INTEGRATED FRAMEWORK FOR FUEL CELL BASED AUXILIARY POWER UNITS: FROM FUEL PROCESSING AND SYSTEM PERFORMANCE, TO HEALTH, ECOLOGICAL IMPACTS AND LIFE CYCLE ANALYSIS

Francesco Baratto and Urmila M. Diwekar
Center for Uncertain Systems: Tools for Optimization & Management
University of Illinois at Chicago
851 S. Morgan Street, Chicago, IL 60607 USA
urmila@uic.edu

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.). An integrated framework has been developed in order to evaluate the trade-offs between cost effectiveness, efficiency and health & environmental impacts of fuel cell power systems considering various stages of the life cycle of the device. The analysis of these trade-offs has been carried out applying the multi-objective optimization technique. Life cycle assessment provided 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 this study. 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.

1. Introduction

Auxiliary power units (APUs) 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. Concerning truck applications, drivers idle truck engines to power climate control devices (e.g., heaters and air conditioners) and sleeper compartment accessories (e.g., refrigerators, microwave ovens, televisions) and to avoid start-up problems in cold weather. Idling of large-displacement diesel engines is an extremely inefficient and polluting way to generate heat and electricity. 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 (Stodolsky et al., 2001). This proves that this problem is not marginal at all.

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 technology is considered the most favorable. APU applications are 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).

Because of the well-known pollution problem and the abundance of data, Los Angeles Air Basin (SoCAB) has been chosen as case study for simulations. Moreover in California there is a law proposal that would require, starting 2007, the installation of a non-adjustable idle reducing system on all new on-road heavy-duty diesel engines in vehicles with a gross vehicle weight rating (GVWR) greater than 14,000 pounds. This clearly shows the interest in that region for the idling emission problem. The time period that we considered is 2010 and beyond, when the SOFC technology will be widespread. Projections for South California Air Basin show that in 2010 there will be about 11500 fuel cell APU candidates (ARB, 2000), which means recreational vehicles and medium-heavy duty trucks with an average range of operation of 500 miles or more (Stodolsky et al., 2001). For lack of more detailed data we assumed that APUs installed on trucks and RVs work the same amount of time. It is expected that the qualitative results will not be different for RVs.

2. The Integrated Framework

An integrated framework that can systematically identify and quantify trade-offs between cost effectiveness, efficiency and environmental & health impacts of fuel cell power systems has been developed (Baratto et al., 2004a-b). The integrated framework has six main components, which are briefly analyzed in the following paragraphs.

2.1 System level modeling

The entire fuel cell system, comprehensive of fuel processing and fuel cell device, is simulated in Aspen Plus, which constitutes the base of the integrated framework. 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 in Berry et al. (2002), the diesel processing system includes an autothermal reformer, a desulfurizer and a combustor that acts as a polishing bed for the exhausts. The exhausts from the combustor are then used to preheat the air for the reformer and the fuel cell and to generate the steam necessary for the reforming. All the water needed by the autothermal reactor is provided by condensation of the exhaust from the combustor. Since kinetic models for the reforming of diesel are still in the early stages, in this work the autothermal reformer is simulated as a Gibbs free energy equilibrium reactor. Surrogate mixtures with similar physical properties to grade 1-D and 2-D diesel and that give reforming concentrations of chemicals inside the experimental bounds (Pereira et al. 1999) have been designed and used for simulations.

An SOFC stack model was developed to complete the APU system. The approach used to model the stack is similar to the one utilized by Geisbrecht (2002). 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. A polarization model derived from literature (Chan et al., 2001) was used for this scope.

2.2 Cost modeling

Estimating the cost of the fuel cell based system is an important task of the framework. A cost estimate of SOFC based APUs that is sensitive to a few major performance parameters was developed. What makes the cost evaluation of SOFC based APUs difficult is the fact that this system is similar to a micro chemical plant (about 100 L). This means that normal factors used in plant cost estimation do not apply to this case and so the parameters have to be calculated trough regression of existing data. The manufacturing cost of the full system can be decomposed in the bare cost of each component and fixed costs. Profits, research and development, marketing expenses and taxes are not included. The operating cost includes fuel and maintenance. The cost of fuel was considered over a life-time of 5 years with 6 hr/day for 303 days/yr operation (Stodolsky et al., 2001). The price of diesel in 2010 was predicted using stochastic techniques (Diwekar, 2003). The main literature source of data is a report of A.D. Little (2001) prepared for the US Department of Energy.

