addition to high-profile applications such as automotive propulsion, the use of small fuel cell stacks (up to 5 kW) as auxiliary power units (APUs) for vehicles is receiving considerable attention. Auxiliary power units are devices that can provide all or part of the non-propulsion power for vehicles. They do not replace the main internal combustion engine, but complement it. The main advantages of these kind of devices are to improve the power generation efficiency, to reduce emissions and noise when the vehicle is parked, and to extend the life of the main engine. Currently, APUs are usually small internal combustion engines equipped with a generator and heat recovery to provide electricity and heat [1]. However, there is a good fit between APU requirements and fuel cell system characteristics in terms of efficiency, load requirement, and physical size and weight. Among the different fuel cell types, the Solid Oxide FC (SOFC) technology is considered the most favorable due to several characteristics, such as the ability to use a variety of hydrocarbon fuels with simpler reforming processes and no need for any water management system. APU applications seem to be attractive because they offer a true mass-market opportunity that does not require the challenging performance and low cost required for propulsion systems for vehicles. Therefore, this is predicted to be the first fuel cell penetration in the transportation sector, in the market of heavy-duty trucks and luxury vehicles (recreational vehicles and limos).

The major advantage of APUs for trucks is reducing the common [1] practice of idling heavy-duty diesel engines. Drivers idle truck engines to power climate-control devices

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(e.g., heaters and air conditioners) and sleeper compartment accessories (e.g., refrigerators, microwave ovens, and televisions) and to avoid start-up problems in cold weather. Idling of the truck's large-displacement diesel engine is an extremely inefficient and polluting way to generate heat and electricity (an idling truck will actually emit twice as much NO_x as it would during cruise at 55 mph [2]). Heavy-duty diesel truck idling contributes significantly to energy consumption in the United States: about 840 million gallons of diesel are consumed each year in the U.S. by idling long-haul trucks [1]. In addition to excess fuel consumption, lubricant consumption, and engine wear, heavy-duty truck idling generates air pollutants, greenhouse gases, noise, and vibrations. Fuel cells instead offer a high-efficiency (equivalent to low consumption), low-emission, and low-noise alternative that would supplant the need for truck engine idle.

Trucks traveling more than 500 miles from their home base each day are likely to be idling overnight during stopovers on long trips. Among these, trucks with gross vehicle weight (GVW) rating of 26,000 lb or greater (classified as class 8 trucks) are the candidates for fuel cell-based APUs [1]. However, in California there is a law proposal [3] that would require the installation of a non-adjustable idle reducing system on all new on-road heavy-duty diesel engines in vehicles with GVW greater than 14,000 pounds. According to [4], in the U.S. in 1997 there were 401,900 heavy trucks (above 26,000 lb) with range of operation greater than 500 miles. The average baseline truck idling estimated by Argonne National Laboratory [1] is 6 h per day for 303 days per year (eighty-five winter days at 10 h per day and 218 non-winter days at 4.5 h per day).

The market of recreational vehicles (RV) is in continuous expansion. A University of Michigan study [5] shows that the number of households that own at least one RV was projected to rise from 6.9 million in 2001 to 7.9 million in 2010 (+15%). This number includes any kind of recreational vehicles of every range of price. Not all RVs are candidates for an auxiliary power source. Because of cost limitations the largest categories, commonly referred to as motorized motorhomes (range of price varying from US$ 42,000 to US$ 1,400,000 [6]), are the most likely candidates for fuel cell-based APUs. These categories absorb about 20% of the shipment market [6,7] and represent about 25% of the RVs owned by households [5]. About 190,000 RVs are sold each year in the U.S. that might be considered candidates for a fuel cell APU [8]. For this kind of vehicles a fuel cell APU is an efficient way to produce the electricity needed for the large number of onboard accessories. Data about the possible operation time of an auxiliary power unit installed on a recreational vehicle were not found. Therefore, for the simulations it was assumed that they work the same amount of time as APUs installed on trucks.

Although a lot of research is active in the fuel cell sector, the trade-offs, in terms of environmental and health impact, as compared to the total cost and the system efficiency have never been systematically studied. An integrated framework that can automatically identify and quantify these trade-offs has been developed. This paper, which is part I of a series of two papers on this topic, describes the first two main components of the integrated framework, namely system level modeling and cost modeling. The remaining components, namely environmental impacts assessment, health impacts assessment, life cycle assessment, and multi-objective optimization, are discussed in the second part.

