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Techno-economic analysis of fuel cell auxiliary power units as alternative to idling

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Abstract

This paper presents a techno-economic analysis of fuel-cell-based auxiliary power units (APUs), with emphasis on applications in the trucking industry and the military. The APU system is intended to reduce the need for discretionary idling of diesel engines or gas turbines. The analysis considers the options for on-board fuel processing of diesel and compares the two leading fuel cell contenders for automotive APU applications: proton exchange membrane fuel cell and solid oxide fuel cell. As options for on-board diesel reforming, partial oxidation and auto-thermal reforming are considered. Finally, using estimated and projected efficiency data, fuel consumption patterns, capital investment, and operating costs of fuel-cell APUs, an economic evaluation of diesel-based APUs is presented, with emphasis on break-even periods as a function of fuel cost, investment cost, idling time, and idling efficiency. The analysis shows that within the range of parameters studied, there are many conditions where deployment of an SOFC-based APU is economically viable. Our analysis indicates that at an APU system cost of \$ 100 $\mathrm{kW^{-1}}$, the economic break-even period is within 1 year for almost the entire range of conditions. At \$ 500 $\mathrm{kW^{-1}}$ investment cost, a 2-year break-even period is possible except for the lowest end of the fuel consumption range considered. However, if the APU investment cost is \$ 3000 $\mathrm{kW^{-1}}$, break-even would only be possible at the highest fuel consumption scenarios. For Abram tanks, even at typical land delivered fuel costs, a 2-year break-even period is possible for APU investment costs as high as \$ 1100 $\mathrm{kW^{-1}}$.

Keywords: Abram tanks; Economics; Fuel cells; Heavy-duty trucks; Idling; Reforming

1. Introduction

Heavy-duty trucks spend considerable amounts of time idling. Idling can be classified into two broad categories: non-discretionary and discretionary [1]. Non-discretionary idling occurs after engine start-up and intermittently in heavy traffic. Discretionary idling occurs during loading/unloading and during stand-by periods in rest stops where the idling engine mainly serves to maintain driver comfort levels. Idling engines operate low levels of efficiency, suffer considerable tear and wear, and cause emissions of NO_x and particulate matter, along with some hydrocarbons, carbon monoxide and carbon dioxide. The US Department of Energy [2] estimates that annually \$ 1 billion worth of diesel fuel is consumed during idling, with an additional \$ 1 billion spent on increased engine maintenance costs. The high cost of idling has prompted many of the large fleets to put voluntary restrictions on idling [2]. Truck idling has attracted increased attention from local and federal air quality regulators, and several municipalities, such as the eight-county Houston, TX area, and New York City are considering regulations limiting truck idling. This has created an impetus to look for technically and economically viable alternatives to discretionary idling, such as, for example, truck stop electrification, batteries, or auxiliary power units.

In the present work, we carry out an economic analysis of the break-even period of using fuel-cell-based APUs to replace

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Abbreviations: ACI, actual cost of idling (\$ (unit time)$^{-1}$); APU, fuel cell as APU; BEP, break-even period (years); CI, cost of idling (\$ (unit time)$^{-1}$); DE, idling diesel engine; DEIC, diesel engine idling cost (\$ year^{-1}); DR, diesel rate (\$ gal^{-1}); FC, fuel consumption (gal (unit time)$^{-1}$); FCC, fuel cell cost (\$ year^{-1}); FCIC, fuel cell investment cost (\$); FCRC, annual fuel cell running cost (\$ year^{-1}); GT, gas turbine engine for M1, M1A1 tanks; IFC, idled fuel cost (\$ gal^{-1}); IR, investment rate (\$ kW^{-1}); IT, idling time (h (unit time)$^{-1}$); MR, maintenance rate (\$ h^{-1}); RR, fuel-cell APU rating required (kW); TD, average number of trucking days in a given unit of time (days (unit time)$^{-1}$)

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Nomenclature

gal	gallon
h	hour(s)
n	time period (years)

Greek letters

η	efficiency

Subscripts

D	day(s)
Y	year

engine idling in long-haul heavy-duty trucks and military vehicles. We also consider the technical challenges involved in onboard conversion of diesel fuel into hydrogen-rich feed streams suitable for fuel-cell APUs. A model is developed for evaluating the break-even period for long-haul trucks and military vehicles as a function of idling rate, idling efficiency, maintenance cost, investment cost, and fuel cost.

2. Background

Power requirements in automotive applications have been increasing over the years, driven by the desires for enhanced performance, emission controls, and creature comforts. Examples of such power needs include electrical power steering, direct fuel injection, electrically heated catalyst, electrical water pump, electro-magnetic valve train, engine cooling fan, electric AC compressor, heated windshields and mirrors, heated and cooled seats, marker lights, and communication, navigation, and entertainment electronics. For heavy-duty trucks, it is also desirable to keep the engine heated when the vehicle is parked in cold climates to facilitate easier starting of the engine. The power demands for all these features are currently met by idling the vehicle's engine.

2.1. Alternatives to idling

Rather than trying to change idling patterns via regulation or other incentives, technological alternatives to displace idling are increasingly gathering attention. To reduce diesel engine idling in trucks, several alternative technologies can be considered [1,3]. The vehicle's battery power presents the first alternative. However, prolonged battery use stresses the vehicle's batteries, shortening their lives and requiring more frequent replacement. Direct fired heaters (DFHs) are another possibility. These units supply heat directly from a combustion flame to a small heat exchanger. Compared to the diesel engine, they use much less fuel for heating the cab/sleeper and/or keeping the engine heated. However, DFHs do not provide electric power for accessories such as televisions, refrigerators and communication equipment. Moreover, concerns have been raised about safety, retrofitting costs, reliability, battery drain, noise, and vibration during idling. Also, thermal storage systems (TSSs) are devices containing a phase change material that stores thermal energy transferred from the vehicle's engine or air-conditioning when the vehicle is in operation. TSSs can supply heating or cooling to the sleeper compartment while the cab's temperature is allowed to change. These systems can only be used for up to 8 h, do not supply electricity, and their effectiveness depends on the duty cycle of the truck. Finally, auxiliary power units (APUs) are devices normally consisting of a small internal combustion engine, usually diesel, equipped with a generator and heat recovery to provide electricity and heat. Yet current models are heavy, expensive and noisy, and will not make a significant difference in emissions. A possible future alternative would be fuel-cell-based APUs, discussed in more detail in Sections 2.2 and 3.

In contrast to these on-board auxiliary power units, the truck stop electrification (TSE) arrangement takes an entirely different approach. To power the non-propulsion requirements of a truck, a trucker could simply "plug in" the truck to outlets at the truck stop [3]. Yet, this proposal is plagued by the chicken-and-egg problem of truckers unwilling to install the necessary equipment when there is no place in which to plug it in while truck stop owners do not wish to install infrastructure when nobody has the equipment to use it. Currently, for the 458,000 Class—8 trucks only ∼210,000 trucks can be simultaneously accommodated in truck stops [3]. Discounting trucks that would be out of operation at a given time, it still means only 47% of the trucks, on an average, would be able to park in a designated spot. Further, with drivers favoring specific driving times, such as weekday nights, overcrowding of busy routes is becoming common. On such routes, occupancy levels of the truck stops availability have reached an average of 90% during peak hours. Thus, even if all truck stops were fully electrified, it would not completely alleviate the need for idling. We discuss the cost of setting up the TSE infrastructure in Section 3.4.