2.3 Environmental Impact Assessment

Ecological and environmental risk impacts were quantified using the generalized WAste Reduction algorithm (WAR) by EPA (Cabezas et al., 1999). The WAR algorithm involves the concept of Potential Environmental Impact (PEI) balance (analogous to mass or energy balance). The potential environmental impact of a given quantity of material and energy can be generally defined as the effect that this material and energy would have if they were to be emitted into the environment. To provide an estimate of the potential environmental impact of a chemical process, eight different categories are considered: Human Toxicity Potential by Ingestion (HTPI), Human Toxicity Potential by Inhalation or Dermal Exposure (HTPE), Ozone Depletion Potential (ODP), Global Warming Potential (GWP), Photochemical Oxidation Potential (PCOP), Acidification Potential (AP), Aquatic Toxicity Potential (ATP) and Terrestrial Toxicity Potential (TTP). WAR algorithm has been fully integrated in the Aspen framework.

2.4 Health Impact Assessment

Health risk is defined as the level of hazard posed to both individual human health and the health of whole population in the selected area due to a risk factor being present in the environment. The methodology used in this work, called Risk Assessment, strictly follows the procedure recommended by US EPA (1989) in Risk Assessment Guidance for Superfund. There are four steps in the baseline risk assessment process: (1) site data collection and analysis; (2) exposure assessment, in which the magnitude of human exposure is estimated; (3) toxicity assessment, in which the relationship between the extent of exposure to a contaminant and increased likelihood and/or severity of adverse effects is found; (4) risk characterization, in which the toxicity and exposure assessments are integrated into quantitative and qualitative expressions of risk. Emission rates, computed by the Aspen simulation, are converted into an estimate of the concentration likely to be contacted over time using the air dispersion model ISC3 (EPA, 1995).

Since trucks and RVs are supposed to idle mainly in rest areas along the communication routes, the stop areas in Los Angeles Basin were detected and placed on the map of the region. It was assumed that the vehicles are evenly distributed among the stop areas and that one candidate out of four is idling at the same time. This makes a total of 2700 vehicles. Concentrations have been computed over a uniform grid with 15 km spacing.

Carcinogenic, chronic and acute effects for adult and children populations in agricultural, residential and industrial scenarios are computed. The whole process was fully integrated into the framework.

2.5 Life Cycle Assessment

Life Cycle Assessment (LCA) provides a tool for identifying and evaluating environmental burdens associated with the life cycles of materials and services in a "cradle-to-grave" approach. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth.

For the LCA of fuel cell based cycles it is possible to identify two main components: (1) fuel life cycle and (2) life cycle of the system (manufacturing and assembly). Fuel cycle includes recovery or production of the feedstock, transportation of the feedstock, conversion of the feedstock to the final fuel (e.g. diesel), distribution of the fuel to the refueling station and finally the use in the vehicles. Among the different possibilities, the GREET model (Wang, 2002) was chosen for this part of the analysis. The second component of the Life Cycle Assessment includes raw material extraction, manufacture and assembly of the stack and balance of plant, their installation and eventual decommissioning. The second component of the life cycle is mainly based on the work of Karakoussis et al. (2001).

Further details about APU life cycle can be found in Baratto and Diwekar (2004b).

2.6 Multi-Objective Optimization

The modeling structure is augmented with a new multi-objective optimization framework for identifying trade-offs between the different objectives: low cost, high efficiency and low health and environmental impacts. It is not possible to find a single solution that is simultaneously optimal for all the objectives, because of the contradiction and possible incommensurability of the objective functions. Therefore, the solution of a multi-objective optimization problem is a set of alternatives called the Pareto set. For each of these solution alternatives, it is impossible to improve one objective without sacrificing the value of another one.

Among the many different solution techniques, the constraint method was chosen. The idea is to pick one of the objectives to optimize while each of the others is turned into an inequality constraint with parametric right-hand side. Solving for different values of these parametric right-hand sides leads to the Pareto set. In order to reduce the number of optimization problems to solve, a new efficient algorithm called MINSOOP (Fu and Diwekar, 2004) was used. The optimization problems were solved using the Aspen inbuilt SQP optimizer. The decision variables were taken so that they were the most influent on the objectives and they were selected applying statistical methods (PRCC) together with knowledge of the problem. The optimizations were performed varying the diesel intake, fuel utilization in the fuel cell, cathode air stoichiometric ratio, reformer temperature, pressure of the system and air preheating temperature.

3. Trade-off surfaces

The contour plots in Figures 1 and 2 give a representation of the trade-off solutions in the Pareto set. Although these contour plots provide several insights into the current problem, they are far from a complete representation as we can only visualize 3 objectives at a time.