2. System level modeling

The entire fuel cell system, comprehensive of fuel processing and fuel cell device, is simulated in Aspen Plus [9] and this constitutes the base model for the integrated framework.

There are many researchers who are actively involved in modeling fuel cell units. However, only few publications report the details of the models. Berry et al. [10,11] addressed the specific case of 5 kW diesel fueled APUs with computer modeling and experimental data. Therefore, this work forms the basis for this component. A study of A. D. Little provides modeling data for 5 kW SOFC systems [12]. Another study by ADL Inc. for auxiliary power systems [13] is also of interest. In a recent publication, Sommer et al. [14] studied the dynamic modeling and simulation of a fuel cell system with autothermal gasoline reformer. The modeling and control of SOFC-based APUs is also subject of the research of Khaleel et al. [15] at Pacific Northwest National Laboratory. Delphi Automotive System developed SOFC technologies for automotive applications, primarily as on-board APUs [16]. A development update from Delphi on this topic can be found in a paper by Zizelman et al. [17]. Crosbie et al. [18] addressed the direct oxidation (without reforming) of liquid hydrocarbon fuels in solid oxide fuel cell for automotive APUs.

Since diesel is commonly used as fuel on Class 8 trucks, this fuel has been chosen for the simulations, even though the processing technology is complex and still under development. The fuel processor is a critical component of a diesel-fueled auxiliary power unit and must be able to provide a clean, tailored synthesis gas to the fuel cell stack. As described in Berry et al. [10,11], the diesel processing system includes an autothermal reformer, a desulfurizer and a combustor that acts as a polishing bed for the exhaust gases from the fuel cell. The exhausts from the combustor are used to preheat the air for the reformer and the fuel cell and to generate the steam necessary for the reforming. With a proper design, all the water needed by the autothermal reactor is provided by condensation of the exhaust in a condenser, which was modeled as an isothermal flash. Basic assumption in the model is that the reforming catalyst can handle high sulfur content of the fuel. However, sulfur must be removed prior to the fuel gas entering the fuel cell [10]. Sulfur removal is achieved with a bed of zinc oxide, but this is just one of the several configurations that can be evaluated. In the model, the desulfurizer is simply a separator that removes H_2S and S with 100% efficiency without any energy-related implica-

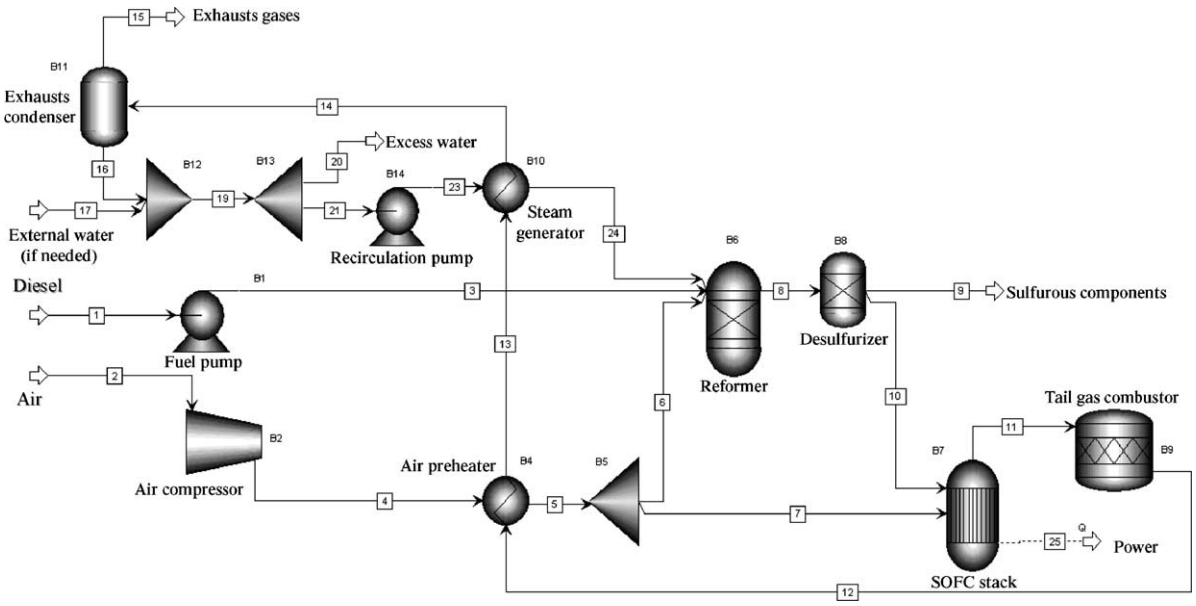

Fig. 1. Flow sheet of the SOFC-based APU.

tion. An SOFC stack model was developed to complete the APU system. The fuel cell stack is modeled in Aspen with an equilibrium reactor that recycles part of the output. The flow sheet of the system is shown in Fig. 1.