2.2. Fuel cells for auxiliary power units

2.2.1. Benefits

Fuel cells as APUs have received considerable attention as they offer a true mass-market opportunity that does not require the challenging performance and low cost required for propulsion systems for vehicles [3,4]. TIAX [5] reports truck manufacturers are looking at fuel-cell APUs seriously as they have the potential to decrease heavy truck fuel and lubricant consumption. This, in turn, would reduce emissions of greenhouse gases and particulate matter, and decrease the dependency on non-renewable energy supplies, running cost, and energy use. Assuming an efficiency of 30% for processing diesel into the fuel for a fuel cell, EPA data indicate, under average driving and idling conditions, a 5–19% reduction of NO_x emissions when using a fuel cell instead of a diesel engine. APUs can also reduce vibration and noise. When heavy-duty trucks are parked in a truck stop, the improved comfort levels made possible by APUs can decrease driver fatigue, thus contributing to increased safety of the driver, vehicle, and highway. APUs can adapt to most environments, even arctic climates. They can also serve as a generator, battery charger, and heat supply. This leads to a decrease in engine wear and tear, reduces requirement of logistics support for vehicles operated in remote areas, and increases energy efficiency and payload capacity. In case of truck breakdown, APUs can also act as survival systems in extreme weather conditions.

APUs are also attractive from a military perspective. Tanks such as the Russian T-80 and the US M1 and M1A1 Abrams are powered by gas turbines [6,7]. While the gas turbine provides unmatched acceleration, its fuel efficiency may be as low as 0.3 mpg depending on conditions [6,8]. There are claims in the literature that for about 3/4th of the Abram's operating hours [8,9], the gas turbine is idled to run a ~5 kW "hotel load"—ventilation, lights, cooling, and electronics at less than 1% efficiency. Lovins et al. [8] state the delivered cost of fuel may be 15 times higher than the wholesale price for fuel excluding the cost of delivery. The delivered fuel cost could reach $ 600 gal^{-1}, accounting not only for the cost of the actual delivered fuel, but also the cost of the fuel consumed during delivery [10].

2.2.2. System requirements

Interest in fuel-cell APU applications exists because there may be a good fit between APU requirements and fuel cell system characteristics. To provide the functionality of interest and to compete with internal combustion engine (ICE) driven APUs, fuel-cell APUs must be capable of using the available fossil-fuel-based energy infrastructure [4]. As the small amount of fuel involved in fueling APUs would not justify the establishment of a specialized infrastructure, e.g., a hydrogen infrastructure, trucks' APUs would have to operate on diesel in order to match the infrastructure available and share on-board fuel tanks with the main engine. APUs, including the associated fuel-processor, also need to be water self-sufficient. Carrying additional water would not only be a major inconvenience, it would also require additional space and associated equipment. For vehicular applications, it is critical that APUs (including the fuel processor) are capable of starting within 10–20 min. They must also be capable of following loads and reach full power rapidly after start-up.

3. Fuel cell technology options available

Among the many different types of fuel cells available, only solid oxide fuel cell (SOFC) and proton exchange membrane fuel cells (PEMFCs) are serious contenders for on-board APUs.

3.1. Solid oxide fuel cell

In SOFCs, oxygen ions are the charge carriers in the electrolyte. To achieve reasonable oxygen diffusion rates, high operating temperatures of 800–1000 °C are required [11]. These high operating temperatures make the performance requirements for the fuel processor much simpler. SOFCs can use CO along with hydrogen as fuel, and are less sensitivity to sulfur contaminants, typically found in diesel fuel [12]. SOFCs do not require humidification, since the electrolyte is an ion-conducting ceramic.

BMW and Delphi Automotive Systems have developed an SOFC that operates on hydrogen obtained from a gasoline reformer built into the APU [13]. While a mechanically driven generator requires about 1.5 L (0.4 gal) of fuel to produce 1 kW (1.3 hp) of electricity, Holt [14] indicated the APU can produce an equivalent amount of power on 46% less gasoline.

On the flip side, due to their high temperature operation, solid oxide fuel cells have long start-up times, in the range of 10–30 min. Also, the fuel processor needed for converting diesel fuel to an SOFC-compatible reformate requires significant start-up times. Consequently, thermal management requirements would probably favor continuous rather than intermittent operation. SOFCs are capable of internally reforming natural gas, ethane, and some other fossil fuels for use in the fuel cell reactions, and can use carbon monoxide as a fuel. SOFCs produce electricity, water, and carbon dioxide. Brodrick et al. [15] noted these fuel cells would make high-grade heat available for cabin and water heating which could partially offset the difficulties of high temperature operation and stringent thermal management requirements.

Typical SOFC-based APUs have the following key features: The air for reformer operation and cathode requirements is compressed in a single compressor and then split between the unit operations. The anode recycle stream provides water for the reformer, thus decreasing the need for external water supply. Unreacted anode tail gas is recuperated in a tail gas burner, and the water generated could also be recycled into the reformer. Reformers for transportation fuel based SOFC APUs will be of the exothermic type; i.e., partial oxidation or auto-thermal reforming, as no viable steam reformers are available for such fuels [4]. For auto-thermal reforming systems, both oxygen and steam are required. Typical steam/carbon ratios for auto-thermal reformers are in the range of 1.5–2. For self-contained on-board reforming of diesel, water can be recycled from the anode of the SOFC. However, the amount of water generated might not be sufficient to provide the required steam/carbon ratio for coke-free operation of typical auto-thermal reforming catalysts.

Reforming catalysts employed currently for partial oxidation of hydrocarbons or methanol vary according to applications and operating conditions [16]. From supported noble-metals, such as iridium, ruthenium, rhodium, palladium, or platinum, supported-nickel, pyrochlore-type oxides such as $Ln_2Ru_2O_7$, and perovskite-type oxides such as $LaMO_3$, and Cu–ZnO, nickel-based catalysts are the most common choice among these due to their low cost; however, rapid catalyst deactivation and coke formation remain major problems in frequent start-up and shut-down cycles. Though the partial oxidation process has some problems with catalyst deactivation and coking, it has the advantage of low residence time and smaller reactors [17].

Auto-thermal reforming (ATR) combines endothermic steam reforming and exothermic partial oxidation reactions. The heat produced by the partial oxidation reaction is used in the steam reforming reaction to generate hydrogen and carbon monoxide. The reactions can be balanced in such a way that the net energy requirement is zero [18].

Typical ATR catalysts contain supported group VIII metals. These catalysts effectively convert C_1–C_{12} hydrocarbons (straight chained, branched, saturated, unsaturated, oxygenated and aromatic) as well as complex commercial gasolines [19].

