Introduction to the
Split Fuel Stream Hybrid Energy System

A Highly Efficient

Fuel Cell/Combustion Engine

Power Generation System

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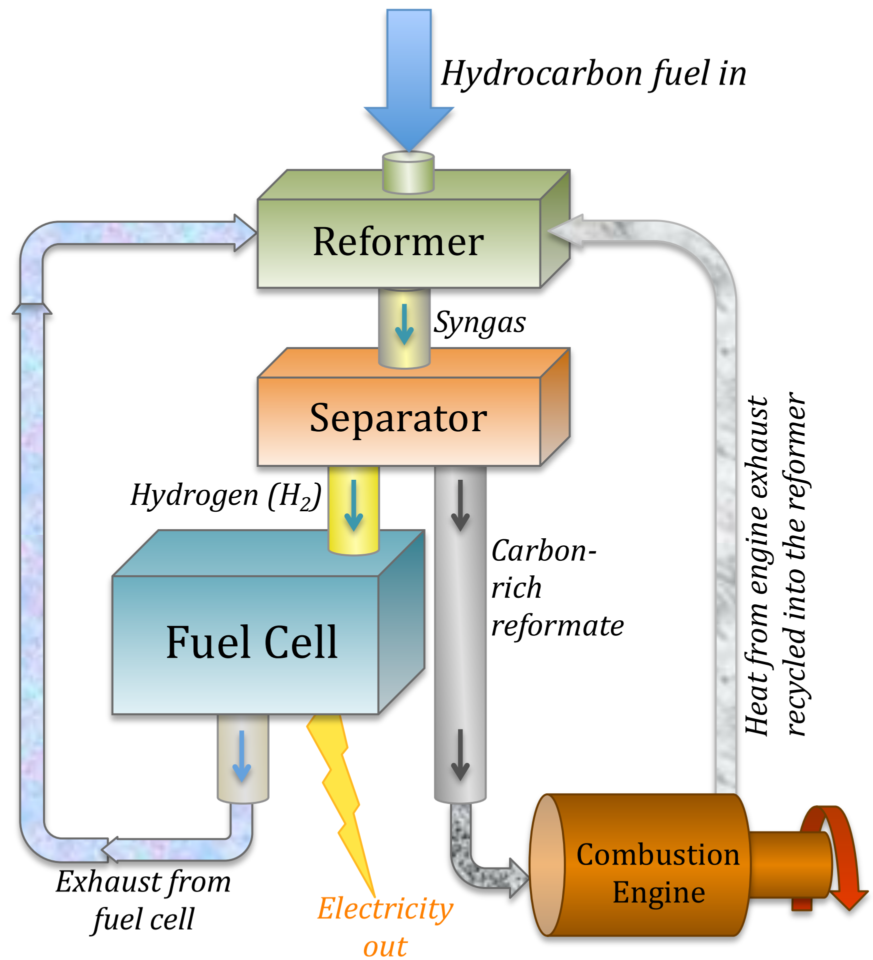
Quick Look

Features of the Split Fuel Stream System:

- This is a hybrid system. It combines two energy generation technologies (fuel cells and combustion engines[1]) in a single, integrated system.
- Reformed fuel (syngas) is separated into two fuel streams.
- H_2 is sent to the fuel cell. H_2 fuel maximizes the efficiency and life of the fuel cell.
- The carbon-rich fuel stream is sent to the engine.
- The exhaust stream from the fuel cell is fed back into the reformer.
- Exhaust from the engine is fed into a heat exchanger at the reformer.
- We believe this design will yield the longest life and highest lifetime efficiency of any fuel cell system developed to date.



Simplified block diagram of the Split Fuel Stream System

[1] Typically the combustion engine will be a gas turbine. Piston engines can also be used.

The Split Fuel Stream Hybrid Energy System

Executive Summary

- A new, patented design for a fuel cell/combustion engine power generation system
- Our estimates indicate the Split Fuel Stream System (SFS) will have the highest real-world efficiency of any power generation system developed to date
- Maximizes fuel cell life
- Uses existing, proven technologies
- Scalable from grid-sized power plants to small on-board vehicle power
- Fuel flexible – can use all common hydrocarbon fuels
- Inherently clean

Overview

The world is transitioning to sources of energy that are renewable and environmentally friendly, but this transition is going to take a long time. Meanwhile, it appears that fossil fuels will be the lowest cost and most abundant source of energy for the foreseeable future.

So we need to utilize energy from fossil fuels as efficiently as possible and minimize harmful chemicals in the exhaust. That is the motivation behind the Split Fuel Stream Hybrid Energy System (also called the SFS System, or just SFS).

This paper presents the Split Fuel Stream System in the following sections:

- Step-by-step description of the SFS
- Comparison to prior fuel cell/combustion engine systems
- Example applications
- Estimate of system efficiency and energy cost
- Status of intellectual property
- Current state of development of the technology

Step-by-Step Description of the Split Fuel Stream System (SFS)