The conversion of hydrocarbon fuel to hydrogen can be carried out by three major techniques: steam reforming (SR), partial oxidation (PO) and autothermal reforming (ATR). Feeding fuel, water and air, together in the presence of a catalyst, ATR combines the heat effects of SR and PO reactions and external heat is not required. Autothermal reforming technology was chosen for simulations because of its potential in applications requiring compact, lightweight hardware capable of frequent start-up/shutdown cycles and variable processing rates [19]. Since kinetic models for the reforming of diesel are still in early stages [10,20], in this work the autothermal reformer is simulated with an equilibrium reactor based on Gibbs free energy minimization. This approach is commonly used in the simulation of fuel processing [21,22] and we validated the results with experimental data in the range of temperature 750–870 °C. The steam over carbon ratio is taken equal to 0.8 [10], while the amount of air is such that the net heat flux from the reactor is equal to zero at the fixed temperature (the reactor runs adiabatically).

The fact that diesel is a complex, multi-component (>100 components) fuel that exhibits varying reaction paths is one of the aspects that makes its reforming difficult. There are mainly two qualities of diesel fuel: grade no. 1-D and 2-D. The principal differences between these two fuels are the aromatic and sulfur contents [23]. Amphlett et al. [22] proposed a mixture of normal paraffins, alkylated benzenes and alkylated naphthalenes as surrogate for diesel. Ref. [22] assumed that no sulfur was present in the mixture to avoid secondary reactions in the reforming. This element was included and the percentage of the other components scaled. This mixture has similar properties (heat of formation, Gibbs free energy, and distillation curve) to diesel, but the equilibrium results from reforming did not fit the experimental data provided by Pereira et al. [23,24]. Surrogate mixtures that match both the physical properties of the real fuel (lower heating value, density and distillation curve) and the reforming output composition of the major species are highly desired. In order to fine-tune the equilibrium model to the experimental results two approaches were used:

(1) General temperature approach: using a temperature approach of ΔT means that the chemical equilibrium constant is actually evaluated at $(T + \Delta T)$, where T is the reactor temperature. This method is usually applied when the reactions do not reach the equilibrium at the specified temperature and the effect is to shift the results along the temperature axis.
(2) Optimization approach: involves modifying the composition of the surrogate diesel mixture while maintaining the original physical properties.

For grade no. 1-D diesel a simple temperature approach of −100 °C predicts correctly the composition of the major species except CO_2 at 750 °C that is about 20% overestimated. Therefore, for this case method (2) was not necessary. The difference in the properties with actual grade 1-D diesel is within reasonable tolerance. For grade no. 2-D diesel, a simple global temperature approach could not make the mixture satisfy the reforming output constraints given by experimental bounds. Therefore, a combined use of methods (1) and (2) was necessary. The major problem of using the original mixture from Ref. [22] is an overestimation of hydrogen output content at low temperatures (770 and 810 °C). Therefore, an