The main focus for developing ATR catalysts will be to increase the thermal stability and mechanical robustness. Other desired characteristics for ATR catalysts would be resistance to intermittent operation and cycles at start-up and shut-down, as well as low light-off temperature and high sulfur tolerance [17,20,21]. Auto-thermal reforming provides a fuel processor compromise that operates at lower oxygen to carbon ratios and lower temperature than the POX. ATR offers the most flexibility in heat management and, thus, potentially higher efficiency than POX.

The power requirements for auxiliary power applications entail smaller fuel cell stack duties. Heat losses for an SOFC stack operating at a smaller power duty are a larger proportion of the gross rating than in a stationary power application. Some energy is available in an SOFC system from enthalpy recovery from tail gas effluent streams that are typically 400–600 °C. Insulation required for specified system skin temperatures requirements could conceivably result in large proportion of the total system volume. Integration of the high temperature components is important in order to reduce the system volume and insulation requirements. SOFC APU systems will require inexpensive high performance insulation materials to decrease system volume and cost.

Carbon formation is a problem in reforming of hydrocarbons [22], and the use of diesel fuels accentuates this issue. Heavier hydrocarbons can form carbon deposits (coking) even at relatively low temperatures of ∼450 °C due to fuel pyrolysis. Several mechanisms have been proposed in the literature, including formation of amorphous flakes and filamentous carbon due to carbon monoxide decomposition, formation of encapsulating carbon due to the decomposition of hydrocarbons, and generation of pyrolytic carbon by thermal cracking of hydrocarbons. Another major challenge is limiting the sulfur content in the diesel fuel to about 0.1 ppm to avoid sulfur poisoning of the reforming catalysts [4,23].

3.2. Proton exchange membrane fuel cell

According to Brodrick et al. [15], truck APUs based on PEM fuel cells are attractive since they permit near ambient temperature operation, thereby facilitating ease of starting and stopping the system. PEM-fuel-cell-based APUs can be fuelled either by pure hydrogen or methanol.

One major drawback of PEM fuel cells is that current anode technology requires platinum catalysts that are intolerant of even traces of CO and sulfur [4]. When hydrogen gas is produced from gasoline or diesel in a reformer, it is accompanied by significant levels of carbon monoxide, which must be removed prior to feeding the hydrogen into the fuel cell stack. A typical gasoline or diesel fuel processing system would require not only a reformer (either exothermic or endothermic overall, ∼850–1000 °C), but also shift reactors (exothermic, 150–500 °C), and CO-cleanup systems (primarily exothermic, 50–200 °C), prior to feeding pure hydrogen into the PEM fuel cell stack (exothermic, 80 °C). Each reaction zone operates at a significantly different temperature thus providing a challenge for system integration and heat rejection. To alleviate some of these drawbacks, and further reduce the cost of the PEMFC systems, developers are investigating the possibility of using higher temperature membranes; e.g., operating slightly above 100 °C. This would increase the carbon monoxide tolerance of the anode catalysts, potentially simplifying the fuel processor design, and simplify the heat rejection. Consequently, fuel processors for PEM fuel cells are rather complex, making on-board deployment difficult.

Recently, the U.S. Department of Energy has made a no-go decision on further funding of on-board fuel processor development for PEM fuel cells. Therefore, deployment of PEM-based APUs would most likely necessitate carrying a supply of pure hydrogen on-board of the vehicle, along with the development of a hydrogen-refueling infrastructure. A further complication is that the PEM stack operating temperature and its humidity requirements require a water management system for hydrating the electrolyte. For on-board APUs the need for external sources of water should be minimized [24].

3.3. Systems configuration and technology issues

If we impose the constraint of using only the primary propulsion fuel as hydrogen source, SOFCs are more attractive than PEMFCs. Since the SOFC stack operates at high temperatures and is capable of utilizing carbon monoxide and certain hydrocarbons as fuel, the reformer design is simple. However, on account of high exhaust temperatures, expensive high temperature recuperators are required to maintain system efficiency. SOFC APUs will consist of a fuel processor, a stack system, and balance of plant components including start-up batteries. Besides being used to supply start-up current for the primary engine, batteries are also used to store current to power the electrical accessories. However, an APU would decrease the reliance on the battery for powering up the accessories. In addition to the primary propulsion motor, an APU can also act as a secondary source for recharging the battery. Thus, the current instances of a “dead battery” could be easily avoided.

In order to minimize system volume, associated system weight, and start-up time, integration of the system components is a key design issue. If anode tail gas were recycled to provide steam, the water management system could be simplified, although a hot gas recirculation system would be required. Furthermore, system design could be simplified further if a sulfur-free fuel were used or if the fuel cell were sulfur tolerant.

3.4. Micro-grids

Interesting possibilities arise when one attempts to interface on-board APUs with stationary power sources. One instance could be the hundreds of long-haul trucks entering and exiting major warehouses, shipping docks, factories, etc. With APUs on-board every vehicle, they can easily be tapped as power sources. Quite often, trucks are waiting for several hours to enter a warehouse, be unloaded, and then be loaded again. During this time, currently the trucks idle their engines. This serves two purposes: providing electricity to power up the accessories, and keeping the engine warm in cold climates. However, both these needs are easily satisfied with a fuel-cell APU on-board. In cases where there is surplus APU electric generation capacity, it raises the question whether it would make sense to interface the APU with the stationary grid, or micro-grids, as an alternative to current concepts of truck stop electrification (TSE). In this scenario, the TSE infrastructure could also be modified to provide electric power to parked trucks, but would also be able to accept power from fuel-cell APU equipped trucks. A similar approach could be taken using this concept in a warehouse. There, instead of having the diesel engine idle, the trucks entering and leaving could have their APUs running and supplying the excess power to the building. These electric sources can be utilized to supply energy to micro-grids powering parking lot lights, general illumination, and ventilation systems.

A back of the envelope calculation on the economics of utilizing APU power of trucks for partially powering a TSE infrastructure reveals that if the energy from the electric utility service is assumed to cost \$ 0.07 kW h^{-1}, then a 5 kW h requirement per truck idling for ~1600 h year^{-1} would translate into a saving of \$ 56,000 year^{-1} realized in a TSE for 100 trucks. This saving pales in comparison to the estimated \$ 1,000,000 required to provide the TSE infrastructure for 100 trucks [25].

An annual saving rate of ~5.6%, makes conventional TSE systems and even modified TSE systems accepting power from fuel-cell APUs appear uneconomical, primarily due to the high infrastructure investment required. The benefits of reduced levels of noise and emissions would be critical in winning the support of local communities permitting trucks stops in their midst [25]. However, the same benefits can be had at much lower cost by simply equipping trucks with on-board APUs, without going through an elaborate TSE infrastructure build-up. Furthermore, truck-mounted APUs provide more flexibility for a driver to park the vehicle overnight, compared to the limited number of potential TSEs.

4. Economic analysis

4.1. Commercial trucks

4.1.1. Idling rate

Although the amount of idling is not well known, it appears to be significant for large long-haul heavy-duty diesel trucks (Classes 7 and 8). According to Argonne National Laboratory estimates [2,3], many of the 458,000 long-haul trucks in the US that travel more than 500 miles from home base each day could idle somewhere between 3.3 and 16.5 h day^{-1}. Table 1 shows the different scenarios, which affect the hourly idling fuel consumption rate.