Step 1: Fuel

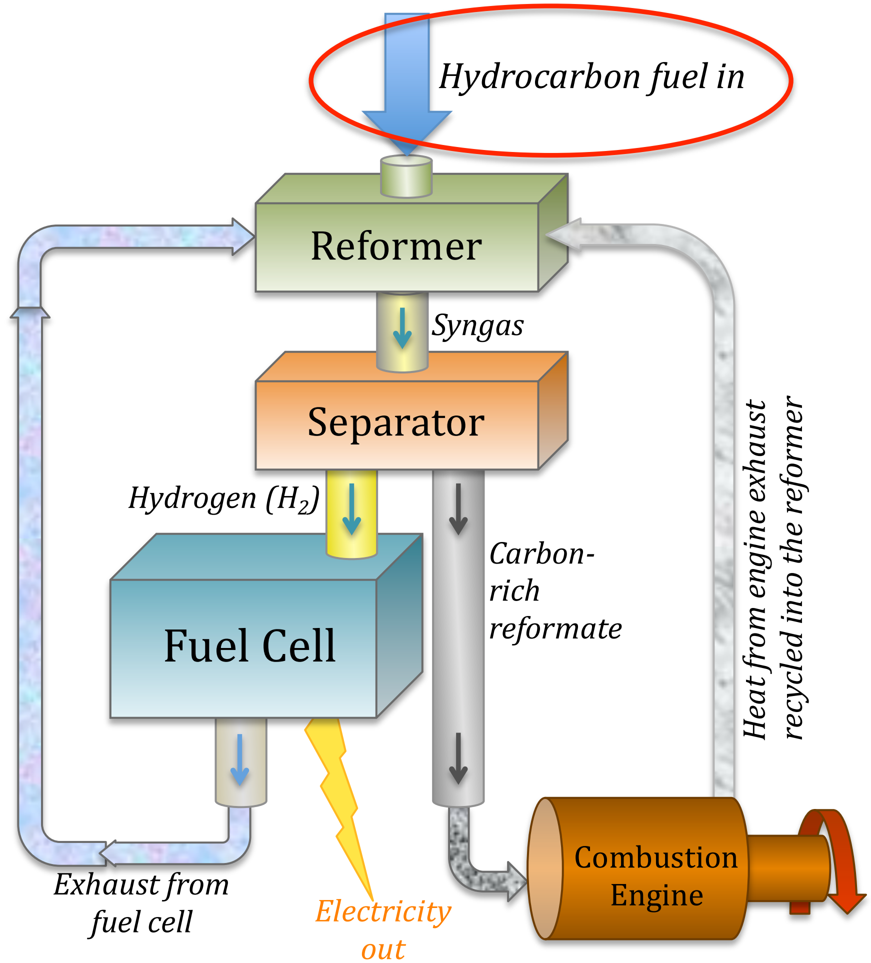
The SFS is compatible with almost any liquid or gas hydrocarbon fuel, including:

- Natural gas
- Gasoline
- Diesel fuel
- Coal gas
- Propane

These fuels are available in abundant supply and at relatively low cost.

The SFS does not require new or exotic fuels. Existing fuel processing infrastructures and supply chains can provide the fuel needs of the SFS.

As biogas production ramps up, biogases can also be used as fuel in a Split Fuel Stream System. This would create an end-to-end green energy generation system.

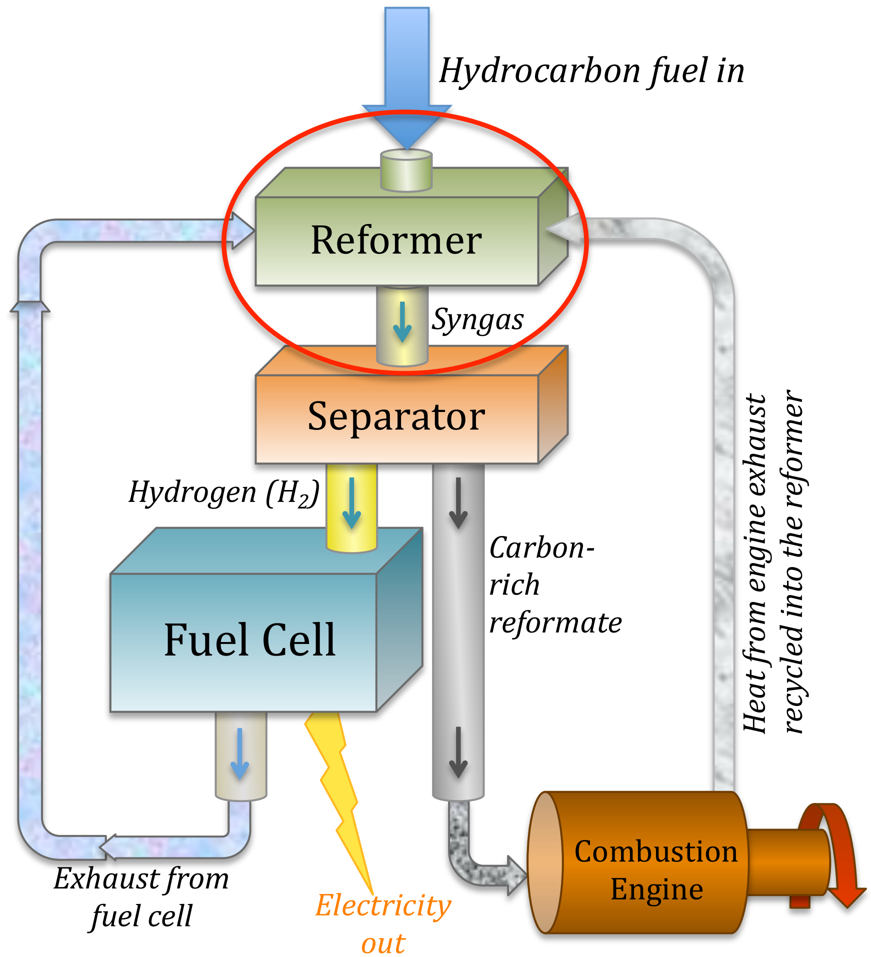


Simplified block diagram of the Split Fuel Stream System

Step-by-Step Description of the Split Fuel Stream System

Step 2: Reforming

Reforming is well-established technology that separates hydrogen from hydrocarbons. Steam reforming is presently best suited for the SFS. Plasma-steam reforming holds promise as an alternate technology.



Simplified block diagram of the Split Fuel Stream System

Steam Methane Reforming

In a natural gas supply, methane is the dominant hydrocarbon. The dominant reaction that takes place in a steam reformer is:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

For each molecule of methane that is reformed, three molecules of hydrogen and one molecule of carbon monoxide are formed. This blend is called syngas.

