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Life cycle assessment of fuel cell-based APUs

Francesco Baratto, Urmila M. Diwekar*

Center for Uncertain Systems: Tools for Optimization and Management, Departments of Bio, Chemical,
and Industrial Engineering, Institute for Environmental Science and Policy, University of Illinois
at Chicago, MC 063, 851 S. Morgan St., Chicago, IL 60607, USA

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Abstract

Fuel cell-based auxiliary power units (APUs) are devices meant to reduce fuel consumption and pollutant emissions when the vehicle engine is used for non-propulsion purposes (space conditioning/heating, refrigeration, lighting, etc.). This paper examines for this new technology the life cycle assessment (LCA) and the comparison with the existing technology, which is commonly idling of diesel engines. Life cycle assessment provides the cumulative impact resulting from all the stages of the product life. Through this analysis it was possible to demonstrate that life cycle emissions cannot be neglected in the impact assessment of fuel cell-based auxiliary power units. However, even considering those emissions, the total amount of pollutant that is released is much less than in the case of idling of diesel engines. SOFC-based APUs showed great potential in terms of human health and environmental impacts reduction if compared to the existing technology and the payback period has been estimated in just a little more than two years.

Keywords: SOFC-based APUs; Life cycle assessment; Idling of diesel engines

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1. Introduction

This paper is the last of a series of publications [1–3] on the impacts assessment and trade-offs of fuel cell-based auxiliary power units (APUs), a new technology meant to reduce fuel consumption and pollutant emissions when the vehicle engine is used for non-propulsion purposes. APUs and, in particular, fuel cell powered APUs will most likely supplant the need for engine idle. When a new technology is proposed, two aspects are of particular importance: to study the complete life cycle of the device and to compare the benefits with the existing technology. This paper addresses these fundamental issues.

The first aspect aforementioned, the life cycle study, is necessary not to neglect important sources of pollutants different from the operation of the device. Life cycle assessment (LCA) is a technique for assessing all the inputs and outputs of a product, process, or service and enables the estimation of the cumulative environmental impacts often including impacts not considered in more traditional analysis (e.g. electricity production, raw material extraction, material transportation, product disposal, etc.).

The results of the life cycle analysis are shown and discussed in the first section after this introduction. These data together with the results of the optimization of the system presented in earlier paper [3] are then used to compare the performances of fuel cell-based APUs with the existing technology. In particular, since the first application of fuel cell-based APUs is predicted to be on heavy-duty trucks, the comparison will be with idling of big displacement diesel engines. The case study that is considered is South California Air Basin in 2010 [3]. Environmental, human health and cost impacts are taken into consideration. These aspects are addressed in the third section of this paper.

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* Corresponding author. Tel.: +1 312 355 3277; fax: +1 312 996 5921.
E-mail address: urmila@uic.edu (U.M. Diwekar).

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2. Life cycle assessment of an SOFC-based APU

2.1. Previous contributions

There are number of papers published that presents complete life cycle of various fuels and fuel cells used in transportation sector. MacLean and Lave [4] made a detailed summary of all the work that has been done on the life cycle implications of a wide range of fuels and propulsion systems that could power cars and light trucks in the U.S. and Canada over the next two to three decades. Pehnt [5,6] published a paper in two parts in which he compared the life cycle impact of a PEM-based passenger car with a conventional internal combustion engine vehicle. The geographical coverage for this study is Germany and the reference time period is 2010. The first part of the paper, which covers mainly methodological aspects, includes the example of manufacturing a 24 kW planar SOFC stack. Weis et al. [7] described in a report the work done at MIT to assess technologies for new passenger cars that could be developed and commercialized by the year 2020. Again, Weis et al. [8] in another MIT report compared the life cycle of different fuel cell vehicle configurations. Some of the earliest Life Cycle Inventory (LCI) models for alternative fuel/propulsion system options were developed by Mark Delucchi at University of California at Davis during the period 1987–1993. Delucchi has continued to update his work [9]. Delucchi's spreadsheet model predicts emissions of greenhouse gases (GHG) and criteria pollutants from a large number of alternative fuel/vehicle options. The model is comprehensive in scope including fuel cycles, vehicle operation, manufacture, service, etc., in predicting GHG and criteria pollutants.