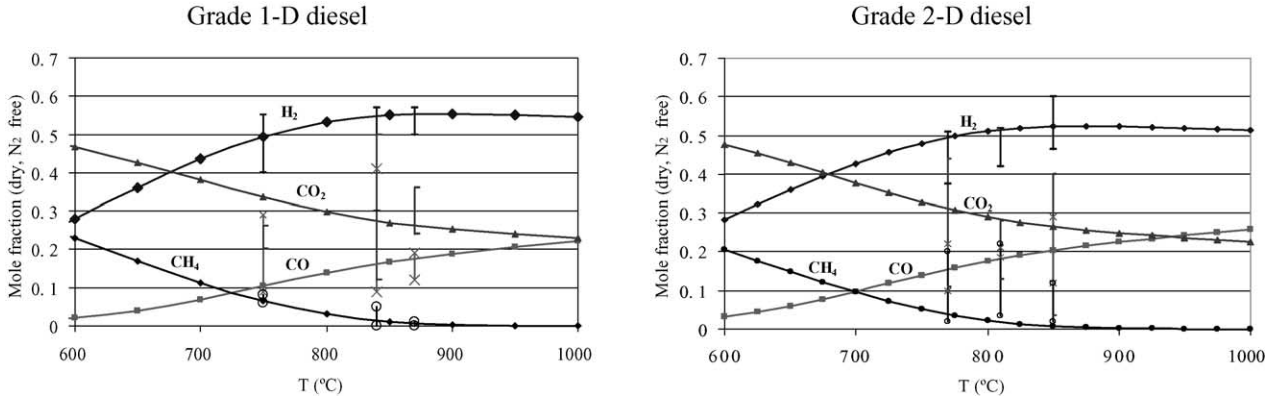

Fig. 2. Reforming output composition using surrogate mixtures. The vertical bars are the experimental bounds from Ref. [23]. Oxygen/fuel = 8, water/fuel=24, pressure = 5 bar (assumed).

optimization problem was set up in which the H_2 content in the reforming output at 770 °C is minimized. The decision variables were the mass fractions of the components in the diesel surrogate. The optimization was constrained so that the total aromatic content of the diesel surrogate was equal to 40% (wt.) and the sulfur content to 0.046% (wt.) [23]. The mixture resulting from the optimization together with a temperature approach of −75 °C gives final concentrations of chemicals inside the experimental bounds of grade no. 2-D diesel. Just CH_4 concentration at 810 and 850 °C is slightly underestimated. Fig. 2 shows the validation of the equilibrium results with experimental data for grade nos. 1-D and 2-D diesel. Table 1 summarizes the composition of the surrogate mixtures, in comparison with the one retrieved from Ref. [22].

As stated in Unnasch et al. [25] for autothermal processing of gasoline, the formation of ammonia, formaldehyde, NO_x, benzene and 1,3-butadiene is possible. The equilibrium composition of these components is in the order of ppm or even ppb, but there are no experimental data available to validate the results for these components. Therefore, the estimates from the equilibrium reactor are used as an approximation (this would generally provide an upper bound for emissions for NO_x [26]). The formation of light and medium hydrocarbons (ethane, propane, *n*-butane, pentane, hexane, heptane and octane), SO_x and carbon (C) was also allowed.

Table 1
Composition of diesel surrogate mixtures (mass fractions)

Component	Ref. [15]	1-D surrogate	2-D surrogate
S	0	0.000290	0.000460
N-Nonane	0.0122	0.012209	0.000000
N-Decane	0.0243	0.024317	0.000000
N-Undecane	0.0517	0.051737	0.002799
N-Dodecane	0.0912	0.091265	0.000000
N-Tridecane	0.2007	0.200843	0.112562
N-Tetradecane	0.1959	0.196039	0.125331
N-Pentadecane	0.098	0.098070	0.047898
N-Hexadecane	0.049	0.049035	0.022288
N-Heptadecane	0.0245	0.024517	0.058158
N-Octadecane	0.0122	0.012209	0.048171
N-Nonadecane	0.0061	0.006104	0.074874
N-Eicosane	0.0031	0.003102	0.107324
N-Pentylbenzene	0.0027	0.002702	0.025278
N-Hexylbenzene	0.0041	0.004103	0.004673
N-Heptylbenzene	0.0055	0.005504	0.000000
N-Octylbenzene	0.0058	0.005804	0.000000
N-Nonylbenzene	0.0059	0.005904	0.000000
N-Decylbenzene	0.0065	0.006505	0.000000
N-Undecylbenzene	0.003	0.003002	0.000000
N-Dodecylbenzene	0.002	0.002001	0.000000
Naphthalene	0.0302	0.030221	0.153674
1-Methylnaphthalene	0.0654	0.065446	0.145726
1-Ethylnaphthalene	0.0453	0.045332	0.070786
1-*N*-Propylnaphthalene	0.0322	0.032223	0.000000
1-*N*-Butylnaphthalene	0.0215	0.021516	0.000000

The methodology that was used to simulate the SOFC stack for impact assessment is similar to the one utilized by Geisbrecht [27]. An equilibrium reactor at fixed temperature performs heat and material balances on the cell and then, after flowsheet convergence, an Aspen calculator block computes voltage, current density and total cell area applying a polarization model.