Non-Methane Hydrocarbon Reforming

For longer chain hydrocarbons, the generalized reaction equation for steam reforming is:

$$C_nH_m + n\,H_2O \rightleftharpoons (n + m/2)\,H_2 + n\,CO$$

Two important points to note about reforming in the SFS:

1. There is more energy in the hydrogen stream than in the carbon stream. This is a key point, discussed in more detail later in this paper.
2. Methanation and the water-gas shift reaction are not required in the SFS. The SFS can use the output from the reformer without further processing (except for separation – see next page).

Step-by-Step Description of the Split Fuel Stream System

Step 3: Separation

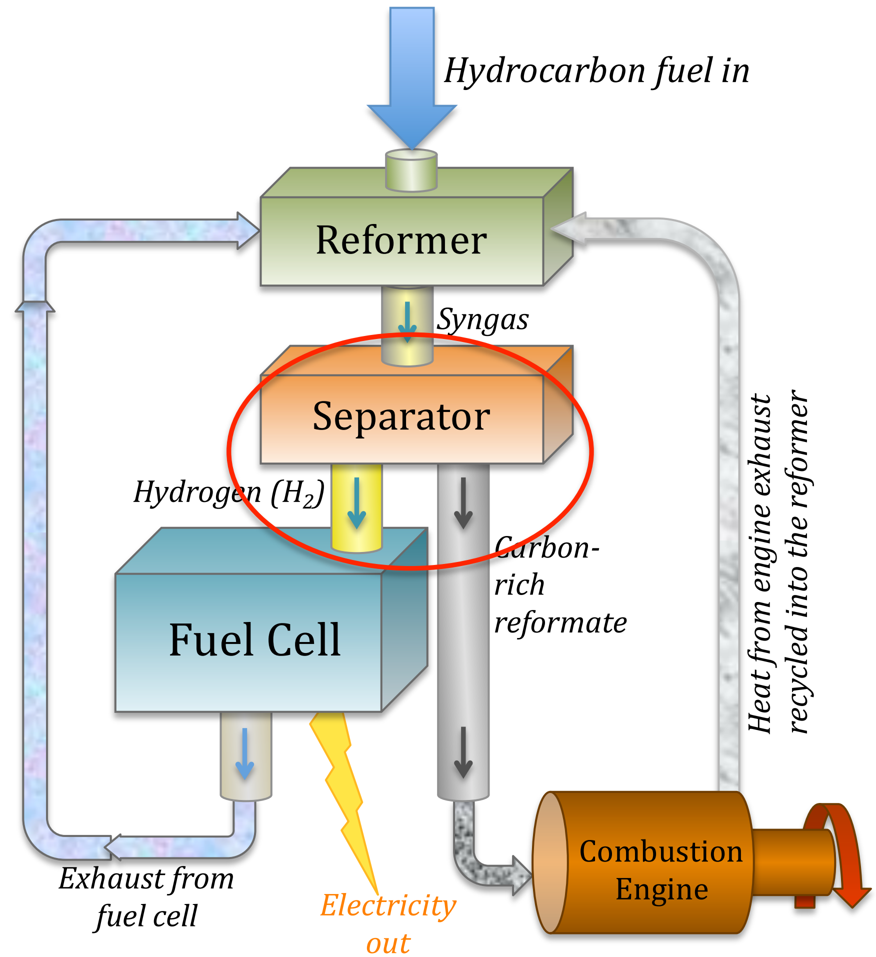
Gas separation is the next step in the SFS. The H_2 in the syngas is separated from the CO (and other carbon compounds that are present).

The separated gases are split into two streams. The hydrogen stream is routed to the fuel cell. The carbon-rich stream is routed to the combustion engine.

The specific gas separation technology is not critical. Any technology that can separate hydrogen from the other components of syngas can be used.

Pressure swing adsorption or membrane gas separation can be used. Both of these are mature, widely used technologies.

The purity of the hydrogen stream is important. In general, the higher the purity of the hydrogen stream, the better. If there are carbon compounds in the hydrogen stream, they will decrease the efficiency of the fuel cell and will shorten its life. This is discussed in more detail later in this paper.



Simplified block diagram of the Split Fuel Stream System

Step-by-Step Description of the Split Fuel Stream System

Step 4: Fuel Cell

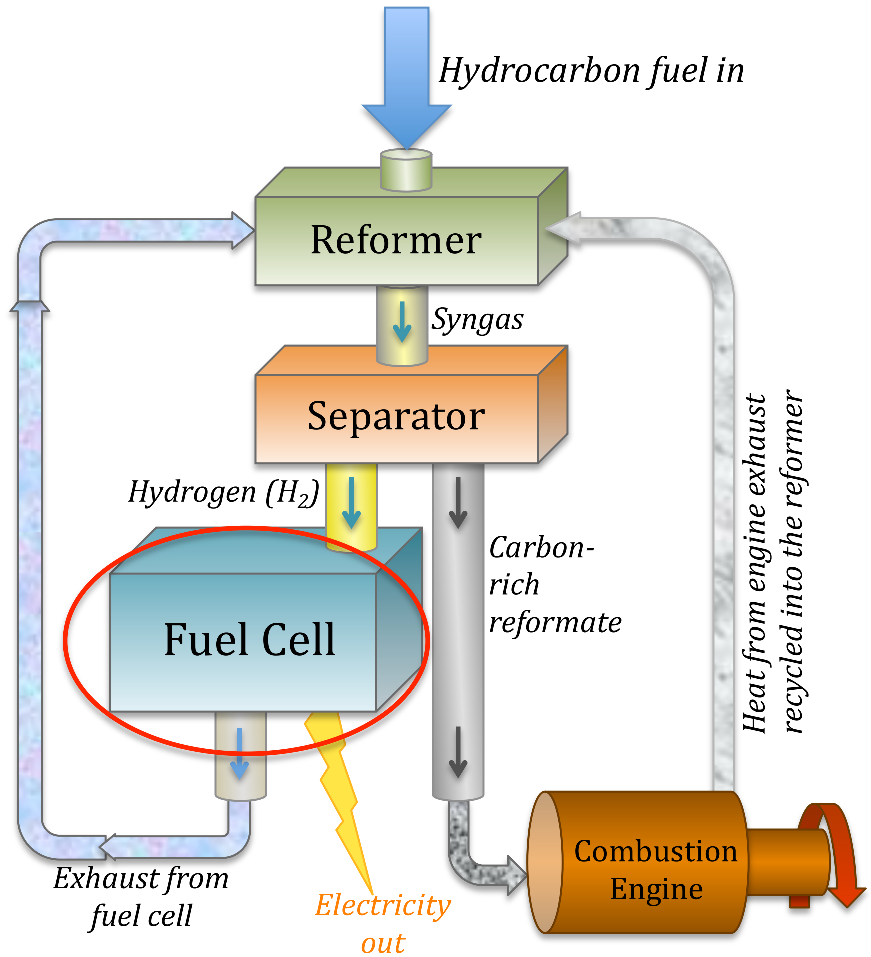
The fuel cell converts the hydrogen into electricity through an oxidation reaction. Any kind of fuel cell can be used in the SFS. In large-scale systems, solid oxide fuel cells (SOFCs) are well suited for the SFS. In small-scale systems, smaller SOFCs or PEM fuel cells can be used.