Concerning the life cycle of the fuel alone, Contadini et al. published three papers on this topic. The first paper [10] deals with the methodology, while the other two [11,12] focus mainly on uncertainties in LCA. A model called Fuel Upstream Energy and Emission Model (FUEEM) is developed to analyze life cycle impacts of future fuel cell vehicles and fuels. Michael Wang of Argonne National Laboratory has produced another life cycle model [13] named Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) that will be discussed later more in detail. Hackney and de Neufville [14] developed and presented a LC spreadsheet model for comparing criteria pollutant, GHG emissions, energy use and cost of alternative fuel/vehicle options.

Zapp [15] performed an environmental analysis of solid oxide fuel cells, from the production of raw materials and technical equipment to operation and dismantling. This study deals with fuel cells for stationary applications. Karakoussis et al. [16] studied the environmental impact of manufacturing SOFC systems. The planar SOFC configuration refers to small-scale power units in the range 1–10 kW, like the one considered in our work. More details about Karakoussis' study are given in a report of the Imperial College of London [17] for the New and Renewable Energy Programme.

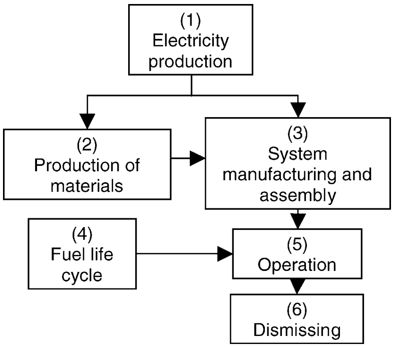

Fig. 1. Conceptual diagram of an APU system life cycle in six stages.

2.2. Boundaries of the study

The life cycle of an SOFC-based APU is defined to include all the steps required to provide the fuel, to manufacture the device, and to operate and maintain the vehicle throughout its lifetime up to disposal and recycling. Fig. 1 shows the stages of the APU life cycle considered in this study.

The life cycle stages of an SOFC-based APU system can be grouped in four components: system production (which includes stage (1), (2) and (3)), fuel life cycle, system operation and dismissing. Different models have been used for the different stages of the life cycle. The system production was adapted from several LCA databases and studies. The fuel life cycle was based on the GREET model [13] by Argonne National Laboratory. The system operation is evaluated by the Aspen model of the device described in [1]. There are no data available regarding future end-of-life management scenarios and so for the purpose of this study the potential for reuse and recycling of individual cells has not been studied.

2.3. System production

This part of the life cycle is mainly based on the work in Ref. [17] and it was carried out with the help of the LCA software tool SimaProTM 5.1 [18]. The following are the boundaries and the main assumptions of the study:

- The study does not take into consideration the energy and the materials input required for the manufacturing of the equipment used in the production of the fuel cell system. Also the impact from land use for the installation of the fuel cell system manufacturing plants is not included.
- The study assumes that internal transport within the fuel cell manufacturing plant is insignificant.
- The material losses from the different manufacturing stages (process efficiencies) could not be quantified and so they were not taken into consideration. This limitation of the study may require in future further investigation.
- For the calculation of energy-related emissions, energy is considered as electricity with production mix as in the U.S. according to IDEMAT 2001 database [19].