Different companies and studies have observed the average idle time per truck observed as 40, 44, and 50%. Following discussions with three long-haul fleets doing intra-state deliveries of bulk products, Brodrick et al. [15] estimated 10% of the total idling time to be non-discretionary idling. Further, since such idling cannot be eliminated by fuel-cell APUs, it should be removed from analysis. Although the actual percentage of non-discretionary idling depends on truck, route, traffic conditions, and delivery location, they considered 40% to be a representative averaged figure. The average idle time used by Argonne National Lab of 6 h day^{-1} for 303 days year^{-1} for long haul sleep trucks is consistent with values of 40% indicated by J B Hunt, 44% by a 90-truck fleet of Freightliner LLC, and 47% of the one-third fleet of Tennessee [3,15]. According to American Trucking Association's (ATA's) Truck Maintenance Council (TMC), 52% of their member fleets had a policy to reduce idling [26]. However, smaller fleets, having fewer than 25 vehicles, which constitute 40% of the long-haul truck industry, were less likely to have these programs [3].

Table 1
Fuel consumption rate data available in literature

Serial number	Description	Fuel consumption rate (gal h^{-1})
1	No accessories, 800 rpm	0.60
2	Year 2000 Argosy tractor, without accessories	1.00
3	Year 2000 Argosy tractor, 1050 rpm, accessories	1.40
4	Accessories (30 bhp), 1200 rpm	2.25

Conclusion: range to be studied: 0.6–2.25 gal h^{-1}.

4.1.2. Idling efficiency

The idling efficiency of a diesel engine is typically around 9–11% [1,27]. For purposes of a conservative estimate of the break-even period we assume it to be 11%. For fuel-cell APUs, efficiency values ranging from 15% to slightly over 40% have been reported in the literatures [1,27,28]. As Lawrence and Boltze [28] state, 30% fuel efficiency with respect to LHV of diesel is realistic, and for the current analysis we select this value. These values have been compiled in Table 2.

4.1.3. Maintenance cost

In addition to fuel costs, engine idling results in increased maintenance costs associated with substantial wear to the engine. TMC [29] estimated idling for only 1 h day^{-1} for a year results in the equivalent of 6400 miles of engine wear. Using TMC's method, Argonne National Laboratory [3] concluded each hour of eliminated idling would result in a savings of \$ 0.07 each in lubricant changes and engine overhauls per truck.

However, the TMC conclusions based on the potential savings on account of idling are valid only if a truck idles for

Table 2
Estimating the average efficiency of a diesel-based fuel-cell APU

Serial number	Description	Efficiency (%)
1	A complete FCV with on-board conversion	30
2	Average fuel cell efficiency in 2001	15
3	Average fuel cell efficiency expected until 2003	19
4	Average fuel cell efficiency expected until 2010	23
5	PEMFC goals [ADL (2000)]	35–40
6	For estimation purposes, efficiency was assumed as	30

Table 3
Estimating the maintenance cost per truck per hour idled from data available in literature

Serial number	Description	Value
Part 1. Estimating the idling time basis		
1	Annual idling fuel cost for the trucking industry	$ 1.17 billion[a]
2	Number of trucks	458,000
3	Idling cost per engine	$ 2555
4	Average annual travel days/truck	303
5	Idling cost/truck/day	$ 8.4
6	Cost of fuel taken in the study	$ 1.03 gal^{-1}[a]
7	Idle time/truck/day	8.2∼8 h
Part 2. Estimating the maintenance cost		
1	Annual maintenance cost for the trucking industry	$ 1.00 billion[a]
2	Annual maintenance cost per truck	$ 2183
3	Daily maintenance cost per truck	$ 7.21
4	Average daily idling duration (Part 1)	8 h
5	Maintenance cost/truck/idling hour	$ 0.90[b]

[a] DoE data.

[b] This analysis assumed the maintenance cost would be linearly proportional to the idling time.

Table 4
Investment cost data available in literature

Serial number	Description	Investment cost ($ kW^{-1})
1	Fuel cell factory cost (500,000 units year^{-1} at 50 kW)	
	(a) Year 2000 estimate	294
	(b) Year 2000 goal	130
	(c) Year 2004 goal	50
2	Direct hydrogen-fuelled PEM fuel cell (high production)	
	(a) 3 kW system	435
	(b) 5 kW system	240
3	Direct hydrogen-fuelled PEM fuel cell (Low production, hand-built prototypes)	1000–3000
4	Gasoline fueled POX reformer (5 kW SOFC APU at 500,000 units year^{-1})	350–550

Conclusion: range to be studied: $ 100–3000 kW^{-1}.

1 h day^{-1} for an year. On the other hand, Brodrick et al. [15] assume an idling of 8 h in their analysis. DoE [2,3] assuming 8 h idling day^{-1}, estimated the idling cost for the trucking industry as $ 1.17 billion. We believe as the idling period increases to ∼8 h day^{-1}, an overall maintenance value of $ 0.9 h^{-1} would be more accurate as it is based on a similar idling period. The manner in which we reach at this value is shown in Table 3.

Although fuel-cell APUs would drastically reduce the need for engine idling, the use of an APU may cause more frequent engine start and stop operations resulting in greater engine wear. The maintenance cost savings by the APU will be the difference between cost savings due to reduced idling and the cost of excess wear caused by increased stops and starts. Brodrick et al. [15] indicated there was inadequate data on these costs to estimate the net impact on operating costs from this factor. It must be noted that fuel-cell APUs are being proposed for a very cost sensitive market where high reliability and durability greater than 15,000 h would be required [30]. However, on account of insufficient quantitative data on the potential costs of frequent engine start-stop operations, incorporating these factors is beyond the scope of this paper.

4.1.4. Investment cost

At this point, fuel-cell APUs are still in their early commercialization stage and it is difficult to predict how the production volumes will change in the foreseeable future. Consequently, as with any technology in its early stages, potential costs of fuel-cell APUs are speculative.

For PEM fuel cell system production in the range of 30,000 units year^{-1}, studies [1,31] have indicated costs in the range of $ 40–200 kW^{-1} for 50 kW systems. Although these estimates include the costs of fuel cell stack, auxiliary systems, power, and control electronics, they do not include the fuel processor and/or hydrogen storage system costs. On account of the higher burden of the "balance of system" components, for smaller systems, production costs of direct hydrogen-fuelled PEM fuel cell systems tend to be higher. Cost of a 3 kW system has been estimated as $ 435 kW^{-1} and a 5 kW system as $ 240 kW^{-1} [1]. For lower volume production systems, the hand-built prototypes are estimated to cost $ 1000–3000 kW^{-1} [1]. Once automated production begins, these costs are likely to drop.