Key goals of all fuel cell systems are:

1. Maximize the fuel energy that is extracted by the fuel cell
2. Maximize the efficiency of operation of the fuel cell
3. Maximize the life of the fuel cell

Prior designs of hybrid fuel cell/gas turbine systems attempted to achieve these goals but failed, as a result of some intuitive but flawed assumptions.

The SFS is a new approach to hybrid fuel cell/combustion engine energy systems, designed specifically to achieve the three goals listed above.



Simplified block diagram of the Split Fuel Stream System

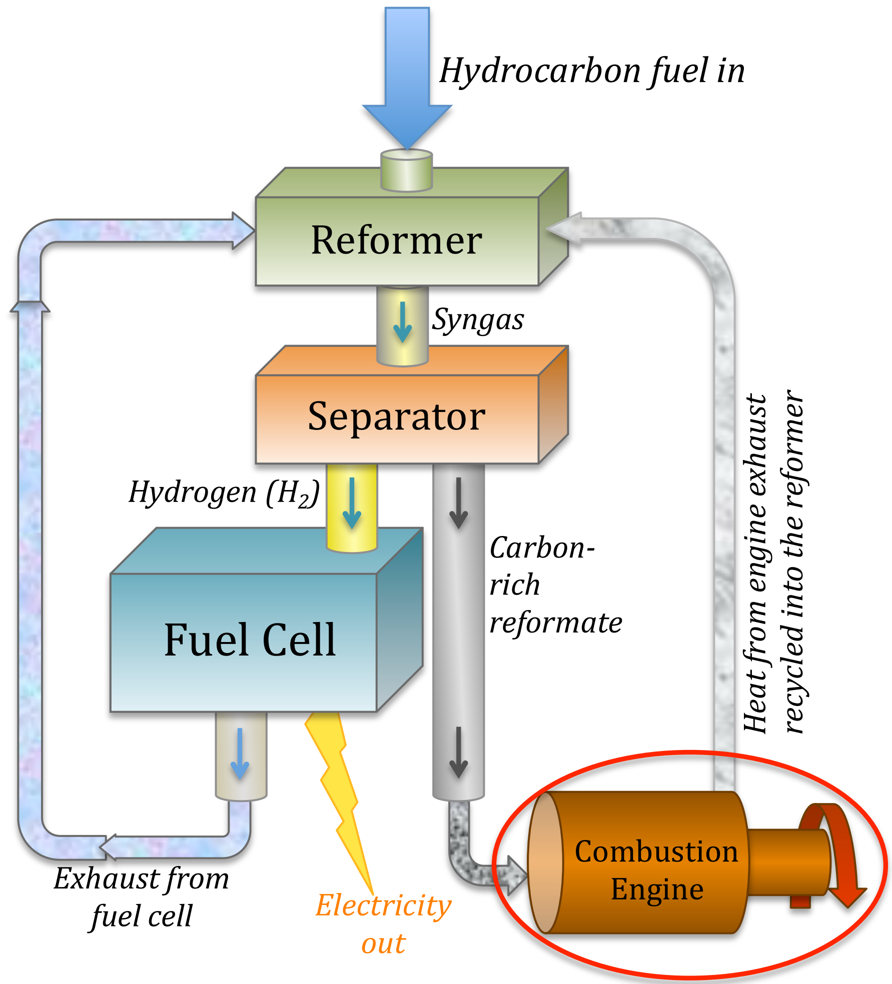
Step-by-Step Description of the Split Fuel Stream System

Step 5: Combustion Engine (Gas Turbine or Piston Engine)

The carbon-rich stream is the fuel supply for a combustion engine. Gas turbines and piston engines are the top candidates.

In systems designed for pure electricity generation, the output shaft of the engine will be coupled to a generator.

In other systems, the engine could be used as a source of mechanical energy.



Simplified block diagram of the Split Fuel Stream System

Step-by-Step Description of the Split Fuel Stream System

Step 6: Recirculate the Exhaust

The exhaust from the fuel cell consists of steam and hydrogen. A fuel cell typically oxidizes about 80% of the H_2 in one pass through the cell, so there is residual H_2 in the fuel cell exhaust.

This exhaust is routed back into the reformer thereby recirculating the heat, steam and hydrogen.

The exhaust from the combustion engine is similarly recycled, taking advantage of the heat in the exhaust. This exhaust is routed to a heat exchanger (not shown) to capture the heat, which is transferred to the reformer.[2]

Steam and heat are two of the key ingredients to make a reformer work. (The other two are pressure and a catalyst.)