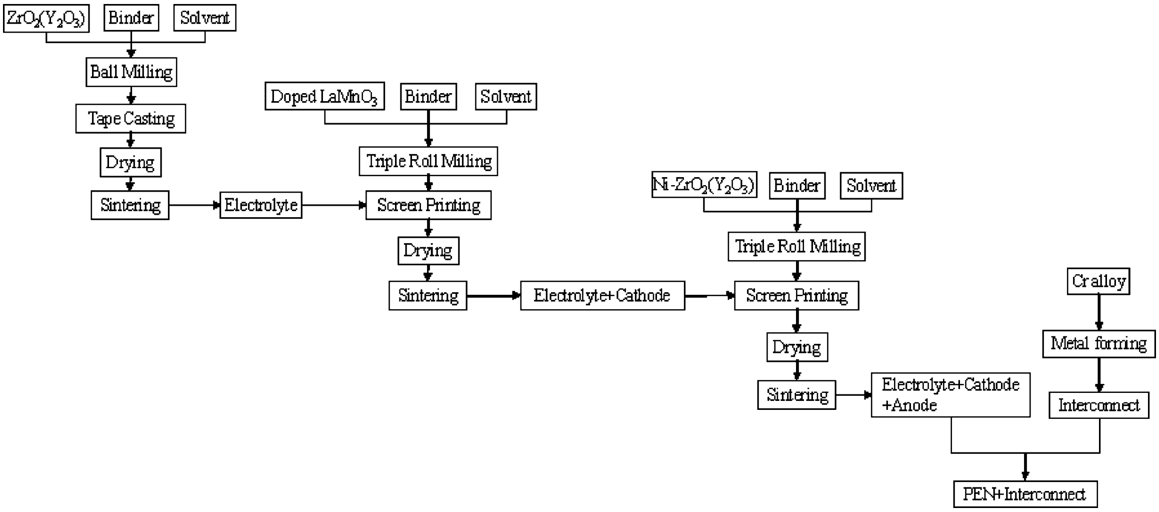

Fig. 2. Manufacturing of the PEN and interconnect for planar SOFC according to Ref. [14].

- The analysis of materials for the manufacturing of the balance of plant composes at least 95% of the mass of the component analyzed.
- For the manufacturing of the balance of plant a generic approach has been adopted and the analysis of this category is less detailed than the analysis of the fuel cell manufacturing, where every individual step of the process is taken into consideration.

As in Ref. [17] this study focuses as case study on the small-scale Sulzer HEXIS system [20], which is aimed to power units in the 1–10 kW range and has a planar configuration. The cells are considered to have a power density of 0.2 W cm^{-2} [17], and so the stack contains about 50 ceramic plates of 100 cm^2 per kW produced. This is a conservative assumption, since projections estimate a power density of 0.5 W cm^{-2} [17] or greater as a future target. The manufacture of flat plate SOFC is characterized by wet chemical processing of ceramic oxide powders for electrolyte, cathode and anode. A flow diagram for the production of a single SOFC cell is shown in Fig. 2. Tables 1 and 2 present the energy and materials inputs for the various stages of the cell manufacturing. Data are specific per kW of power produced by the fuel cell.

The balance of plant includes casing, air and fuel supply systems, desulfurizer, air preheater, fuel reformer, heat exchangers and tail gas burner. In Ref. [17] an AC/DC converter is considered, but this device is not included in an APU system. It was assumed that the same material and energy values are representative for controls and electrical devices in the APU.

In Ref. [17] nickel is assumed as reformer catalyst. This is not the usual catalyst for diesel reforming (which is commonly Pt–Rh–Pd/Al_2O_3 [22]), but no data were found on the amount of catalyst needed for diesel processing and so that assumption was kept. Moreover the use of nickel as diesel-reforming catalyst is currently studied [23]. No catalyst was assumed for the tail gas burner. Tables 3 and 4 show materials and energy inputs for the manufacturing of the balance of plant. Data are specific per kW of power produced by the fuel cell.

Table 1
Materials inputs for the manufacturing of planar SOFC

Material	Quantity (kg kW^{-1})	Reference for LC emissions
$ZrO_2(Y_2O_3)$	4.0310	[17]
Polyvinil butyral	0.2110	[17]
Ethanol	0.7477	[17]
Trichloroethylene	1.5665	[17]
Polyethylene glycol 200	0.1939	[17]
Dibutyl phthalate	0.1669	Dimethyl *p*-phthalate ETH ETH-ESU 1996 [21]
Ni–$ZrO_2(Y_2O_3)$	0.1167	[17]
Doped $LaMnO_3$	0.1279	[17]
Cr alloy	13.4130	Chromium ETH S ETH-ESU 1996 [21]

Table 2
Energy inputs for the manufacturing of planar SOFC

Process stage	Energy input (MJ kW^{-1})[a]
Ball milling	0.95
Tape casting	0.07
Drying	1.71
Sintering	10.53
Preparation of cathode ink	0.14
Screen printing	0.13
Drying	1.71
Sintering	8.60
Preparation of anode ink	0.15
Screen printing	0.13
Drying	1.71
Sintering	8.60
Metal forming interconnect	0.43

[a] All the data are retrieved from Ref. [17].