On the other hand, for complete solid oxide fuel cell systems, figures varying by 250% have been quoted. While in PEM fuel cells, expensive platinum or platinum/ruthenium electrode catalysts are needed, SOFCs can utilize inexpensive nickel or copper based catalysts. Even then, companies like Westinghouse have targeted $ 1000 kW^{-1} [32] for a complete cell cogeneration systems based on tubular cell construction; while proponents of stacked planar cell configuration target costs as $ 400 kW^{-1}. The National Energy Technology Laboratory, with private industry partners, is targeting $ 400 kW^{-1} as the cost of the Solid State Energy Conversion Alliance (SECA) SOFC APUs [33]. Table 4 gives an overview of the expected investment rate. SOFCs use a simpler system configuration and, unlike PEMFCs, their stacks do not contain the high-cost precious metals. However, SOFC electrode and electrolyte plates involve a more complex manufacturing process and have a lower power density. EG&G [4] report that although plant costs are lower on account of the simpler reformer, they are partially offset by the cost of the recuperating heat exchangers. An NETL sponsored study to analyze the financial viability of SOFCs in APU applications operated on gasoline concluded that, while the manufacturing cost for such systems could be close to comparable PEM systems, SOFC systems are likely to provide somewhat higher system efficiency [4]. Assuming the typical non-propulsion requirement to be around 5 kW, we believe that a fuel-cell APU would be introduced for heavy-duty trucks as this segment has the capacity to absorb higher per kilowatt fuel cell costs due to the likelihood of significant fuel cost savings.

4.1.5. Fuel costs

While the post-tax fuel cost data available for the 1990s and 2000 indicate the diesel cost range as $ 1.02–1.72 gal^{-1}, data

Table 5
Estimation of fuel consumption during idling

Serial number	Idle time		Fuel consumption (gal year^{-1})				
	h day^{-1}	h year^{-1}	0.60 gal h^{-1}	1.00 gal h^{-1}	1.50 gal h^{-1}	2.00 gal h^{-1}	2.25 gal h^{-1}
1	3.3	1000	600	1000	1500	2000	2250
2	6.0	1818	1091	1818	2727	3636	4091
3	9.0	2727	1636	2727	4091	5454	6136
4	12.0	3636	2182	3636	5454	7272	8181
5	16.5	5000	3000	5000	7499	9999	11249

[34] from the period of 20 January 2004 to 11 July 2005 saw the nationally averaged diesel price increasing to \$ 2.392 gal^{-1}—an increase of 64.8% in just 1 year. On 11 July 2005, the national average was \$ 2.408 gal^{-1} and in CA as high as \$ 2.589 gal^{-1} [34]. Diesel retail prices reflect the trading price of light crude oil [35] and Brent crude oil [36]. Thus, for economic analysis in this paper, to encompass the effect of varying fuel prices, we have used a range of \$ 0.6–2.5 gal^{-1}.

4.2. Economic analysis: heavy-duty trucks

4.2.1. Analysis

If the current non-discretionary idling is completely eliminated, at no extra costs, the savings in fuel that would incur are reflected in Table 5. However, these savings are somewhat offset when the investment cost of the diesel APU is included. Assuming that a typical APU would be a 5 kW unit, our analysis for a single, heavy-duty long-haul truck used the following formulae.

For annual idling time, in hours, the time is a product of the hours idled per day and the days a truck is in operation in a year:

$$\mathrm{IT_Y} = \mathrm{IT_D}\,\mathrm{TD_Y} \tag{4}$$

Annual amount of fuel consumed, in gallons, during idling in 1 year depends on the amount of fuel consumed in an hour and the hours idled in 1 year:

$$\mathrm{FC_Y} = \mathrm{FC_H}\,\mathrm{IT_Y} \tag{5}$$

Annual cost of fuel consumed on idling is a product of the diesel rate, \$ gal^{-1}, and the amount of fuel consumed in idling:

$$\mathrm{IFC_Y} = \mathrm{DR}\,\mathrm{FC_Y} \tag{6}$$

Annual maintenance cost of a diesel engine is proportional to the maintenance rate per hour and the idling time:

$$\mathrm{MC_Y} = \mathrm{MR}\,\mathrm{IT_Y} \tag{7}$$

Total cost of idling a diesel engine is the sum spent on the fuel for idling and the associated maintenance cost:

$$\mathrm{DEIC_Y} = \mathrm{IFC_Y} + \mathrm{MC_Y} \tag{8}$$

Actual cost of idling, accounting for diesel engine inefficiency:

$$\mathrm{ACI_Y} = \mathrm{DEIC_Y}\,\eta_{\mathrm{DE}} \tag{9}$$

Total fuel-cell APU investment cost is dependent on the investment rate per kilowatt and the APU rating required:

$$\mathrm{FCIC} = \mathrm{IR}\,\mathrm{RR} \tag{10}$$

Fuel-cell APU running cost, based on the analysis for diesel engines, with the APU efficiency:

$$\mathrm{FCRC_Y} = \frac{\mathrm{ACI_Y}}{\eta_{\mathrm{APU}}} \tag{11}$$

Total cost of running a fuel cell is the sum of the investment cost and the running cost:

$$\mathrm{FCC_Y} = \mathrm{FCIC} + \mathrm{FCRC_Y}\,n \tag{12}$$

Break-even period, in years, of a fuel-cell APU would be when the cost of diesel engine idling equals the investment and running cost of a fuel cell:

$$\mathrm{BEP} = \frac{\eta_{\mathrm{APU}}}{\eta_{\mathrm{APU}} - \eta_{\mathrm{DE}}}\,\frac{\mathrm{FCIC}}{\mathrm{IFC_Y} + \mathrm{MC_Y}} \tag{13}$$

Based on these formulas, Fig. 1 captures the impact of investment cost, idling consumption per hour, and hours idled per day on the break-even period. Fig. 2 shows the break-even period as a function of idling time per day and two different investment costs with two fuel costs.

4.3. Economic analysis: Abram tanks

Extending the analysis done for heavy-duty trucks into gas-turbine powered, armored military vehicles, this section explains the manner in which we carried out an analysis for M1 and M1A1

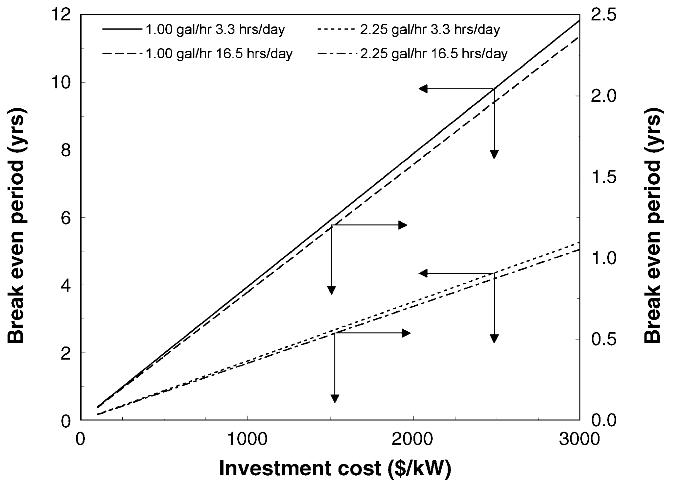

Fig. 1. Break-even period (BEP) (years) as a function of the investment rate (\$ kW^{-1}) when the diesel costs \$ 2 gal^{-1}. At two idling fuel consumption rates – 1 and 2.25 gal h^{-1} – the graph examines the effect on BEP through the range of hours idled per day.