Internal reforming is a common feature in solid oxide fuel cells because it provides additional cooling to the stack [28,29]. Methane and ethane are the most prevalent hydrocarbons in diesel reforming outlet and are supposed to react in the SOFC. Therefore, the reactions that take place in the cell are: methane and ethane steam reforming, carbon monoxide–water-shift and hydrogen electrochemical oxidation. The first three reactions are at equilibrium [30], while hydrogen oxidation has fixed extent in order to match the given fuel utilization. Fuel utilization is defined as:

$$U_f = \frac{H_2^{reacted}}{7C_2H_6^{in} + 4CH_4^{in} + CO^{in} + H_2^{in}} \quad (1)$$

where $H_2^{reacted}$ are the total moles of hydrogen reacted, $C_2H_6^{in}$, CH_4^{in}, CO^{in}, H_2^{in} are the moles of ethane, methane, carbon monoxide, and hydrogen entering the cell, 7 are the moles of H_2 generated by each mole of ethane, 4 are the moles of H_2 generated by each mole of methane and 1 is the mole of H_2 generated by each mole of CO. The electrochemical oxidation of CO was neglected because in presence of water the favorable path for the oxidation of carbon monoxide is generating hydrogen by the water-shift reaction [28,30].

At fixed temperature, a heat balance around the reactor gives the power output of the cell. Pyke et al. [31] considered heat losses through insulation of about 10% of the power output. Since the gross power of the stack of our interest is between 5 and 6 kW, a conservative value of 750 W was specified for heat losses. The power output divided by the current (known once the fuel utilization is fixed) gives the voltage of the cell. Current can be computed as:

$$I = 2FH_2^{reacted} = 2FU_f(7C_2H_6^{in} + 4CH_4^{in} + CO^{in} + H_2^{in}) \quad (2)$$

where I is the current and F is the Faraday constant (96485 C mol^{-1}).

An SOFC polarization model is used to find the current density of the cell at that given voltage. A one-dimensional, steady-state, algebraic polarization model derived from literature [32] was used for our study. This particular model was chosen because of its simplicity and comprehensive nature (applicability to every operating condition and sensitivity to the various design components of the cell). Moreover, the model describes an SOFC with flat-plate design that, according to Petruzzi et al. [30], will be used for APU applications. Overpotential equations, based on the complete Butler–Volmer and diffusion equations, are obtained together with the necessary parameters from Ref. [32]. This polarization model was tested with experimental results from Ref. [12]. As it can be seen in Fig. 3, even if the original cell parameters from Ref. [32] were kept (since no data were provided in Ref. [12]), the fitting between the model and the experimental data is acceptable.

Once the current density is obtained, current divided by current density gives the total cell area (area of the electrodes), important for cost estimations.

In the APU flowsheet there are three heat exchangers: the air preheater, the steam generator and the exhaust condenser. The air preheater and the steam generator are modeled in Aspen as heat exchangers in design mode. The overall heat transfer coefficient was set equal to 100 W m^{-2} K^{-1} for the steam generator [33] and 26 W m^{-2} K^{-1} for the air preheater [34]. For simplicity, the heat exchangers were modeled as countercurrent shell and tube, even if this may not be the preferred configuration in the reality. The ex-

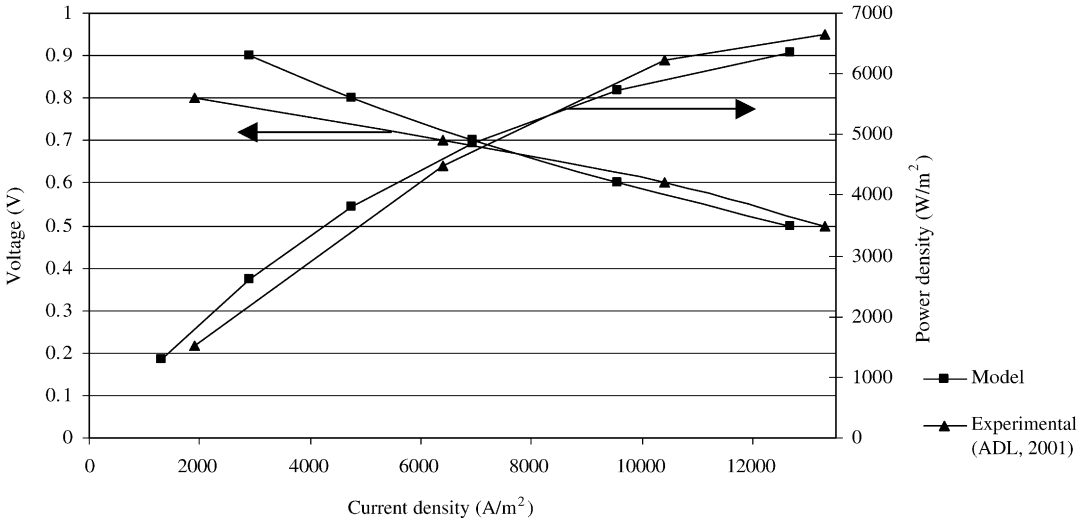

Fig. 3. Comparison between model and experimental data for a solid oxide fuel cell.