Table 3
Materials inputs for the manufacturing of the balance of plant

Material	Component	Quantity (kg kW^{-1})[a]	Reference for LC emissions
Steel	Casing	10	Steel ETH S ETH-ESU 1996 [21]
	Air supply system	10	
	Fuel supply system	10	
	Desulfurizer	0.5	
	Reformer	5	
	Heat exchangers	2	
	Tail gas burner	5[b]	
Zinc	Desulfurizer	0.1	Zinc I IDEMAT 2001 [19]
Nickel	Reformer	0.5	Nickel I IDEMAT 2001 [19]
Incaloy	Heat exchangers	2	NiCu30Fe I IDEMAT 2001 [19]
Aluminum	Controls and electrical devices	0.3	Aluminum 0% recycled ETH ETH-ESU 1996 [21]
Purified silica	Controls and electrical devices	0.004	[17]
Plastic	Controls and electrical devices	0.02	PVC emulsion polymerization: a Boustead Consulting [24]
Copper	Controls and electrical devices	0.006	Copper ETH S ETH-ESU 1996 [21]

[a] Unless specified, the source is Ref. [17].

[b] The size of the tail gas burner is assumed equal to the size of the reformer, as in Ref. [25]. The original value in [17] is 50 kg kW^{-1}, which apparently refers to a different system.

Tables 5–7show the results for life cycle emissions to air, water and soil from the manufacturing of a 5 kW stack. As already stated, no reuse, recycling or waste treatment has been considered. Only the emissions greater than 5 g are shown. Since data comes from different databases, different levels of aggregation may be found. Unless evidently referring to the same substance, components with different names have been kept separated. All the data have a high degree of uncertainty. The effects of this uncertainty should be object of further investigation.

Table 4
Energy inputs for the manufacturing of the balance of plant

Component	Energy input (MJ kW^{-1})[a]
Casing	11.2000
Air supply system	11.2000
Fuel supply system	11.2000
Desulfurizer	0.8099
Reformer	12.8850
Heat exchangers	4.7040
Tail gas burner	56.0000
Controls and electrical devices	4.3329

[a] All the data are retrieved from Ref. [17].

Table 5
Total airborne life cycle emissions from the manufacturing of a 5 kW SOFC system

Substance	Unit	Emission
CO_2	kg	1630
SO_x	kg	23.910
CO	kg	6.9
Methane	kg	3.75
NO_x	kg	3.199
Dust (coarse) process	kg	2.334
Dust (PM10 and SPM)	kg	1.269
General VOC	kg	1.136
Soot	g	334
Particulates (unspecified)	g	206
HCl	g	125
General hydrocarbons	g	142.7
K	g	45
HF	g	43.1
Si	g	35.1
N_2O	g	30.4
N_2	g	25
Fe	g	24.1
Ethane	g	21.6
CFC-14	g	19.8
Al	g	17.8
Pentane	g	16.3
Propane	g	15.9
H_2S	g	14.5
Butane	g	12.9
Mn	g	11.7
Xylene	g	10.2
He	g	8.66
V	g	8.02
Ethene	g	7.93
Zn	g	6.57
Mg	g	6.29
Alkanes	g	5.33

2.4. Fuel life cycle

This part of the life cycle is based on the work by Wang [13] at Argonne National Laboratory. Michael Wang's work dates back to 1995 and has been updated with additional information, parametric assumptions, fuels, and vehicle options. GREET, as Wang's model is called, estimates energy use (total, fossil, petroleum) and emissions (GHG and criteria pollutants) resulting from the LC of alternative transportation fuels and vehicles. GREET model performs what it is called a Well-To-Wheels (WTW) analysis, which includes the feedstock, fuel and vehicle operation stages. The feedstock and fuel stages together are called "Well-To-Pump" (WTP) or "upstream" stages, and the vehicle operation stage is called the "Pump-To-Wheels" (PTW) or "downstream" stage. Only the first part of this study (WTP) has been considered for our purposes, since the operation of the device is simulated by the Aspen model presented earlier.

