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Cost reductions of fuel cells for transport applications: fuel processing options

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Abstract

The highly favorable efficiency/environmental characteristics of fuel cell technologies have now been verified by virtue of recent and ongoing field experience. The key issue regarding the timing and extent of fuel cell commercialization is the ability to reduce costs to acceptable levels in both stationary and transport applications. It is increasingly recognized that the fuel processing subsystem can have a major impact on overall system costs, particularly as ongoing R&D efforts result in reduction of the basic cost structure of stacks which currently dominate system costs. The fuel processing subsystem for polymer electrolyte membrane fuel cell (PEMFC) technology, which is the focus of transport applications, includes the reformer, shift reactors, and means for CO reduction. In addition to low cost, transport applications require a fuel processor that is compact and can start rapidly. This paper describes the impact of factors such as fuel choice, operating temperature, material selection, catalyst requirements, and controls on the cost of fuel processing systems. There are fuel processor technology paths which manufacturing cost analyses indicate are consistent with fuel processor subsystem costs of under $150/kW in stationary applications and $30/kW in transport applications. As such, the costs of mature fuel processing subsystem technologies should be consistent with their use in commercially viable fuel cell systems in both application categories. © 1998 Elsevier Science S.A.

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1. Introduction

In order to achieve widespread commercialization of fuel cells in transport application, current costs for equipment must be brought down by at least an order of magnitude. In the area of polymer electrolyte membrane fuel cell (PEMFC) stack technology, this recognition has already led to successful efforts to reduce platinum costs. Progress has also been reported for the cost of other stack elements particularly membrane and bi-polar plates.

Developers are now increasingly evaluating costs from a system level perspective. Examples of system level tradeoffs that can significantly alter total fuel cell power system costs (and other key product parameters) include:

- system operating pressure
- efficiency/cell voltage level
- design life

However, cost tradeoffs do not stop at the fuel cell powerplant level. At the powertrain level, original equipment manufacturer (OEM) specifications reflect the fact that increasing the fuel cell powerplant voltage level can have a very large positive influence on the inverter and motor weight and costs. Thus, transport fuel cell powerplant developers have been asked to pursue less than optimal stack geometries in order to realize the vehicle-level benefits of a higher fuel cell voltage. Successful commercialization will require that cost tradeoffs be conducted at the highest level possible since competing internal combustion (IC) engine technology enjoys a well developed, cost-efficient manufacturing and fuel delivery infrastructure. In this paper, we will explore two closely related system-level tradeoffs with a surprisingly large leverage on the total cost of fuel cell vehicle powerplants.

- fuel choice
- fuel processor technology

2. Fuel choice for fuel cell vehicles: large hidden costs

Until recently, the most commonly researched fuels for fuel cell vehicles have been hydrogen and methanol. Early fuel cell vehicle prototypes have utilized hydrogen to minimize system complexity and technical risk. Methanol stores more compactly than hydrogen on board a vehicle but

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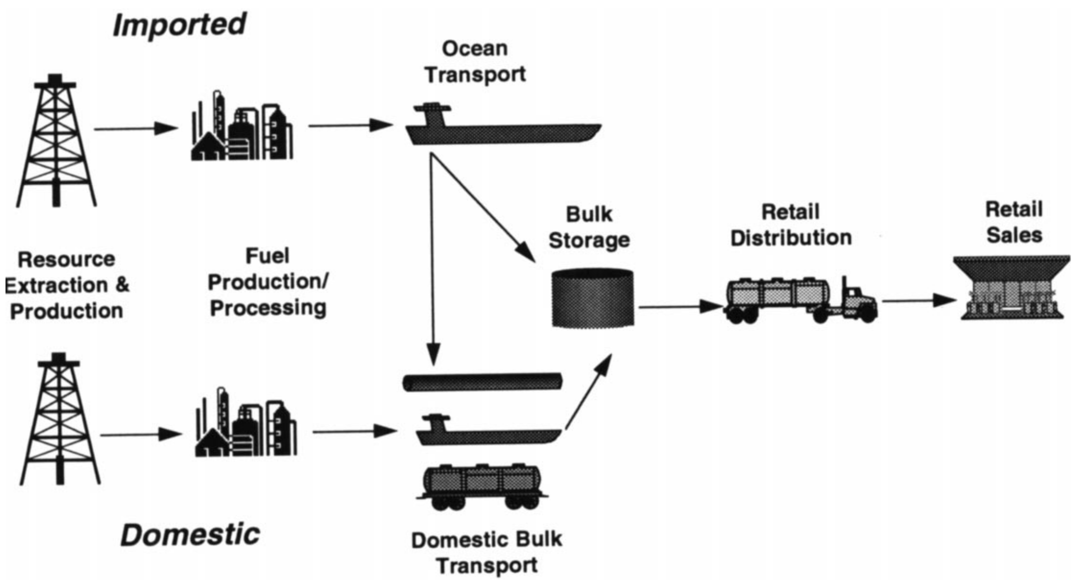