Table 2
Simulation details for base case design in Ref. [12]

	ADL "Base Case"
Fuel Utilization (%)	90
Cathode inlet air temperature (°C)	650
Cathode excess air (%)	760
Compressor pressure (atm)	1.28
Net power rating (W)	5008
SOFC temperature (°C)	800
Reformer temperature (assumed) (°C)	800
Steam/fuel mass ratio (assumed)	0.69[a]
Steam temperature (assumed) (°C)	260
Diesel (grade 1-D) intake (computed) (kmol h^{-1})	0.00621

[a] Corresponding to a mass Steam/Carbon ratio of 0.8 [3].

haust condenser was modeled with an isothermal flash at 30 °C.

The catalytic tail gas combustor is modeled with a stoichiometric reactor with fixed conversion that runs adiabatically. The reactions taking place in the reactor are the complete oxidation of methane, hydrogen, carbon monoxide and ammonia (giving nitrogen dioxide). According to Ref. [35], 60% of methane and 100% of hydrogen are converted in the burner. The conversion of carbon monoxide and ammonia is such that the concentration of CO in the outlet is 50 ppm and the concentration of NH_3 is 1 ppm [36]. Other species are not considered to react in the tail gas combustor since no experimental data have been found. The adiabatic temperature of the reactor is computed by the simulator.

The air compressor is simulated as isentropic compressor with efficiency equal to 0.72, while fuel and recirculation pumps have efficiency equal to 0.296 (Aspen default values).

The overall efficiency of the system is defined as the net power extracted from the cell over the lower heating value of the fuel entering the system:

$$\eta_{\text{overall}} = \frac{\text{Power}^{\text{out}}_{\text{SOFC}} - \text{Power}^{\text{in}}_{\text{compressor}} - \text{Power}^{\text{in}}_{\text{pumps}}}{\dot{m}_{\text{diesel}}\text{LHV}_{\text{diesel}}} \quad (3)$$

where $\text{Power}^{\text{out}}_{\text{SOFC}}$ is the power produced by fuel cell, $\text{Power}^{\text{in}}_{\text{compressor}}$ and $\text{Power}^{\text{in}}_{\text{pumps}}$ are the power required by the air compressor and the two pumps, $\dot{m}_{\text{diesel}}$ is fuel flow rate and $\text{LHV}_{\text{diesel}}$ is the specific lower heating value of the fuel (calculated by the simulator).

The results in terms of efficiency and fuel cell performance are compared with the ones predicted by the detailed model developed by A. D. Little [12] in the base-case configuration. Details about the input parameters are given in Table 2. The matching between the data from the two models is very good: the APU model proposed in this paper predicts a system efficiency of 37.4% and cell voltage of 0.69 V; while the model by ADL, a system efficiency of 37% and a cell voltage of 0.7 V.

3. Cost modeling

Estimating the cost of the fuel cell-based system is an important task of the framework. A simplified cost model where cost estimates of SOFC-based Auxiliary Power Units are sensitive to a few major performance parameters has been developed. This dependence is important in identifying trade-offs between cost and other objectives.

There are not many fuel cell cost models available in the published literature, especially referring to SOFC-based Auxiliary Power Units. Most of the works concerning the use of fuel cells in the transportation sector deal with Proton Exchange Membrane (PEM) fuel cells for pure or hybrid fuel cell vehicles. Ekdunge and Råberg [37] analyzed, using a dynamic model, energy consumption, emissions and cost of PEM fuel cell vehicles running on different primary fuels. Xue and Dong [38] used the Ballard Mark V Transit Bus fuel cell system to find the optimal design that maximizes performances and minimizes production costs. Barbir and Gómez [39] studied the relationship between efficiency and economics (capital cost and cost of hydrogen) of PEM systems for various load profiles and development scenarios. Jeong and Oh [40] addressed the problem of the whole life cycle cost of fuel cell vehicles, including vehicle cost and fuel cost. Ogden et al. [41] also considered externality costs for oil supply security and damage cost for emissions of pollutants. Hackney and de Neufville [42] included cost considerations in their life cycle model of alternative fuel vehicles. Teagan et al. [43] explored the effect of different fuel processing options on the cost reduction of fuel cells for transport applications. ADL [44] and DTI [45,46] developed detailed manufacturing cost estimates of PEM fuel cells systems for automotives. The different assumptions of the two previous cost models were analyzed by Bar-On et al. [47]. Khandkar et al. [48] and Woodward [49] implemented performance-based cost models of Solid Oxide Fuel Cell (SOFC) systems. ADL [50] addressed, specifically, the case of planar SOFC technology. The only detailed study on the cost of SOFC 5 kW systems comprehensive of fuel cell stack, fuel reformer and balance of plant has been found in a report by ADL [12] prepared for the U.S. Department of Energy. Therefore, this study forms the basis of the cost models presented in this work.