With the help of GREET graphical interface [26] we set up a simulation with the following assumptions:

- Diesel fuel with 290 ppm of sulfur
- California as location for use

Table 6
Total waterborne life cycle emissions from the manufacturing of a 5 kW SOFC system

Substance	Unit	Emission
Metallic ions	kg	15.7
Inorganic general	kg	8.88
Cl^-	kg	8.78
Sulphates	kg	3.999
Na	kg	2.75
Calcium ions	g	802
Al	g	711
Mg	g	585
Undissolved substances	g	572
TOC	g	416
Fe	g	335
Dissolved solids	g	511
Salts	g	288
K	g	243
Baryte	g	137
Fats/oils	g	120
Ba	g	72.5
Suspended solids	g	66.57
Sr	g	46.6
Fluoride ions	g	43.6
Phosphate	g	42.6
Ti	g	42.5
COD	g	36.1
Fatty acids as C	g	32.1
BOD	g	27.8
Mn	g	15.3
NH_3 (as N)	g	11.9
Nitrate	g	11
Zn	g	9.72
Pb	g	8.26
Cr (III)	g	7.76
N-tot	g	7.5

- California electricity generation mix
- Default values for all the other parameters (for details refer to [27])

The results from GREET model are given in grams per mm Btu of fuel available at the station pump. These values were converted in grams per gallon of diesel using 138,496 Btu gal^{-1} as diesel energy content [28]. The results are shown in Table 8.

Table 7
Total life cycle emissions to the soil from the manufacturing of a 5 kW SOFC system

Substance	Unit	Emission
Minerals	kg	2.77
Slag/ash	g	625
Inert chemicals	g	470
Mixed industrial	g	49.1
Regulated chemicals	g	43.9
Ca	g	35.7
C	g	27.6
Fe	g	17.9
Al	g	8.92
Oil	g	5.54
S	g	5.37

Table 8
Results for diesel life cycle using GREET model

Pollutant	WTP emission in g gal^{-1} of diesel
CO_2	180.6957
CH_4	1.3978
N_2O	0.0031
VOC	0.1066
CO	0.1590
NO_x	0.3755
PM_{10}	0.0325
SO_x	0.1870

2.5. *Relevance of life cycle emissions*

Life cycle emissions have been compared to the emissions during the operation of an SOFC-based APU over a lifetime (9090 h of operation [1]) in order to establish the importance of the life cycle study. The “minimum cost” design among the multi-objective designs of Ref. [3] is used as benchmark. The input parameters of this configuration are presented in Table 9.

Table 9 shows the values of emissions during operation, principal airborne emissions from system manufacturing and diesel life cycle emissions. The fuel consumption for the design that we considered is equal to 0.297 gal h^{-1}, which corresponds to 2701.8 gal over the lifetime. For manufacturing emissions dust and soot were aggregated in the general entry “particulate” and different hydrocarbons (according to EPA definitions [34]) in the general entry “VOC”. For operation emissions, the only VOC produced is formaldehyde.

With the exceptions of carbon dioxide and ammonia, for which diesel LC and system LC represents a small percentage of total emissions, life cycle considerations cannot be neglected in the release of the other species. Manufacturing of the APU design is responsible for 36% of the carbon monoxide and 27% of the NO_x liberated to the atmosphere. VOC, SO_x, N_2O, and particulate are produced almost exclusively during the system life cycle. Methane emissions are evenly distributed between diesel and system life cycle.

Therefore, life cycle emissions are important in the study of environmental and health impacts of SOFC-based APUs.

Table 9
Input parameters of the “minimum cost” design

System pressure (bar)	1.20
Reformer temperature (°C)	821.82
Fuel utilization	0.79
Air preheating (°C)	626.61
Diesel intake (kmol h^{-1})	0.00484
SOFC air stoichiometric ratio	3.01
Steam/diesel ratio in the reformer	0.69
Steam temperature	260
Cell voltage (V)	0.9
Cell current density (A m^{-2})	1967.7
Cell temperature (°C)	800

Table 10
Emissions from operation over a lifetime, fuel life cycle, and system life cycle

Pollutant	Operation (kg)	%	Diesel LC (kg)	%	System LC (kg)	%
CO_2	25033.3	92.2	488.2	1.8	1630.0	6.0
CO	11.9	61.8	0.4	2.2	6.9	36.0
NO_x	7.6	64.3	1.0	8.6	3.2	27.1
NH_3	0.130	97.5	0.0	0.0	0.003	2.5
VOC	0.0028	0.2	0.288	17.1	1.389	82.7
CH_4	0.0004	0.0	3.777	50.2	3.750	49.8
SO_x	0.0	0.0	0.505	2.1	23.910	97.9
Particulate	0.0	0.0	0.088	2.1	4.143	97.9
N_2O	0	0.0	0.008	21.6	0.030	78.4

3. Comparison with idling of diesel engines

In this section idling of diesel engines is compared with the operation of SOFC-based APUs. The "minimum cost" design from Ref. [3] is chosen again for comparison purposes in order to show the potential impacts of this new technology for an economically favorable configuration.