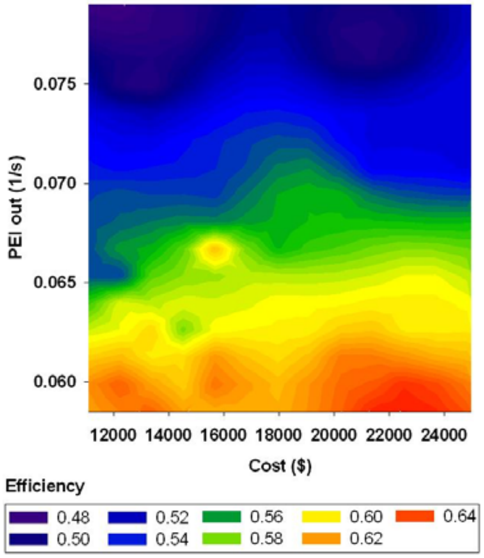

Figure 1. Contour plot of Pareto trade-off designs in terms of environmental impact (y-axis), cost (x-axis) and

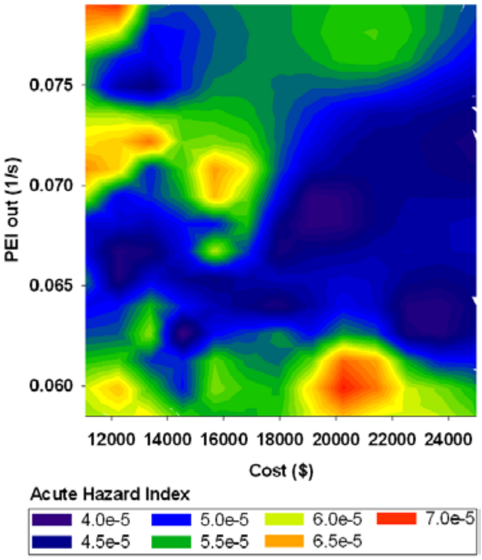

Figure 2. Contour plot of Pareto trade-off designs in terms of environmental impact (y-axis), cost (x-axis) and acute effects

Figure 1 clearly shows that high efficiency designs are possible to obtain with wide range of cost. These designs guarantee also minimum potential environmental impact. However, in order to obtain the highest efficiency value (65 %), one has to pay a steep penalty in terms of cost (about $22000). Therefore, it is possible to have maximum efficiency and minimum environmental impact at the same time, but trading off with cost values. There is a good region of operation in terms of these three objectives close to the lower left corner of figure 1, where costs and total PEI are at their minimum and efficiency is around 0.60-0.62 (the base case was 0.374). This region has also very low carcinogenic and chronic effects, but does not perform very well in terms of acute hazard index, as it can be seen in figure 2. Figure 2 shows also that it is possible to operate with very low acute effects (dark blue contour) at the entire range of costs, but the environmental impact will never be minimum for these designs. If the objective is to operate at low health effects (carcinogenic, chronic, and acute simultaneously), it is possible to do it at low cost but moderate environmental impact and efficiency. Further details about multi-objective optimization of APU systems can be found in Baratto and Diwekar (2004a).

4. Comparison with idling of diesel engines

In this section idling of diesel engines is compared with the operation of SOFC based APUs. The design that minimizes the costs is chosen for comparison purposes in order to show the potential impacts of this new technology for an economically favorable configuration. Emissions for idling of diesel engines are mainly retrieved from EPA (1998). In this analysis life cycle emissions are not taken into consideration.

The results of the health risk assessment can be seen in figure 3. 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.

Also the analysis using the potential environmental impact showed the tremendous disparity between the two technologies, with a difference of three orders of magnitude in the total output rate of PEI. The impact category with the biggest difference between the two cases is photochemical oxidation potential, due to higher emissions of hydrocarbons (aldehydes in particular).

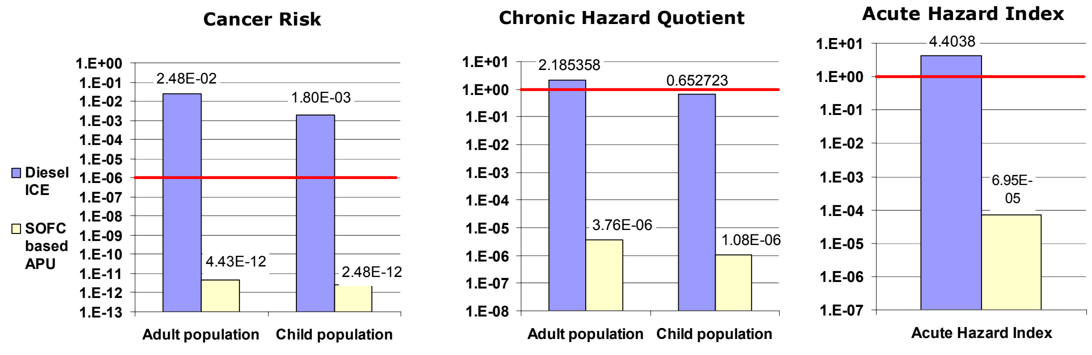

Figure 3. Comparison between idling of diesel engines and SOFC based APUs in terms of health impacts. The horizontal lines represent the limit of safety regions.