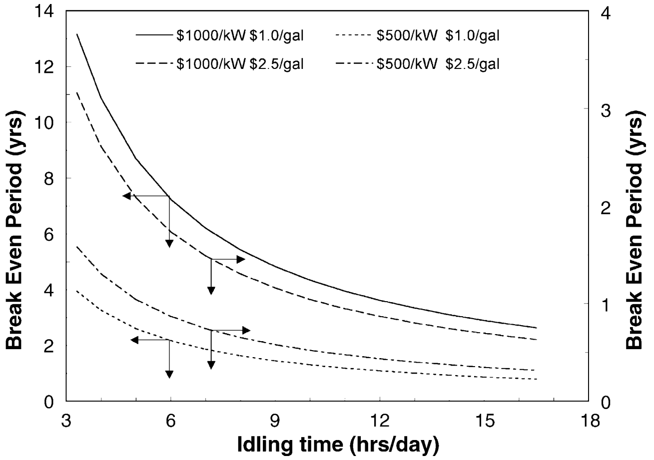

Fig. 2. Break-even period (years) as a function of the idling time (h day^{-1}) when the fuel consumption rate is 1 gal h^{-1}. At two investment rates – \$ 500 and 1000 kW^{-1} – as parameters, the graph shows the BEP through the range of fuel cost—\$ 1 to 2.5 gal^{-1}.

Abram tanks. Lovins et al. [8] report that according to a brief to the Defense Science Board Task Force in August 2000, the M1A1 tank idles at 12 gal h^{-1}. The fuel consumption rate of an APU to be used instead of the gas turbine engine idling would be around 0.5 gal h^{-1}. This indicates that the fuel consumption of the APU being considered is 24 times less than that of the gas turbine engine idling. Since gas turbines are optimized for high acceleration, they tend to be extremely inefficient when idling. Replacing a gas turbine idling at 1% efficiency with an APU would bring the efficiency of the APU to 24% (due to the 24-fold decrease in fuel consumption)—very close to the 30% fuel-cell APU efficiency used in this paper.

While some data is available for the idling fuel consumption rate of gas turbines, no data could be found for the impact of idling on the maintenance costs of a gas turbine. When compared to the heavy-duty truck, the gas turbine engine is not only required to carry a heavier load, under more severe conditions, but also may idle for a larger fraction of its operation time and is more sensitive to dust. When the idling efficiency of a truck is compared to that of the gas turbine, it is clear that the gas turbine is about 10 times less efficient. Thus, all these factors lead us to believe that if an APU replaced an idling gas turbine engine, the savings on the maintenance cost would be significant. Unfortunately, unlike maintenance data for idling of fuel cells, no data could be found for tanks. Thus, in the present situation, since the maintenance cost for idling a tank would be at least that of a truck, this value would be a conservative choice and the actual break-even period so computed is estimated to give an upper estimate of the actual period. Thus, based on the data presented in Table 6 on the idling and maintenance cost of a gas turbine engine, the break-even period can be estimated using the following formula:

$$\mathrm{BEP} = \frac{\eta_{\mathrm{APU}}}{\eta_{\mathrm{APU}} - \eta_{\mathrm{GT}}} \frac{\mathrm{FCIC}}{\mathrm{IFC_Y}} \tag{14}$$

$$\mathrm{BEP} = \frac{30}{29} \frac{\mathrm{FCIC}}{98\mathrm{DR}} \tag{15}$$

Table 6
Potential savings by prevention of idling in M1 and M1A1 Abram tanks

Serial number	Parameter	Unit	Quantity
1	Non-discretionary idling	h year^{-1}	98
2	Gas turbine while idling		
	(a) Fuel consumption	gal h^{-1}	12
	(b) Efficiency	%	1
	(c) Maintenance cost	\$ (idling h)$^{-1}$	0.90
	(d) Maintenance cost	\$ year^{-1}	88.2
3	Fuel-cell APU		
	(a) Fuel consumption	gal h^{-1}	12
	(b) Efficiency	%	30
	(c) Fuel consumption	gal h^{-1}	0.4
4	Projected fuel savings		
	(a) Currently fuel spent on idling	gal year^{-1}	1176
	(b) Projected fuel spent on idling	gal year^{-1}	39.2
	(c) Potential savings	gal year^{-1}	1136.8

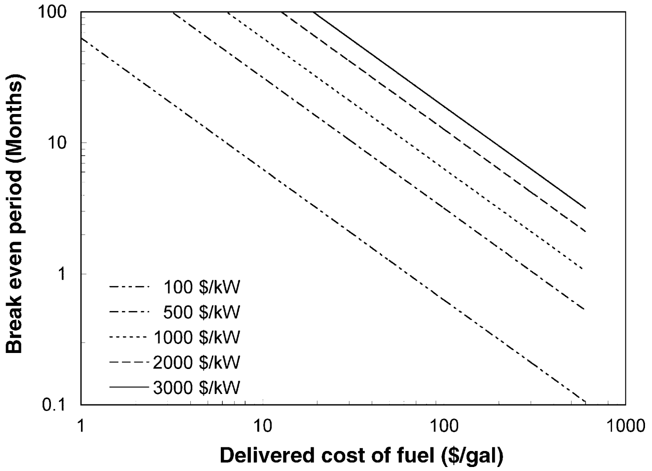

Fig. 3. Break-even period (months) as a function of the actual delivered cost of fuel (\$ gal^{-1}) for a 5-kW APU to be mounted on M1 and M1A1 Abram tanks. The parameter is the investment rate (\$ kW^{-1}).

Fig. 3 captures the effect of investment cost and delivered cost of fuel on the break-even period for M1 and M1A1 tanks.

5. Results

5.1.1. Approach validation with direct hydrogen fuel cell result

To validate our approach and assumptions while estimating the break-even period for a fuel-cell APU equipped with on-board diesel reformers, we compared the result to a direct hydrogen fuel cell [15] drawing hydrogen from a storage tank under identical conditions: \$ 2000 kW^{-1} investment cost, 1 gal h^{-1} fuel consumption costing \$ 1.51 gal^{-1} and 8 h idling day^{-1} for 303 days year^{-1}. While the analysis of Brodrick et al. [15] for the estimated value for a hydrogen fuel cell included the fuel cell stack, auxiliary systems, and power and control electronics, they did not include the hydrogen storage system. As our value of 4.31 years break-even period for a diesel-powered fuel-cell

Table 7
Sample break-even estimates at \$ 500 kW^{-1} when fuel costs \$ 1.5 gal^{-1}

Serial number	Idle time		Pay back time (year)				
	h day^{-1}	h year^{-1}	0.60 gal h^{-1} [a]	1.00 gal h^{-1} [a]	1.50 gal h^{-1} [a]	2.00 gal h^{-1} [a]	2.25 gal h^{-1} [a]
1	3.3	1000	4.39	2.63	1.75	1.32	1.17
2	6.0	1818	2.41	1.45	0.97	0.72	0.64
3	9.0	2727	1.61	0.97	0.64	0.48	0.43
4	12.0	3636	1.21	0.72	0.48	0.36	0.32
5	16.5	5000	0.88	0.53	0.35	0.26	0.23

[a] Fuel consumption rate.