Fig. 1. Simplified fuel infrastructure.

requires a fuel processor to convert the methanol to hydrogen for the PEMFC. Reformer-based fuel cell vehicles have been or will shortly be demonstrated (Georgetown, Fuji, Toyota, Daimler-Benz). These vehicles are all expected to operate exclusively on methanol. Last January, Chrysler Corporation announced plans to build a prototype fuel cell vehicle operating on gasoline. Chrysler cited the poor market track record of previous alternative fuel vehicle efforts as one of the reasons to focus on gasoline. Cost is one of several issues that must be overcome for any alternative fuel to reach market success. Data from a recently completed study makes it possible to assess the system-level costs associated with several proposed alternative fuels.

In a recent study conducted for a major automotive company, Arthur D. Little analyzed the efficiency, emissions and cost associated with a number of possible fuel infrastructure options. The cost analysis looked broadly at all of the infrastructure elements involved in fuel production as shown in Fig. 1. The fuel/resource combinations analyzed are shown in Fig. 2. This paper will focus only on the implications of the fuel infrastructure cost analysis.

To permit a meaningful comparison, this analysis looked at all of the cost elements for a very robust fuel infrastructure that would displace 1 million barrels per day (MMBPD) of current gasoline consumption, about 10% of US gasoline demand or enough for about 25 million vehicles. At this penetration level, full utilization of all infrastructure elements was assumed, making this a ‘steady-state’ analysis. An economic model was developed reflecting all capital and operating costs using industry standard cost components. The model aggregates total capital cost to implement a variety of alternative fuel infrastructures. The results of our comprehensive cost analysis are shown in Fig. 3.

The aggregate capital investment numbers to achieve each candidate alternative fuel infrastructure are very substantial, ranging from $50 billion for a compressed natural

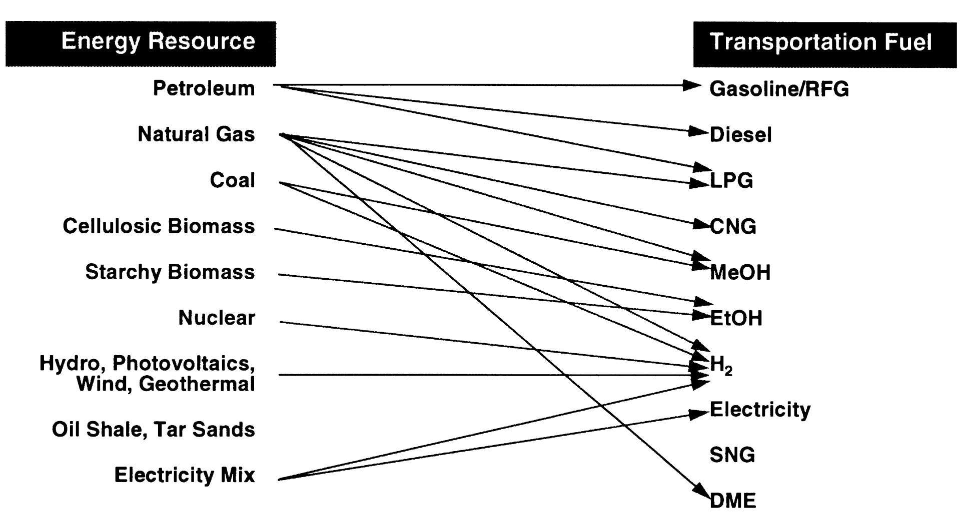

Fig. 2. Many possible resource/fuel combinations were analyzed.