Emissions from idling of diesel engines can be seen in Table 10. Since the category "hydrocarbons" was too general for environmental and health impacts assessment, some assumptions had to be made. Ref. [29] gives an analysis of the hydrocarbon composition of diesel exhausts. For each hydrocarbon category one or two components (the most relevant) were taken as reference. Tables 11 and 12 show the composition of diesel exhausts.

3.1. Human health and environmental impacts

Using the same methods described in [1,2], environmental and health impacts were computed for idling of internal combustion engines. The case study is South California Air Basin in 2010 as described in Ref. [3].

Fig. 3 shows the results in terms of potential environmental impact. As it can be seen the total output potential environmental impact (PEI) for diesel engines is 3 orders of magnitude greater than in the case of SOFC APUs. Aquatic toxicity potential is still the major contribution to total PEI, but in the case of diesel engines all the impact categories (except ozone depletion potential) are important. The impact category with the biggest difference between the two cases is photochemical oxidation potential, due to higher emissions of hydrocarbons (aldehydes in particular).

Table 11
Emissions from idling of a diesel engine

Component	Emission ($g\,h^{-1}$)	Reference
Hydrocarbons	12.55	[30]
CO	94.30	[30]
CO_2	8224.00	[31]
NO_x	144.00	[31]
PM10	2.57	[30]

For dispersion modeling, a volumetric flow rate of the diesel engine exhausts equal to 0.12262 $m^3\,s^{-1}$ [31] at a temperature of 300 °F [32] was considered. Stack height and diameter are the same as for SOFC-based APUs (4 m height and 20 cm diameter). The results of the health risk assessment can be seen in Fig. 4. In all the categories there are several orders of magnitude of difference between idling of diesel engines and SOFC-based APUs. In almost all the categories idling of diesel engines is beyond the acceptable values (red lines in the graph). Cancer risk in particular is very high mainly because of the emissions of particulate matter (PM_{10} and $PM_{2.5}$), but also for the release of benzene and aldehydes.

In Section 2 it has been shown that life cycle emissions are important in the study of impacts assessment of SOFC-based APUs. However, even considering these emissions, the total amount of pollutants that are released is lower than in the case of idling of diesel engines considering diesel life cycle. As it can be seen in Table 13, a reduction from 64% to 99% of all the major pollutants is achievable. This result is of particular importance, especially regarding NO_x and particulate which are the major emissions from diesel engines.

3.2. Cost impact

The average fuel consumption of an idling diesel engine is estimated as 0.82 gal h^{-1} [31], while the predicted diesel intake of an SOFC-based APU with the minimum cost design is 0.297 gal h^{-1}. Assuming that the diesel engine and the SOFC-based APU are producing the same net power output (5 kW), the fuel consumption of the internal combustion

Table 12
Simplified composition of the hydrocarbon part of diesel engine exhausts

Compound	Composition (wt.%)	Emissions ($g\,h^{-1}$)
n-Butane	11.4	1.431
Benzene	3.2	0.396
Toluene	4.6	0.575
Formaldehyde	17.3	2.169
Acetaldehyde	32.4	4.067
Acrolein	10.2	1.286
Acetone	10.8	1.360
Butanone	3.7	0.464
Benzaldehyde	2.7	0.343
Acetophenone	3.7	0.460