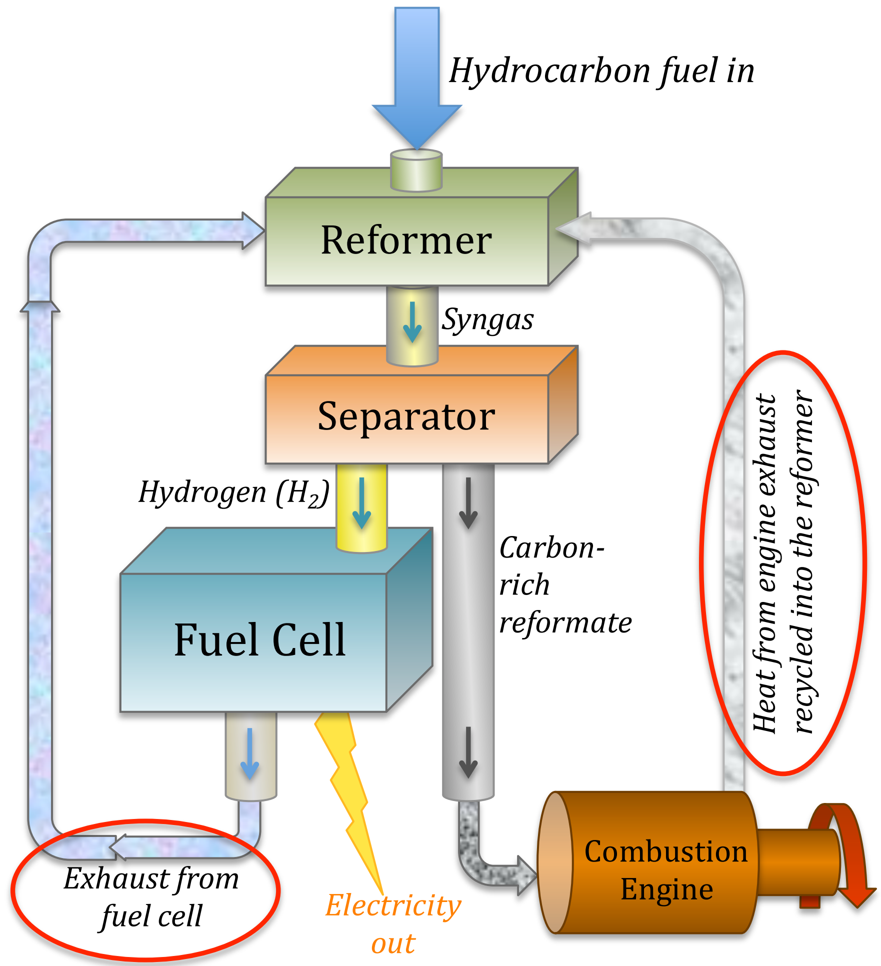
Recirculating the two exhaust streams to the reformer increases the total energy efficiency of the SFS in three ways:

1. Unoxidized H_2 is cycled back to the fuel cell
2. Steam from the fuel cell is fed to the reformer
3. Heat from the engine exhaust is captured and fed to the reformer

Points 2 and 3 minimize the amount of external heat and steam that needs to be fed into the system.

The SFS is inherently a combined heat and power (CHP) system. CHP is designed into the system, rather than being created as an afterthought by adding hardware to the system.

This solution increases efficiency, reduces system cost and complexity, and lowers maintenance costs.



Simplified block diagram of the Split Fuel Stream System

[2] The heat-depleted exhaust can be vented to the atmosphere or, preferably, captured for subsequent sequestration.

Step-by-Step Description of the Split Fuel Stream System

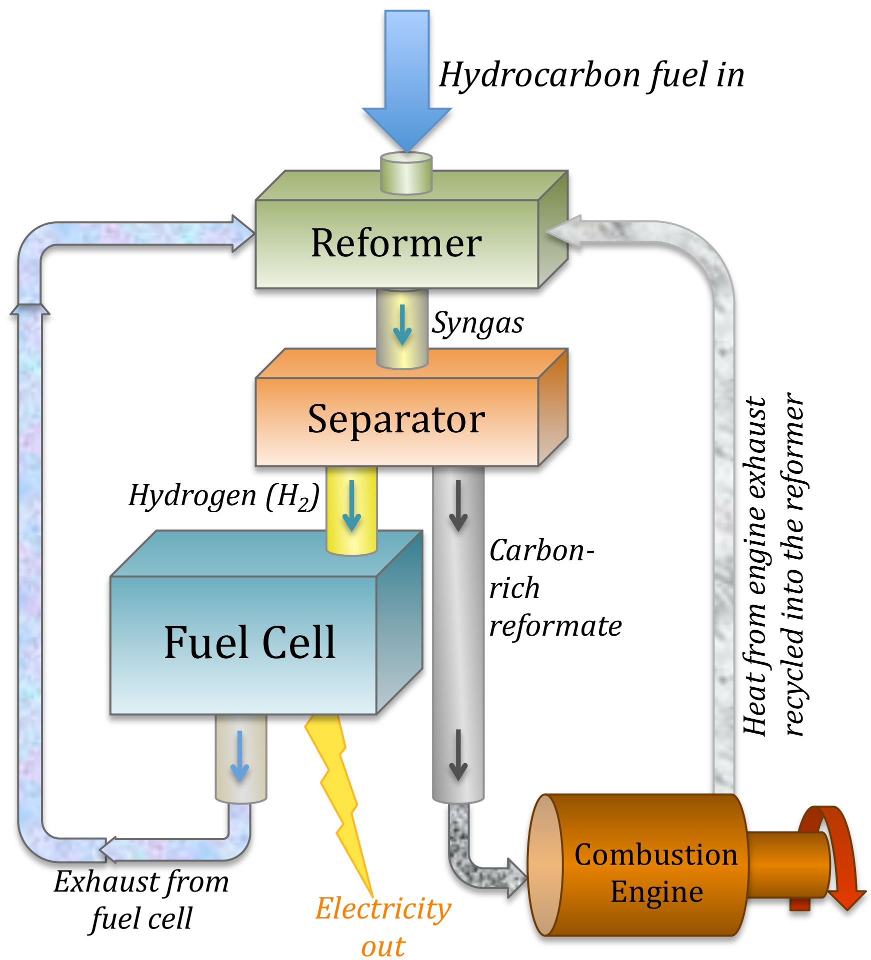
Conclusion

Two differences between the SFS and prior hybrid fuel cell systems are:

- Separating the syngas into a hydrogen stream and a carbon stream, and feeding these streams into the fuel cell and the combustion engine respectively
- Making CHP an integral part of the system rather than extra hardware that is tacked on.