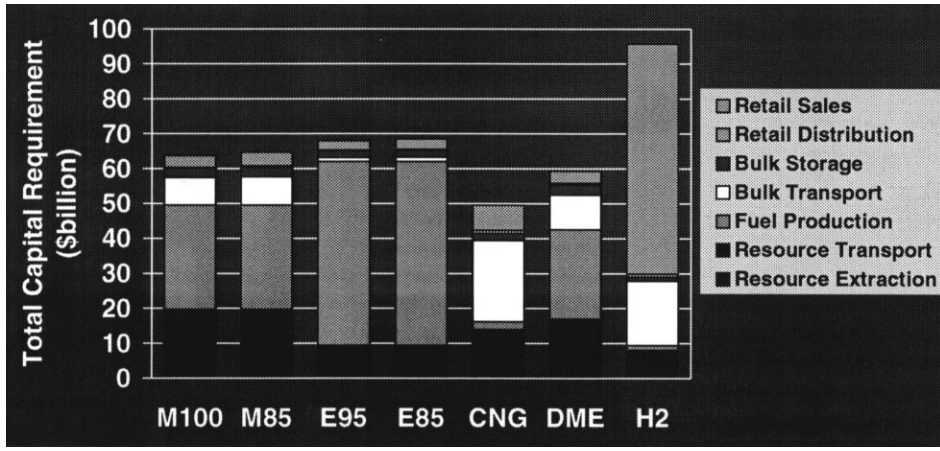

Fig. 3. Capital costs for a 1 million barrel/day fuel infrastructure.

gas (CNG) infrastructure to over $95 billion for a hydrogen infrastructure. Obviously, a very large capital investment will be required to implement even an infrastructure which would displace only about 10% of the US gasoline demand.

It is useful to look at these same cost numbers in a slightly different way. Table 1 shows these costs on a vehicle and kW basis.

From Table 1 it can be seen that the incremental cost contribution of a methanol infrastructure is approximately $\$65/kW_e$. To reach overall cost parity with a fuel cell vehicle operating on gasoline (which enjoys an existing infrastructure that has already been amortized), the methanol powerplant will need to be around $\$65/kW_e$ cheaper. However, such significant cost savings from using methanol will clearly be difficult since the year 2000 fuel processor cost goal is only $\$30/kW_e$ and the overall system cost goal for the year 2004 is $\$50/kW_e$ (Table 2).

The above analysis indicates that, in addition to refueling convenience and consumer familiarity, a gasoline fuel cell vehicle will also enjoy a substantial total system cost advantage over any alternative fuel when the cost of a new infrastructure is included; and, since the vehicle user will ultimately bear the cost of such an infrastructure, this is the most appropriate method for comparing costs. However, some policy makers may advocate the use of alternative fuels to achieve other goals such as reduced carbon emissions or energy resource diversification. To support such eventualities, a fuel flexible fuel processor provides the most options. For instance, ADL's fuel processor has been operated on every major alternative fuel (ethanol, methanol, natural gas, propane) as well as conventional transport fuels. In addition, we recently demonstrated the ability to switch 'on the fly' in seconds from gasoline to propane with no hardware changes.

Table 1

Infrastructure costs normalized on a vehicle and kW basis

Alternative fuel	Total infrastructure cost ($)	Infrastructure cost/vehicle (25 million vehicles) ($)	Infrastructure cost/kW (40-kW_e powerplant) ($)
Compressed natural gas	50 billion	2000	50
Methanol	65 billion	2600	65
Hydrogen	95 billion	3800	95

3. Fuel processor costs: meeting the program for new generation vehicle (PNGV) targets

As the implications of the above analysis begin to be realized, it is likely that gasoline and the alternative fuels with lower infrastructure cost will receive the most attention. The two leading fuel processor technology candidates for these fuels are partial oxidation (POX) and high-temperature steam reforming. Depending on the system integration techniques used, steam reforming may have an efficiency advantage over partial oxidation; however, this has not been verified in actual system operation. More importantly, steam reformers may be more costly and cannot process gasoline on board a vehicle.

To develop a low-cost, fuel flexible fuel processor with

Table 2

PNGV cost targets for fuel cell vehicle powerplants

Year	2000	2004
Fuel cell stack	100	35
Fuel processor	30	10
Total fuel cell system ($/kW)	150	50

Table 3

Weight and volume characteristics of an early generation ADL fuel processor compared with PNGV goals

	1996 50-kW_e fuel processor		PNGV Year 2000 goal
Weight	96 kg	500 w/kg	800 w/kg
Size	70 l	700 w/l	600 w/l