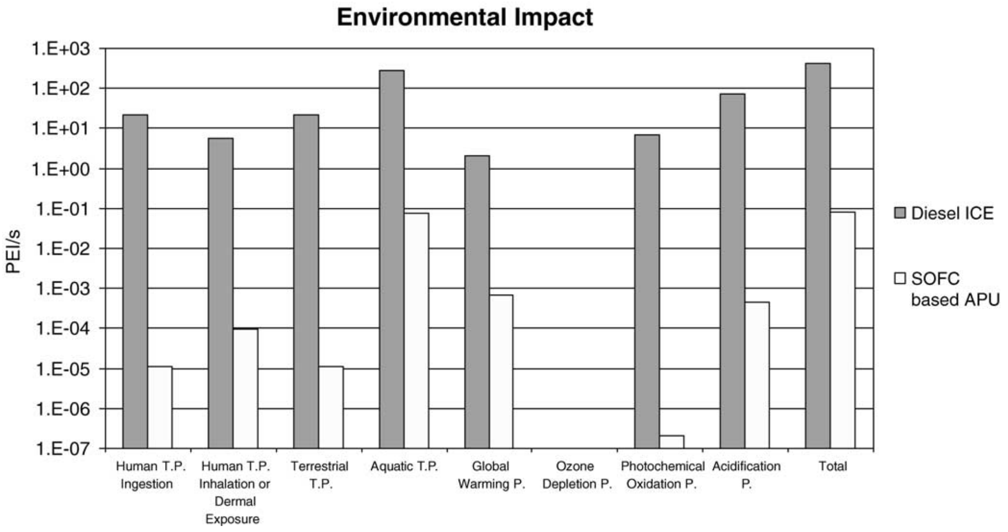

Fig. 3. Comparison between output rates of PEI ($1\,\mathrm{s}^{-1}$) for each category impact for idling of diesel engines and SOFC-based APUs.

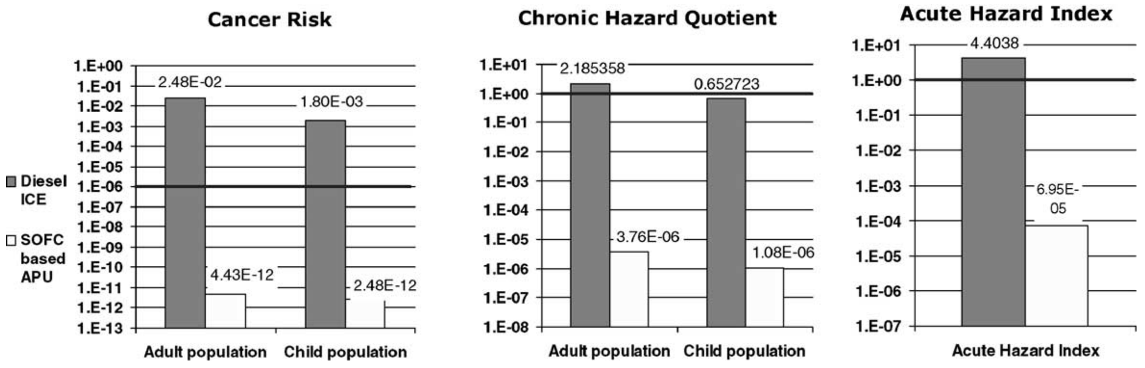

Fig. 4. Comparison between idling of diesel engines and SOFC-based APUs in terms of health impacts. The horizontal lines represent the limit of safety regions.

engine is 2.76 times higher. This means that the efficiency is 2.76 times lower (17% versus 47%). Therefore, the cost associated with the fuel cell APU system is balanced by fuel saving.

A brief economic analysis was carried out to determine the payback period for the fuel cell APU. The net present value (NPV) predicts what an investment today, with costs and benefits in the future, is worth. The recursive formula for the NPV is given as

$$\begin{aligned} \mathrm{NPV}_0 &= -K_0 \\ \mathrm{NPV}_x &= \mathrm{NPV}_{x-1} \\ &\quad + \frac{\sum(\text{Benefits, year } x) - \sum(\text{Costs, year } x)}{(1+d)^x} \end{aligned} \tag{1}$$

where K_0 is the cost of the fuel cell stack and installation (estimated in \$4735 per APU for minimum cost design) and d is the real discount rate (assumed 10% [33]).

$$\begin{aligned} \text{Benefits, year } x &= (C_{\mathrm{oil}} + C_{\mathrm{overhaul}}) \cdot \mathrm{Idle}_{\mathrm{hours}} \cdot (1+i)^x \\ &\quad + C_{\mathrm{fuel}} \cdot \mathrm{Fuel}_{\mathrm{E}} \cdot \mathrm{Idle}_{\mathrm{hours}} \\ \text{Costs, year } x &= C_{\mathrm{FC}} \cdot \mathrm{Idle}_{\mathrm{hours}} \cdot (1+i)^x \\ &\quad + C_{\mathrm{fuel}} \cdot \mathrm{Fuel}_{\mathrm{FC}} \cdot \mathrm{Idle}_{\mathrm{hours}} \end{aligned} \tag{2}$$

where C_{oil} is the lubricant cost for diesel idling (\$0.07 per hour [30]), C_{overhaul} is the overhaul cost for diesel idling (\$0.07 per hour [33]), $\mathrm{Idle}_{\mathrm{hours}}$ is annual vehicle idling (1818 h), i is the inflation rate (assumed 3% [33]), C_{fuel} is diesel cost ($2.46\,\$\,\mathrm{gal}^{-1}$), $\mathrm{Fuel}_{\mathrm{E}}$ is the fuel consumption for diesel engines ($0.82\,\mathrm{gal\,h}^{-1}$), C_{FC} is the maintenance cost of