These features are design breakthroughs that are intended to make the SFS the most efficient and longest-lived fuel cell system yet developed.

The next section of this paper compares the SFS design to prior hybrid designs and explains the how the improvements in the SFS are expected to overcome shortcomings in prior fuel cell systems.



Simplified block diagram of the Split Fuel Stream System

Comparison of SFS to Prior Hybrid Fuel Cell Designs

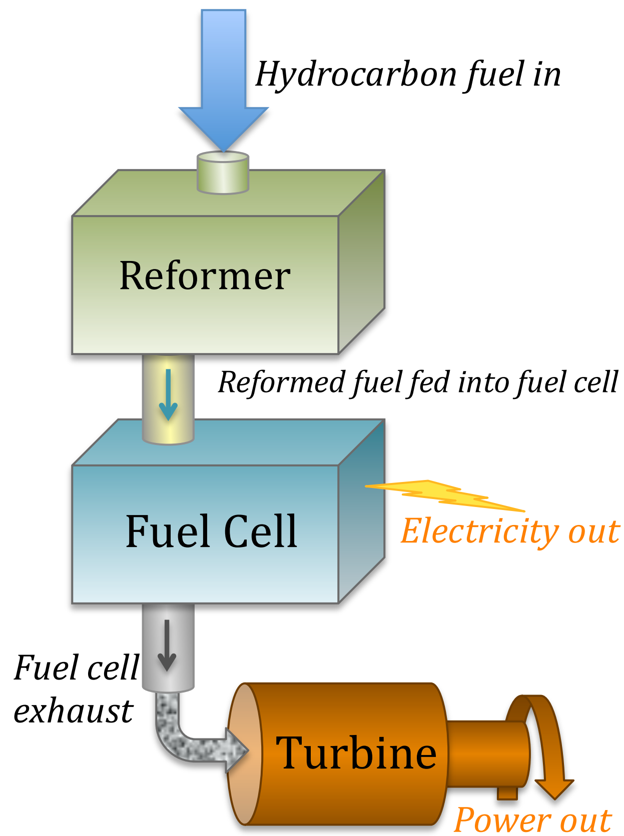
Description of Prior Design

This figure shows a typical hybrid fuel cell/turbine energy system, prior to the SFS. The figure is simplified to high-light differences between prior designs and the SFS.

In this design strategy, the syngas from the reformer (hydrogen gas and carbon compounds) is fed into the fuel cell. The syngas is not separated.

The major components in the fuel cell exhaust are:

- Steam
- Hydrogen that was not oxidized by the fuel cell
- CO_2 – created by oxidation of CO in the syngas that entered the fuel cell
- Low concentrations of CO (carbon monoxide that was not oxidized in the fuel cell)



Simplified block diagram of a hybrid fuel cell/turbine system. This is typical of hybrid systems prior to the SFS System.

The fuel cell exhaust is fed to the turbine. In some designs a compression turbine is used, extracting the heat from the fuel cell exhaust. In other designs, the fuel cell exhaust is burned in a combustion turbine.

A major difference between the prior designs and the SFS is that in prior designs all of the syngas is fed to the fuel cell. The rationale for this is that fuel cells are (in theory) the most efficient means of converting hydrocarbons to electricity. So to achieve the highest efficiency from the system all of the fuel is fed to the fuel cell. Then the turbine harvests residual energy from the fuel cell exhaust.

Shortcomings of Prior Design

In theory, the prior design will maximize fuel efficiency because fuel cells have higher hydrocarbon conversion efficiency than any other known technology. In reality, the prior design has shortcomings that reduce total energy efficiency, raise operating and maintenance costs, and shorten system life.

To explain this, we start with an analysis of the energy content in the fuel. For this analysis we will assume the fuel is natural gas.

As mentioned above, the primary reaction in reforming natural gas is:

$CH_4 + H_2O \Rightarrow CO + 3H_2$

A secondary reaction that occurs at a lower rate is:

$CH_4 + 2H_2O \Rightarrow CO_2 + 4H_2$

Hydrocarbon gases (before reforming) have about half their energy contained in the hydrogen bonds and about half in the carbon bonds. During reforming, water donates hydrogen atoms to create hydrogen gas. Post-reforming, the ratio of energy is skewed towards hydrogen. The mix of gases coming out of the reformer is more than three parts H_2 to one part $\{CO + CO_2\}$. More than 75% of the available energy is now in hydrogen bonds. The shift in energy content towards H_2 is key.[3]

What happens if this entire syngas mix (H_2 plus carbon compounds) is fed into the fuel cell?

Carbon Degrades the Fuel Cell

Feeding the carbon compounds into the fuel cell to extract energy from the carbon sounds like a good idea. Combustion engines are subject to the well-known Carnot heat engine efficiency limitation. Fuel cells are non-Carnot energy systems and can generate electricity from fuels at efficiencies that exceed Carnot limitations.

But carbon compounds have insidious side effects in fuel cells. To explain how this happens, we start with a list of relevant chemicals in the syngas.

[3] The information in this paragraph is a simplification. In the real world, there are small percentages of longer chain hydrocarbons in natural gas, and a more complex mix of reactions in the reformer. But the principal of energy shift towards hydrogen bonds is a valid and key point.