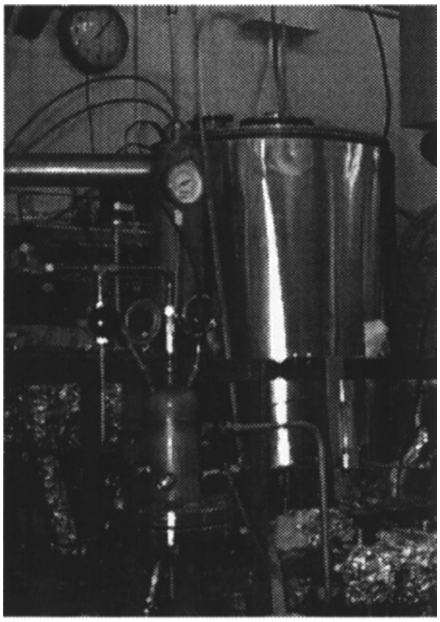

Fig. 4. Generation 3 50-kW$_e$ fuel processor.

Fig. 5. Generation 4 small fuel processor for portable and remote power.

the capability to process gasoline and ethanol, Arthur D. Little has engaged in a five-year partial oxidation fuel processor development program, sponsored initially by the US Department of Energy and the State of Illinois. Extensive brassboard and analytical efforts were conducted in 1992–1994, leading to a unique hybrid partial oxidation approach which has been previously reported. The understanding of partial oxidation processes gained in this early work was used to design ADL's first generation integrated fuel processor in 1995. Though several 'generations' of hardware had previously been fabricated and tested, these new prototypes integrate hybrid partial oxidation reformation with shift reactors, steam generators and means of sulfur removal and can accept gasoline as well as the various alternative fuels cited above. The external features of each subsequent prototype are similar, but the internal aspects reflect improved thermal integration, increasingly sophisticated application of catalysts, and other improvements. Each generation of fuel processors has yielded a significant improvement in one or more key operating characteristics. The fuel processor designed and implemented at 50 kW$_e$ in 1996 exhibited volume characteristics ahead of PNGV year 2000 targets (Table 3) and weight well on the way to meeting automotive requirements.

Thus, our automotive and other customers have asked us to focus recent development work on other important aspects of the fuel processor such as cost, fuel flexibility, hydrogen yield, and start-up time. Table 4 shows the evolution of these fuel processors and some of the key aspects of each generation.

The attributes of several of the early generation fuel processors have been discussed in other forums (Fig. 4). In particular, the ability of our Generation 2 fuel processor to operate on pump grade gasoline has resulted in this option being seriously pursued by a number of automotive companies.

Table 4
ADL integrated hybrid partial oxidation multi-fuel processors have evolved over the last three years of development

Generation	Application	Size (kW$_e$)	Fuels	Start-up (min)	Key improvements
1	Transport	50	Ethanol methanol	60	First compact fuel processor for ethanol
2	Transport	50	Gasoline ethanol methanol natural gas propane JP-8[a]	30	Sulfur removal down to 1 ppmv, operates on pump grade gasoline
3	Merchant hydrogen	50	Gasoline ethanol methanol natural gas propane JP-8[a]	10	Improved catalyst thermal management, low-cost steam generator, fuel switching on-the-fly
4	Portable power	0.3	Gasoline ethanol methanol natural gas propane JP-8[a]	10	Demonstrates POX technology can be scaled to sub-kW range
5 (next)	Transport	50	Gasoline ethanol methanol natural gas propane JP-8[a]	2	Catalyst and cost improvements

[a]Integrated with solid oxide fuel cell.