APU compares well with the direct hydrogen fuel cell period of 3.2 years, it validates our assumptions and overall approach.

Although based on our calculations in Table 3, the maintenance cost for idling 8 h day^{-1} should be \$ 0.90 h^{-1}, for the purpose of validating our approach, we used the same total maintenance cost as used by Brodrick et al. [15]; i.e., \$ 0.14 per hour of idling.

5.2. Fuel-cell APU break-even analysis

In order to carry out a break-even analysis for a fuel-cell APU, investment cost, consumption rate, and maintenance costs are some of the key required parameters. However, at present, there are no clear estimates of these parameters in the literature. The cost of fuel itself is highly dependent on global prices and the local tax regime. All these factors tend to make the analysis more complex. Thus, we look at the whole range of parameters and come up with cut-offs: sets of conditions making economic sense. Our analysis explored the range of:

1. Investment costs from \$ 100 to 3000 kW^{-1} at discrete values of \$ 100, 500, 1000, and 3000 kW^{-1}.
2. Cost of diesel fuel from \$ 1.0 to 2.5 gal^{-1} at discrete values of \$ 1.0, 1.5, 2.0, and 2.5 gal^{-1}.
3. Fuel consumption rate from 0.6 to 2.25 gal h^{-1} at discrete values of 0.6, 1.0, 1.5, 2.0, and 2.25 gal h^{-1}.
4. Idling time from 3.3 to 16.5 h day^{-1} at discrete values of 3.3, 6.0, 9.0, 12.0, and 16.5 h day^{-1}.

5.3. Economic analysis trends

Since the typical warranty period of a heavy-duty truck is 4 years, truckers, especially those owning smaller fleets, are not likely to be interested in a technology having a break-even period of greater than 2 years. Thus, the following cut-off conditions emerge:

1. At an investment cost of \$ 3000 kW^{-1}, break-even is observed only at the extreme higher end of the fuel consumption and idling rates, e.g., if the fuel costs \$ 2.0 gal^{-1}, the break-even period makes the cut-off only when fuel consumption exceeds 2.0 gal h^{-1} and the idling time is greater than 9 h day^{-1}.
2. When the investment cost comes down to \$ 1000 kW^{-1}, with fuel consumption 1.5 gal h^{-1} or more, with 6 h day^{-1} or more idling per day, investing into an APU makes sense for the entire range of fuel costs.
3. At \$ 500 kW^{-1} investment rate, barring the lowest end of the range, i.e., fuel consumption 1 gal h^{-1} or less and idling less than 6 h day^{-1}, all other conditions make sense.
4. If the investment rate falls to \$ 100 kW^{-1}, not only do all combinations make the 2-year cut-off, the break-even is well within 1 year for almost the entire range of fuel cost, idling per day, and fuel consumption per idling hour.

To illustrate our approach, a sample break-even period estimation has been shown in Table 7.

Fig. 1 shows the break-even period as a function of the investment cost (\$ kW^{-1}) for a 5-kW APU at two fuel consumption rates: 1 and 2.25 gal h^{-1} when fuel costs \$ 2 gal^{-1}. The trends cover the whole idling range from 3.3 to 16.5 h day^{-1}. The graph shows that when the idling rate is 3.3 h day^{-1}, to make the 2-year break-even window, the investment cost would have to be between \$ 500 and 1200 kW^{-1}. On the other hand, when the idling rate goes up to 16.5 h day^{-1}, at the lowest fuel consumption rate during idling of 1 gal h^{-1}, the break-even period is attained at \$ 2500 kW^{-1}. When the idling fuel consumption rate goes up to 2.25 gal h^{-1}, even at the highest investment cost considered – \$ 3000 kW^{-1} – it is possible to break-even in about 1 year. Thus, this graph reveals that the maximum investment cost that can be sustained – with the required break-even period still met – is heavily dependent on the fuel consumed per hour during idling and the engine idling duration in a day.

The next graph, Fig. 2, captures the effect of idling rate on the break-even period. This graph is based on a 1 gal h^{-1} fuel consumption rate which, besides being one of the most commonly used values for analysis, falls in the middle of the fuel consumption range under consideration. Investment rates chosen – \$ 500 and 1000 kW^{-1} – reflect the investment cost at the lower and medium end of the range analyzed. When the fuel cost is \$ 1 gal^{-1}, at a consumption rate of 1 gal h^{-1}, and investment rate is \$ 1000 kW^{-1}, the break-even period is not attained even at the maximum level of idling per day considered in this study. When the investment cost is halved, to \$ 500 kW^{-1}, at the same fuel cost, for break-even to be attained, the engine would have to be idling for at least 6.5 h day^{-1}. With prices of fuel at historic highs, and with no indication that the prices will decrease anytime soon, the graph also projects the trends when the fuel costs \$ 2.5 gal^{-1}. At this price, when the investment rate is \$ 1000 kW^{-1}, the engine would have to be idling at about 5 h day^{-1}. In case the investment rate drops to \$ 500 kW^{-1}, the break-even period is met well at idling rates even lower than the minimum amount of 3 h day^{-1} taken in this study.

Now, we extend the above analysis for M1 and M1A1 Abram tanks. Unlike heavy-duty trucks on account of insurance policies, requiring a 2-year break-even for any new technology, military vehicles are not subject to such strict time limits. However, compared to commercial vehicles, on account of higher fuel delivery costs, break-even is possible even at higher investment rates. The final graph, Fig. 3, shows the effect of the actual delivered cost of fuel on the break-even period for M1 and M1A1 Abram tanks. Investment rate through a \$ 100–3000 kW^{-1} range has been used a parameter. From the graph it becomes clear, that even at typical land delivered costs – \$ 30 gal^{-1} – the 5 kW APU breaks even within 2 years at about \$ 1100 kW^{-1} investment rate. At higher delivered rates, the APU breaks even inspite of higher investment rates.

6. Conclusions

Reliable, efficient, and quiet APUs might become the first major automotive application of fuel cells due to their potential for significant environmental and economic benefits and relative affordability. SOFC APUs are an attractive, efficient, clean source of power for transportation, military, and stationary applications. Furthermore, the economic analysis presented above shows that fuel-cell APUs can be cost competitive with the existing diesel engines for fulfilling non-propulsion power requirements.

To achieve the 2-year economic breakeven period required for small fleet owners, the most critical parameter is the investment cost of the APU system. Current investment costs are highly dependent on cost of manufacturing of fuel cells and fuel processors. To gradually bring down manufacturing costs, the APU application for fuel cells could potentially combine with demand from other small and medium-sized fuel cell market segments. Examples of such segments include light-duty vehicles, buses and delivery vehicles, commercial and residential stand-alone and backup power systems. Our analysis indicates that there are large ranges of operating conditions and fuel costs where APU systems would be economical. In particular, SOFC-based APUs, thanks to their simpler fuel processing requirements, have the potential to meet the allowable cost targets, provided successful demonstrations prove the technology.