Table 1: Chemicals of interest in syngas

Chemical	Comments
H_2	Created in these reactions: $CH_4 + H_2O \Rightarrow CO + 3H_2$ $CH_4 + 2H_2O \Rightarrow CO_2 + 4H_2$
CO	Created in this reaction: $CH_4 + H_2O \Rightarrow CO + 3H_2$
CO_2	Created in this reaction: $CH_4 + 2H_2O \Rightarrow CO_2 + 4H_2$
C (fine carbon soot)	Created in small quantities in the reformer
CH_4	Reformers are not 100% efficient. About 15% to 20% of the methane is not reformed and is a constituent of the syngas.

The H_2 in the syngas is like nutritious organic food for the fuel cell. The fuel cell oxidizes hydrogen efficiently and the hydrogen has no adverse effects on the fuel cell.

Continuing the food analogy, all of the carbon compounds listed above are like junk food to the fuel cell. The effect of these chemicals on the fuel cell is listed in Table 2.

Table 2: Effects of carbon compounds on the fuel cell

Chemical	Positive Effects	Negative Effects
CO	CO is oxidized in the fuel cell, creating electricity. About 80% of the CO that passes through the fuel cell is oxidized (similar to the rate of oxidation of H_2 in the fuel cell).	CO contributes to carbon deposition in the fuel cell. This occurs on the electrodes, in the electrolyte and on the interconnects. Carbon deposition accumulates over the operating life of the fuel cell. It causes internal resistance, decreases performance and shortens fuel cell life. Additionally, CO has a slower transport rate through the fuel cell. This lowers the efficiency of the fuel cell.

Chemical	Positive Effects	Negative Effects
CO_2	None - CO_2 is not oxidized in the fuel cell	CO_2 contributes to carbon deposition with the same negative effects noted above. The presence of CO_2 also reduces fuel cell efficiency.
C (fine carbon soot)	None – carbon soot is not oxidized in the fuel cell	Carbon soot contributes to carbon deposition and lowers average operating efficiency of the fuel cell
CH_4	None – methane is not oxidized in the fuel cell	The presence of methane reduces fuel cell efficiency.

Specific Comments on Carbon Compounds in SOFCs

SOFCs can tolerate some carbon, but they must operate at very high temperatures – around 1000°C – to process the carbon molecules. The high operating temperatures add to system cost and maintenance cost. Start-up times are longer (due to the warm up period) and there is thermal stress on the fuel cell, especially during start up and shut down. All of these side effects reduce operational life. And even at the high operating temperatures carbon deposition (coking) takes place on the electrodes.[4]

Another problem created by feeding carbon into the fuel cell is that CO acting on the anode of the SOFC reduces the reaction rate of the fuel cell by 40% to 50%. Lower CO oxidation rates in the SOFC (in comparison to the hydrogen oxidation rates) are caused by the slower transit time of the CO through the fuel cell and by carbon deposition in the fuel cell. This further decreases the efficiency of the fuel cell.[5]

[4] The following references discuss carbon-induced degradation of fuel cell electrodes:

"Low Temperature SOFC for Lifetime and Reduced Costs", Bert Rietveld, Energy Research Center of the Netherlands (ECN)

"Evaluation of carbon deposition behavior on the nickel/yttrium-stabilized zirconia anode-supported fuel cell fueled with simulated syngas ", Tao Chen, Wei Guo Wang, He Miao, Tingshuai Li, Cheng Xu -- Journal of Power Sources 196 "(2011).

Journal of Power Sources, Volume 205, 1 May 2012, Pages 377-384, "The Interaction of SOFC Anode Materials with Carbon Monoxide", Barbara Novosel, Mihael Avsec, Jadran Maček

[5] The following references discuss the effect of carbon on fuel cell efficiency:

"Durability of Low Pt Fuel Cells Operating at High Power Density (a/k/a SPIRE : Sustained Power Intensity with Reduced Electrocatalyst" – Olga Polevaya; Scott Blanchet; Rajesh Ahluwalia; Rod Borup; Rangachary Mukundan

"Fundamentals of electro- and thermochemistry in the anode of solid oxide fuel cells with hydrocarbon and syngas fuel—a review", Jeffery Hanna, Won Yong Lee, Yixiang Shi, and Ahmed F. Ghoniem

The fuel cell is the most expensive component in the entire system. At present prices, the fuel cell can account for up to 75% of system cost.[6] So when carbon compounds are injected into the fuel cell, the most expensive component in the system experiences continually degrading efficiency and shorter life. This phenomenon is possibly the single largest impediment to commercial viability of fuel cell energy systems.

The SFS eliminates this problem. By splitting the syngas into hydrogen and carbon streams, and by feeding only the hydrogen stream into the fuel cell, the SFS eliminates the problems of carbon fouling and reduced efficiency caused by carbon fuels. This, in turn, maximizes the operating life and long-term operating efficiency of the fuel cell. An added benefit of eliminating carbon from the fuel cell is that SOFCs can operate at lower temperatures. Lower temperature operation of the SOFC further reduces the cost of the system and further lengthens system operational life.[7]

For the first few hours of operation, the prior designs operate fairly efficiently – but not at optimum efficiency because of the slow conversion rate of carbon in the fuel cell. And as the fuel cell degrades due to coking, efficiency falls steadily. If you look at average fuel conversion efficiency over the life of the system, the combustion engine in the Split Fuel Stream System will extract energy from the carbon-rich fuel stream more efficiently than the fuel cell in the prior designs.

Water-Gas Shift Reaction

Some fuel cell systems use a water-gas shift reaction to convert CO in the syngas as follows: $CO + H_2O \Rightarrow CO_2 + H_2$

The goal of the water-gas shift reaction (WGSR) is to increase the amount of hydrogen in the syngas. However there are drawbacks to the WGSR. WGS reactors typically require three vessels and use a costly catalyst. And the WGS reactor costs more than the fuel cell, even at today's high prices for fuel cells. The extreme costs and minimal efficiencies of the WGSR to convert the residual CO into hydrogen is a losing cost function.