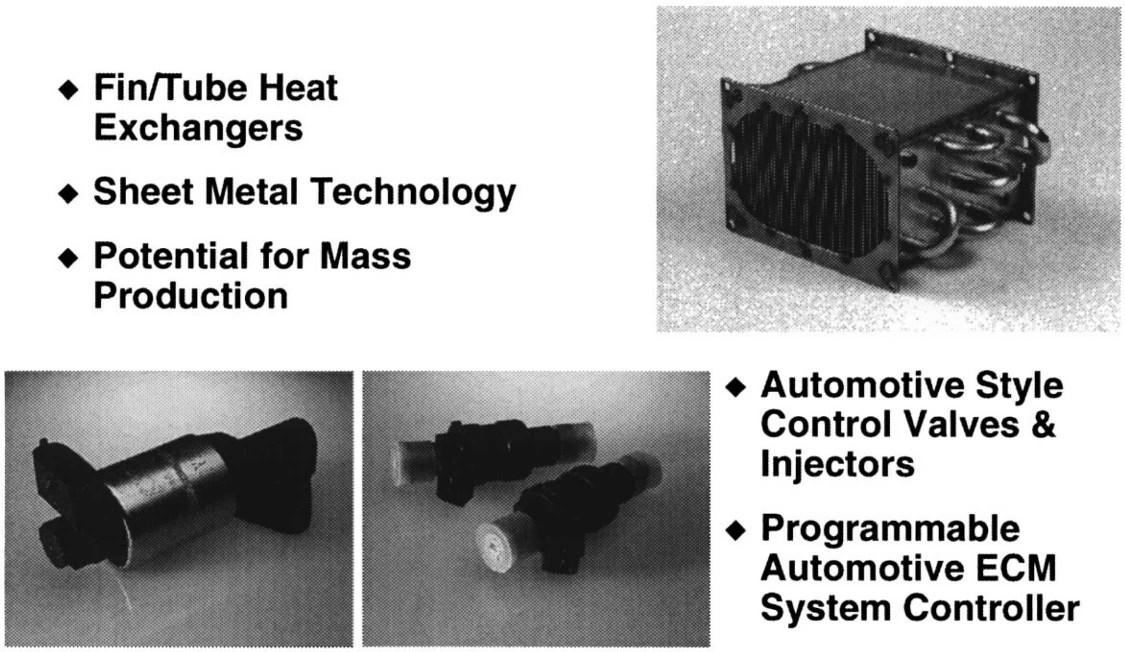

Fig. 6. The Gasoline POX fuel processor uses common materials and processing techniques.

The cost: characteristics of this family of fuel processors are equally attractive as the technical characteristics (Fig. 5). Low cost was one of the key objectives that led to ADL's initial decision to pursue partial oxidation. Each generation of fuel processors has retained the focus on low cost. Fundamental attributes of ADL's hybrid POX fuel processor design which provide for low cost include:

- gas phase reactions limit the amount of reforming catalyst needed;
- absence of high-temperature heat exchangers eliminates the need for exotic metal or insulating materials or difficult fabrication techniques; and
- simple closed-loop controls implemented with low-cost automotive technology.

Fig. 6 shows some of the fabrication techniques and components utilized in these fuel processors.

The 50-kW_e Generation 2 gasoline/ethanol fuel processor for transport has been subjected to several cost analyses. This effort involved three separate analyses – two conducted by ADL manufacturing experts (using different

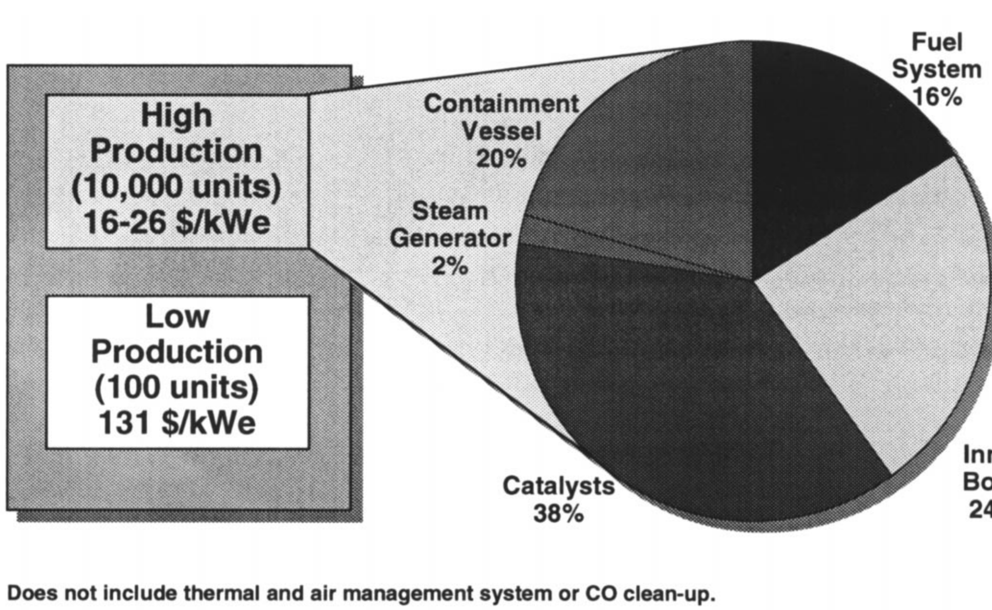

Fig. 7. Major cost elements of a Generation 2 50-kW_e gasoline/ethanol fuel processor.