Table 13
Comparison between SOFC-based APUs emissions including LCA and idling of diesel engines emissions

Pollutant	ICE operation + diesel LC (kg)	SOFC-based APU operation + diesel LC + system LC (kg)	% Reduction
CO_2	76103.03	27151.49	64.32
CO	858.37	19.18	97.77
HC	125.29	9.21	92.65
NO_x	1311.76	11.82	99.10
Particulate	23.60	4.23	82.08

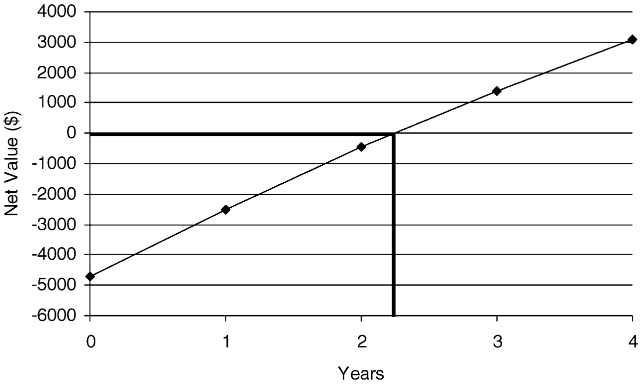

Fig. 5. Net present value of a fuel cell APU purchase and installation.

fuel cell APUs (0.072 \$ h^{-1}) and $Fuel_{FC}$ is the fuel consumption for fuel cell APUs (0.297 gal h^{-1}). No inflation rate was considered for diesel prince since the value that was used is already an average over five years (estimated in [1]).

When the NPV for a given year is greater than zero, the investment pays for itself, or it is said to "break even". Using the equations above, an NPV greater than zero was computed for the third year after the investment. Fig. 5 shows that the payback period is just a bit longer than two years. This value is in line with American Trucking Association requests for equipment purchases [33]. Further analysis should be performed to find the sensitivity of the result to the different assumptions that were taken. Moreover, the investment cost does not take into consideration the profits, taxes and sales expenses that will certainly raise the price of fuel cell-based auxiliary power units.

4. Conclusions

This paper addresses two fundamental issues for the introduction of a new technology: the life cycle analysis and the comparison with the existing technology. The life cycle of an SOFC-based APU is defined to include all the steps required to provide the fuel, to manufacture the device, and to operate and maintain the vehicle throughout its lifetime up to disposal and recycling. Different models have been used to quantify the emissions of the different stages. The last stage, product dismissing, has been neglected due to lack of data. A large amount of pollutants is released to air, water, and soil during the system manufacturing and assembly. The detailed list of all the releases greater than 5 g has been shown. The total amount of pollutants, which is released during the system and diesel production, has been compared to the emissions during operation over a lifetime (9090 h) in order to establish the importance of life cycle analysis. CO_2 life cycle emissions, despite being the most prevalent, are not important if compared to the operation (92.2%). For other pollutants, however, like CO or NO_x the share of releases from the system and fuel life cycles become more important. Some hazardous substances like VOC, SO_x, particulate matter, and metals are emitted mainly or only during the production stages. Therefore, life cycle considerations cannot be neglected in this study.

The environmental and health impacts of SOFC-based APUs in a design that minimizes the total cost have been compared to the impacts of idling of diesel engines. In all the cases there are several order of magnitude of difference between the two technologies. This great reduction potential of fuel cell-based APUs is particularly important because the health impact of idling of diesel engines is almost always above the safety limits. Even considering life cycle emissions, the total amount of pollutants that are released by SOFC-based APUs is up to 99% lower than in the case of idling of diesel engines considering diesel life cycle. The payback period for this investment has been estimated in about two years.

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