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 hr of operation) in order to establish the importance of the life cycle study. The design that minimizes the costs has been chosen again as benchmark.

Table I 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/hr, which corresponds to 2701.8 gal over the lifetime. 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 NOx liberated to the atmosphere. VOC, SOx, N2O, and particulate are produced almost exclusively during the system life cycle. Methane emissions are evenly distributed between diesel and system lifecycle.

TABLE I. 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

From those data it can be seen that lifecycle emissions are important in the study of environmental and health impacts 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 II, 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.

TABLE II. Comparison between emissions of SOFC based APUs including LCA and idling of diesel engines

Pollutant	ICE operation + Diesel LC [a] (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

6. Conclusions

An integrated framework that can automatically identify and quantify trade-offs between cost effectiveness, efficiency and environmental & health impacts of fuel cell based auxiliary power units has been developed. 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.

South California Air Basin (SoCAB) has been chosen as case study mainly because of the well-known pollution problem and the relatively abundance of data.

The analysis of the tradeoff surfaces shows that high efficiency (above 60%) can be achieved at any range of cost and with minimum environmental impact. However, in order to obtain the highest efficiency value (65 %), one has to pay a steep penalty in terms of cost (about $ 22000). If the main objective is to operate at low health effects (carcinogenic, chronic, and acute simultaneously), it is possible to do it at low cost but moderate environmental impact and efficiency.

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, which proved to be not negligible, 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.

7. Acknowledgements

This work is funded by National Energy Technology Laboratory (NETL), DOE, Morgantown

8. References

ARB. 2000. California’s Diesel Risk Reduction Program (Appendix III).

Baratto F., U.M. Diwekar, and D. Manca, 2004a. Impacts Assessment and Tradeoffs of Fuel Cell based Auxiliary Power Units - Part I: System Performance and Cost Modeling. Journal of Power Sources (in press).

Baratto F., U.M. Diwekar, and D. Manca, 2004b. Impacts Assessment and Tradeoffs of Fuel Cell based Auxiliary Power Units - Part II: Environmental and Health Impacts, LCA, and Multi-Objective Optimization. Journal of Power Sources (in press).

Baratto F., U.M. Diwekar, 2004a. Multi-objective Optimization of Fuel Cell Based Auxiliary Power Units: Southern California Case Study. Journal of Power Sources (in press).

Baratto F., U.M. Diwekar, 2004b. Life Cycle Assessment of Fuel Cell Based APUs. Journal of Power Sources (in press).

Berry D., D. Shekhawat, T.H. Hardner and W.Rogers. 2002. Fuel Processing of Diesel Fuel for Auxiliary Power Units. FY 2002 Progress Report, U.S. Department of Energy.

Cabezas H., J.C. Bare and S.K. Mallick. 1999. Pollution Prevention with Chemical Process Simulators: The Generalized Waste (WAR) Algorithm - Full Version. Comp. Che. Eng. 23: 623-634

Chan S. H., K.A. Khor and Z.T. XIA. 2001. Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant. Journal of Power Sources 109: 111-120.

Diwekar U. M. 2003, Introduction to Applied Optimization, Kluwer Academic Publishers, Dordrecht, Netherlands.
Fu Y. and U.M. Diwekar. 2004. An Efficient Sampling Approach to Multi-objective Optimization. Annals of Operations Research (in press).
Geisbrecht R.A. 2002. Theory based process modeling for evaluation of fuel cells in advanced energy systems. AIChE National meeting 2002, New Orleans, LA
Karakoussis V., N.P. Brandon, M. Leach and R. van der Vorst: The environmental impact of manufacturing planar and tubular solid oxide fuel cells. Journal of Power Sources 101:10-26, 2001.
Little A.D. 2001. Conceptual Design of POX/SOFC 5kW net System. Final report to DOE NETL.
Pereira C., R. Wilkenhoener, S. Ahmed and M. Krumpelt. 1999. Liquid Fuel Reformer Development. Proceedings of the 1999 U.S. DOE Hydrogen Program Review
Stodolsky F., L. Gaines and A. Vyas 2001. Technology Options to Reduce truck idling. Argonne National Laboratory, Argonne, IL.
U.S. Environmental Protection Agency. 1989. Risk Assessment Guidance for Superfund. Vol. 1, Human Health Evaluation Manual (Part A).
U.S. Environmental Protection Agency. 1995. Industrial Source Complex Model (ISC 3). Office of Air Quality Planning and Standards.
U.S. Environmental Protection Agency. 1998. Emission Facts. Idling Vehicle Emissions. EPA420-F-98-014.
Wang M. 2002. Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts. Journal of Power Sources, 112(1):307-321

9. Contact

Francesco Baratto: francesco.baratto@tiscali.it

Urmila M. Diwekar: urmila@uic.edu

http://www.uic.edu/labs/custom/