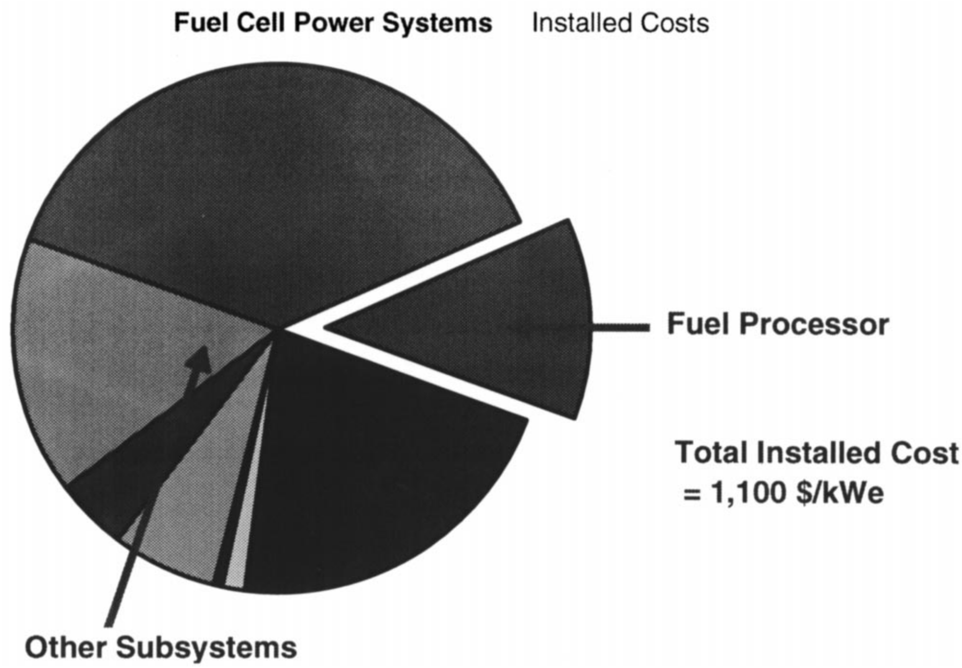

Fig. 8. Installed cost for a 50-kW_e stationary natural gas PEMFC (1000 units/year).

approaches), and one independent analysis conducted by the cost estimation group of a US automotive OEM. These manufacturing cost estimates included material, labor, manufacturing overheads, and expenses (tooling, facilities, and engineering).

For quantities typical of the early years of a successful automotive introduction (10 000 units/year), resulting cost estimates ranged from 16 to \$29/kW_e. Fig. 7 shows some of the details from one of the cost estimation efforts.

In stationary applications, the fuel processor cost will also be a key to early market penetration. The hybrid POX fuel processor design fits well in the range being considered for most stationary PEM fuel cell systems (2–250 kW_e) and will utilize core technology and low-cost features from the transport fuel processor design. The cost analysis described above was extended to the lower quantities (100–1000 fuel processors/year) which may be typical of early stationary fuel cell markets. For this application and manufacturing volume, our estimates indicate a cost significantly below \$150/kW_e.

In system level cost studies, we have found that a low-cost fuel processor is a fundamental requirement for achieving a small stationary fuel cell power system installed cost of less than \$1500/kW_e. Fig. 8 illustrates this point using cost estimating data taken from an extensive cost tradeoff analysis of 50-kW_e natural gas PEM fuel cell power systems (1000 units/year). Several different powerplant configurations (representing different efficiencies and other parameters) were developed which meet the key cost goals for stationary market entry. If the ADL low-cost, efficient, fuel processor strategy is pursued, the cost of the fuel processing subsystem is no longer a major barrier to achieving overall system cost goals.

4. Conclusions

Fuel choice and fuel processing technology choice will be fundamental factors in the success of fuel cell vehicles. Linking fuel cell vehicle entry strategies with a specific alternative fuel with expensive infrastructure costs will ultimately create fuel cost burdens that exceed the cost targets for fuel cell powerplants themselves. As improvements to IC engines narrow the efficiency and emissions advantages of fuel cell powerplants, this added cost burden could render fuel cell vehicles non-competitive. A competitively priced fuel and a low-cost fuel processor are critical to the success of early fuel cell vehicle entries.

Fuel flexible fuel processors offer an attractive alternative to cost and fuel selection issues. Complete fuel flexibility has been demonstrated operating on conventional transport fuels and alternative fuels such as ethanol, natural gas and methanol. This eliminates the need to narrow the fuel choice until environmental, political and economic tradeoffs become clearer. The low cost of these fuel processors will contribute to early market success for fuel cells in both transport and stationary markets.