References

[1] C.J. Brodrick, T.E. Lipman, M. Farscchi, N.P. Lutsey, H.A. Dwyer, D. Sperling, S.W. Gouse, D.B. Harris, F.G. King, Evaluation of fuel cell auxiliary power units for heavy-duty diesel trucks, Transport. Res. Part D 7 (2002) 303–315.

[2] DoE, Don't idle your profits away, Office of Heavy Vehicle Transportation Brochure, Department of Energy, Washington, DC, 1999.

[3] F. Stodolsky, L. Gaines, A. Vyas, Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks, Argonne National Laboratory, Argonne, IL, 2000, ANL/ESD-43.

[4] Fuel Cell Handbook, EG&G Services Parsons Inc., S.A.I.C., Office of Fossil Energy, National Energy Technology Laboratory, WV, 2000. http://216.51.18.283/fhandbook.pdf.

[5] A.P. TIAX LLC, Cambridge, MA, Assessment of fuel cells as auxiliary power systems for transportation vehicles, In: Hydrogen and Fuel Cells Merit Review Meeting, Berkeley, CA, 2003.

[6] C.E. Meyer, Diesel tank engines, G2mil—Warfare Research Portal (2005), Summer 2005. http://www.g2mil.com/abramsdiesel.htm.

[7] Wikipedia, Tanks—gas turbines, Wikipedia—the free encylopedia, 2005. http://en.wikipedia.org/wiki/Tanks#Gas_turbines.

[8] A.B. Lovins, E.K. Datta, O.E. Bustnes, J.G. Koomey, N.J. Glasgow, Winning the Oil Endgame, Rocky Mountain Institute, CO, 2005, http://www.oilendgame.com.

[9] IAGS, Fueling Coalition Forces in the Desert, Institute for the Analysis of Global Security, Washington, DC, 2003.

[10] K. Buchholz, K. Jost, Military wants quiet power, improved efficiency, global vehicles, AEI (2003).

[11] C.I. Sandrine, Solid oxide fuel cells—ready to market? Fuel Cell Today, January 7, 2004.

[12] J. Zizelman, S. Shaffer, S. Mukerjee, Solid oxide fuel cell auxiliary power unit—a development update, SAE Technical Paper Ser. 4–7 (2002).

[13] C. Severin, S. Pischinger, J. Ogrzewalla, Compact gasoline fuel processor for passenger vehicle APU, J. Power Sources 145 (2005) 675–682.

[14] D.E. Holt, Auxiliary power units, Serv. Tech. Mag. (2001).

[15] C.J. Brodrick, T. Lipman, M. Farscchi, A.A. Dwyer, S.W. Gouse III, D.B. Harris, F.G. King Jr., Potential Benefits of Utilizing Fuel Cell Auxiliary Power Units in Lieu of Heavy-Duty Truck Engine Idling, Institute of Transportation Studies, University of California Davis, 2001.

[16] L. Pino, Catalytic partial-oxidation of methane on a ceria-supported platinum catalyst for application in fuel cell electric vehicles, Appl. Catal. A 225 (2002) 63–75.

[17] D.L. Trimm, Onboard fuel conversion for hydrogen fuel cell driven vehicles, Catal. Rev. 43 (2001) 31–84.

[18] L. Carrette, Fuel cells—fundamentals and applications, Fuel Cells 1 (2001) 1–39.

[19] J. Larminie, A. Dicks, Fuel Cell Systems Explained, vol. 2, John Wiley & Sons, Chichester, West Sussex, England, 2003.

[20] A.F. Ghenciu, Review of fuel processing catalysts for hydrogen production in PEM fuel cell systems, Curr. Opin. Solid State Mater. Sci. 6 (2002) 389–399.

[21] Q. Ming, Steam reforming of hydrocarbon fuels, Catal. Today 77 (2002) 51–64.

[22] A. Sacco Jr., F.W.A.H. Geurts, G.A. Jablonski, S. Lee, R.A. Gately, Carbon deposition and filament growth on Fe, Co, and Ni foils using CH_4—H_2—H_2O—CO—CO_2 gas mixtures, J. Catal. 119 (1989) 322–341.

[23] C. Pereira, J.-M. Bae, S. Ahmed, M. Krumpelt, Liquid fuel reformer development: auto-thermal reforming of diesel fuel, US DoE 2000 Hydrogen Program Technical Review, San Ramon, CA, Argonne National Laboratory, University of Chicago, DoE, NREL/CP-570-28890, 2000. http://fuelreformer.sirti.org/docs/1D560936-C04F-791A-3C432863CA4D61A2.pdf.

[24] F. Baratto, U.M. Diwekar, D. Manca, Impacts assessment and trade-offs of fuel cell-based auxiliary power units. Part I. System performance and cost modeling, J. Power Sources 139 (2005) 205–213.

[25] DoE, Town looks to truck stop electrification to resolve idling conflict, FreedomCAR and vehicle technologies Program, Energy Efficiency and Renewable Energy, Department of Energy, Washington, DC, 2005. http://www.eere.energy.gov/vehiclesandfuels/pdfs/newsletters/may05_network_news.pdf.

[26] TMC, Fleet Managers Guide to Fuel Economy, T.M. Council, American Trucking Associations, Alexandria, VA, March 1995.

[27] C.-J. Brodrick, Fuel Cell Auxiliary Power Units: The Future of Idling Alternatives? Institute of Transportation Studies, University of California at Davis, 2004, http://www.eere.energy.gov/vehiclesandfuels/pdfs/idling_2004/brodrick.pdf.

[28] J. Lawrence, M. Boltze, Auxiliary power unit based on a solid oxide fuel cell and fuelled with diesel J. Power Sources 154 (2006) 479–488.

[29] TMC, Fleet Managers Guide to Fuel Economy, T.M. Council, American Trucking Associations, Alexandria, VA, March 1995.

[30] J. Garbak, Fuel cell auxiliary power units for trucks, in: SECA Meeting, Seattle, WA, April 15–16, 2003.

[31] D. Arthur, I. Little, Cost Analysis of Fuel Cell System for Transportation: Baseline System Cost Estimate, Department of Energy, 2000, SFAA No. DE-SCO2-98EE50526.

[32] R.F. Service, New tigers in the fuel cell tank, Science 288 (5473) (2000) 1955–1957.

[33] M.C. Williams, J.P. Strakey, W.A. Surdoval, The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program, J. Power Sources 143 (2005) 191–196.

[34] Energy Information Administration, Weekly Retail On-highway Diesel Prices, Department of Energy, Washington, DC, 2005. http://tonto.eia.doe. gov/oog/info/wohdp/diesel.asp.

[35] T.C. Charts, Light Crude Oil (CL, NYMEX), Weekly Price Chart, 11 July 2005. TradingCharts.com (2005). http://futures.tradingcharts.com/chart/CO/W.

[36] T.C. Charts, Brent Crude Oil (LO, IPE), Weekly Price Chart, 11 July 2005. TradingCharts.com (2005). http://futures.tradingcharts.com/chart/BC/W.