What makes the cost evaluation of SOFC-based APU difficult is the fact that this system is similar to a chemical plant in a very small scale (about 100 l). This means that the normal procedures and factors used in plant cost estimation do not apply here.

The manufacturing cost of the full system can be decomposed in the bare cost of each component and fixed costs. The former, which reflects the direct cost, includes raw material and processing of each piece of equipment and it is dependent on a characteristic measure of the unit (the choice of just one parameter was made for simplicity). The production volume that was considered is around 500,000 pieces per year [12]. The second component instead—which includes equip-

ment, plant depreciation and maintenance, tooling amortization, utilities, indirect labor and cost of capital—was added as a percentage of the first category. According to the data in Ref. [12], indirect costs were set to be 8.6% of total direct cost. Profits, research and development, sales and marketing expenses, general and administration expenses and taxes are not included in the cost estimate.

The units considered in the Aspen model are ATR reformer (with desulfurization unit included), SOFC stack, catalytic burner, air compressor, fuel pump, recirculation pump, high temperature heat exchanger, steam generator and exhaust condenser. The cost of each of these units was estimated independently (the modeling equations are summarized in Table 2), while the cost of other devices not considered in the Aspen model, such as insulation, controls and electrical, piping etc., was added as a fixed value not dependent on any design parameter (US$ 450 according to Ref. [12]). On top of that installation cost was considered (US$ 1500 according to Ref. [51]).

One of the simplest possible methodologies to estimate the cost of the solid oxide fuel cell is to consider a single parameter to characterize the stack. The area of the cell appears to be a suitable measure to base the cost model on. A. D. Little [50] derived area-based cost estimates of SOFC devices analyzing different possible production pathways. The predicted cost is US$ 429 m^{-2}. This estimate was used by the same authors to predict the cost of 5 kW systems [12].

The only cost estimate for an autothermal reformer for automotive application was found in a study conducted by Directed Technology Inc. [45]. Since DTI considered a PEM technology for propulsion, the dimension of the system was different from the case of this study. Therefore, the cost of the reformer was scaled using an exponential cost-capacity factor [52]:

$$C_x = C_k \left(\frac{E_x}{E_k} \right)^y \tag{4}$$

where C_x is the unknown cost of a piece of equipment size E_x, C_k is the known cost of a piece of equipment size E_k and y is the cost-capacity factor. Total volumetric feed-flow rate—which is equivalent to the reactor volume if fixed space velocity in the reactor is considered—was used as characteristic measure (E). Even if the cost-capacity factor y has an average value of 0.6, it can vary over a wide range [46]. Therefore, it was decided to get its value through regression of available data. As already discussed, ADL performed a cost analysis of 5 kW SOFC systems [12]. In that study, the fuel considered was gasoline and the reformer was a POX (preferential oxidizer), but these differences are not relevant for the level of detail that is requested here. Two cases analyzed in [12] were simulated in order to get the total volumetric feed-flow rate of the reformer. Regressing those data with the model given by Eq. (4), a cost-capacity factor of 0.94 is obtained. The methodology that was used to estimate the manufacturing cost of the catalytic tailgas burner is completely analogous.

The equation that is commonly used to estimate the cost of compressor is given below [53]:

$$C_{\text{compressor}} = A P^{0.82} \tag{5}$$

where A is a multiplicative factor and P is the power which is required. Since the dimension of the compressor in the APU system is much smaller than the dimension of compressors commonly used in process industry, the value of the multiplicative factor was derived from regression of data again from Ref. [12].

According to Ref. [53] the cost of heat exchangers follows the equation:

$$C_{\text{heat exchanger}} = B \times \text{Area}^{0.65} \tag{6}$$

where B is a multiplicative factor and Area is the required exchange area. The value of the multiplicative factor B is obtained with a regression of the data from Ref. [12]. The cathode air pre-heater and the steam generator are modeled in Aspen as heat exchangers and so, the value of the exchange area can be retrieved directly from the process simulator; the exhaust condenser is modeled as a flash and so, the value of the exchange area has to be computed indirectly. The procedure is derived from Ref. [54] assuming the overall heat transfer coefficient equal to 37.5 $W m^{-2} K^{-1}$ [35].

As in Ref. [12], the cost of the fuel pump was considered constant and equal to US$ 109 per pump. The recirculation pump was assumed equal to the fuel pump.

The operating cost includes the cost of fuel and maintenance. In Ref. [51] regular maintenance cost is estimated in US$ 0.05 h^{-1} and this value was used in this study. The maintenance of the desulfurizer has to be added to regular maintenance, since the zinc oxide bed needs periodical replacements. According to Ref. [55] a 1.5 l zinc oxide bed can accumulate 422.37 g of sulfur. Dividing this value by the grams of sulfur per hour extracted from the fuel (retrieved from Aspen simulation), it is possible to calculate how often the bed has to be replaced in 5 years (9090 h) of operation. The cost of a new zinc oxide bed has been estimated in US$ 50 [12].

The cost of fuel is considered over the entire life time of the device, considered 5 years with 6 h per day for 303 days per year operation [1]. This estimate is in line with Ford's [18] performance goal for this kind of systems (>8000 h). Since the time period that is simulated is 2010–2015, an estimate of the average price of diesel in that period is needed. Diesel price can be modeled as a stochastic process, since it is a variable that evolves over time in a way that is, in part, random [56]. Among the different possible continuous-time stochastic processes, "Brownian motion with drift" is the one that fits better, since over the long haul diesel price has a positive expected rate of growth [57]. The predicted average price of diesel in the period 2010–2015 is US$ 2.46 per gal.

Since the technology is not yet at commercial stage, process contingencies have to be included. For SOFC-based

Table 3
Summary of the cost modeling equations

	Cost model component	Cost (US$)
C_1	SOFC stack	429 cell area [m^2]
C_2	Autothermal reformer + desulfurizer	13.79 (feed [$m^3\,h^{-1}$])$^{0.94}$
C_3	Tailgas catalytic burner	0.46 (feed [$m^3\,h^{-1}$])$^{0.82}$
C_4	Air compressor	256.3 (power [hp])$^{0.82}$
C_5	Heat exchangers (3×)	32.5 (area [ft^2])$^{0.65}$
C_6	Fuel and recirculation pumps (2×)	109
C_7	Balance of system	450
C_8	Indirect costs	$0.086 \sum_{i=1}^{7} c_i$
C_9	Installation	1500
C_{10}	Contingencies	$0.3 \sum_{i=1}^{7} c_i$
C_{11}	Regular maintenance	454.5
C_{12}	Desulfurizer maintenance	50 (Int (21.52 $\dot{m}_S$[$g\,h^{-1}$]) + 1)
C_{13}	Fuel cost	22361.4 V_{diesel} [$gal\,h^{-1}$]
	Total cost	$\sum_{i=1}^{13} C_i$

APUs, 30% contingency costs (pilot/demonstration stage) seems to be a sensible value. Table 3 gives a summary of the equations in the cost model.

4. Conclusions

Fuel cells are an important technology for a potentially wide variety of applications. However, the benefits of fuel cell technology in terms of health and environmental impacts as compared to efficiency and cost effectiveness have not been systematically studied. An integrated framework that can automatically identify and quantify trade-offs between cost effectiveness, efficiency and environmental & health impacts of fuel cell power systems has been developed. The integrated framework has been applied to the case of SOFC-based auxiliary power units. Auxiliary power units are devices that can provide all or part of the non-propulsion power for vehicles (space conditioning/heating, refrigeration, lighting, etc.) offering a high-efficiency (equivalent to low consumption), low emission, and low-noise alternative that would supplant the need for engine idle. The entire system, comprehensive of fuel processing and fuel cell device, has been simulated in Aspen Plus, which constitutes the base model of the integrated framework. Whenever available, the modeling results have been compared to experimental data and other models published in the literature showing good agreement. The steady-state simulations that have been performed were useful to compute system efficiency, regular running emissions and size of the main equipments. The other component of the framework described in this paper is useful to quantify costs. A simplified cost model, where cost estimates of SOFC-based auxiliary power units are sensitive to a few major performance parameters, has been developed with the help of regression analysis. The other components of the integrated framework will be presented in part II.

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