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[6] A discussion of the cost of fuel cells appears later in this paper.

[7] This reference discusses the advantages of higher efficiency and increased life achieved by lowering SOFC temperature by providing an external reformer:

"Demonstration of a highly efficient solid oxide fuel cell power system using adiabatic steam reforming and anode gas recirculation", M Powell, K Meinhardt, V Sprenkle, L Chick and G McVay, Additionally, there are safety issues associated with WGS reactors. They are volatile systems that are prone to explosions if not designed, managed and maintained with utmost care.[8]

The SFS does not require a WGS reactor. Sufficient hydrogen gas for the fuel cell is created during reforming, and the carbon-based energy in the fuel is burned in the combustion engine with good efficiency.

Composition of Exhaust

A major goal of most fuel cell systems is to create a clean, green energy generator. Including a combustion engine as part of the system would appear to produce exhaust gases containing NO_X and SO_X and particulates. So combustion engines are generally not considered suitable components for fuel cell energy systems.

However the engine exhaust from the SFS can be much cleaner than what is typical for a combustion engine, as follows.

- Creation of SO_X can be kept to a minimum by putting a sulfur scrubber in front of the reformer.
- Only about 25% of the fuel feedstock is routed to the engine. This is the carbon stream. About 75% of the fuel (in the form of H_2) is sent to the fuel cell. So in the SFS, the total amount of exhaust from the engine is about one-fourth what the exhaust would be if all of the fuel were fed to a combustion engine.
- High temperatures of combustion create NO_X. In the SFS, some of the steam from the fuel cell exhaust can be diverted to the combustion engine to hold combustion temperature just below the level at which NO_X is created.[9]
- Particulate formation in combustion engine exhaust is an interesting problem. Benzene rings act as seeds that spawn the growth of particulates. The mechanism

[8] The following references discuss issues related to water-gas shift reaction:

“Comparative studies of low-temperature water–gas shift reaction over Pt=CeO2, Au=CeO2, and Au=Fe2O3 catalysts”, Apanee Luengnaruemitchai, Somchai Osuwan , Erdogan Gulari

“Deactivation Mechanisms for Pd/Ceria During the Water-Gas Shift Reaction”, X. Wang, Raymond J. Gorte, J. P. Wagner

“Preferential CO oxidation in hydrogen (PROX) on ceria-supported catalysts, part II: Oxidation states and surface species on Pd/CeO_2 under reaction conditions, suggested reaction”, O Pozdnyakova, D Teschner, A Wootsch, J Kröhnert

[9] This web site discusses ways to limit NO_X creation in combustion reactions, including injection of steam into the combustion chamber: http://www.e-inst.com/combustion/nox-reduction

for producing carbon particulates in a combustion engine is hydrogen abstraction-acetylene addition, or HACA. In the SFS, the portion of the reformate that is sent to the turbine is hydrogen-depleted. This limits the HACA process, which in turn limits the production naphthalene that is the seed for large particulates.[10]

Clean exhaust with minimal particulate content is an inherent feature of the SFS design.

Summary

The Split Fuel Stream System provides the following advantages over prior fuel cell systems:

- Increased fuel efficiency
- Longer fuel cell operational life
- More efficient operation of the fuel cell
- Scalable to operate in a variety of applications
- Fuel flexible – will work with almost any hydrocarbon fuel
- Compatible with a variety of fuel cell technologies
- Compatible with a variety of combustion engine types
- Compatible with existing reforming and separation technologies
- Reduced temperature operation – specifically, the SFS enables lower temperature SOFCs
- Increased power density
- Reduced component costs
- Reduced carbon and particulate emissions
- Decreased carbon capture costs

[10] The following references discuss the formation of particulates and soot in combustion:

"Formation and consumption of single-ring aromatic hydrocarbons and their precursors in premixed acetylene, ethylene and benzene flames", Henning Richter and Jack B. Howard

"Effects of Equivalence Ratio on Species and Soot Concentrations in Premixed N-Heptane Flames", Fikret Inal, and Selim M. Senkan

An important pattern in the above points is the word “compatible”. The SFS works with existing fuels, reformers, separators, fuel cells, and combustion engines. No major new technology needs to be developed and proven.

In this context, the SFS is not “disruptive” technology. It is “enabling” technology.

Example Applications

Overview

Any energy generation system that can make significant improvements in fuel efficiency will be in high demand for many applications. The National Energy Technology Laboratory (NETL) under the US Department of Energy has identified hybrid fuel cell systems as the best candidate for what it calls “FutureGen” – the future of energy generation. NETL considers hybrid fuel cell systems the most efficient and environmentally cleanest technology for fossil fuel conversion presently available.

NETL, in partnership with private industry, attempted to develop a hybrid fuel system that would live up to the expectations and possibilities envisioned. Unfortunately, the effort fell short of expectations because of the problems described in the previous section.

The Split Fuel Stream System was designed to overcome the technical issues that impeded NETL’s effort.

As a system that is scalable, that is fuel flexible, and that maximizes the life and efficiency of the fuel cell, the Split Fuel Stream System has promise to be the dominant energy generation system for the coming 30 to 50 years – for as long as fossil fuels are abundant and relatively low-cost, and until renewable energy sources become mature and cost effective.

Here are some applications where the SFS can be used:

Stationary platforms

- Primary electrical generators
    - Initially small to medium sizes
    - Eventually scale up to major plants for the grid
- Distributed power generation for:

    - Industrial parks
    - Shopping malls
    - Commercial buildings
    - Residential homes
- Sever farms
- Emergency backup

Mobile platforms

- Ship-based power plants – for on-board electrical power and propulsion
- Automotive propulsion systems
- Trains
- Auxiliary power units (APUs) on aircraft and ships
- Military frontline power supplies

A document titled SFS Introduction (available from EnergYield) has illustrations of some of the applications listed above.

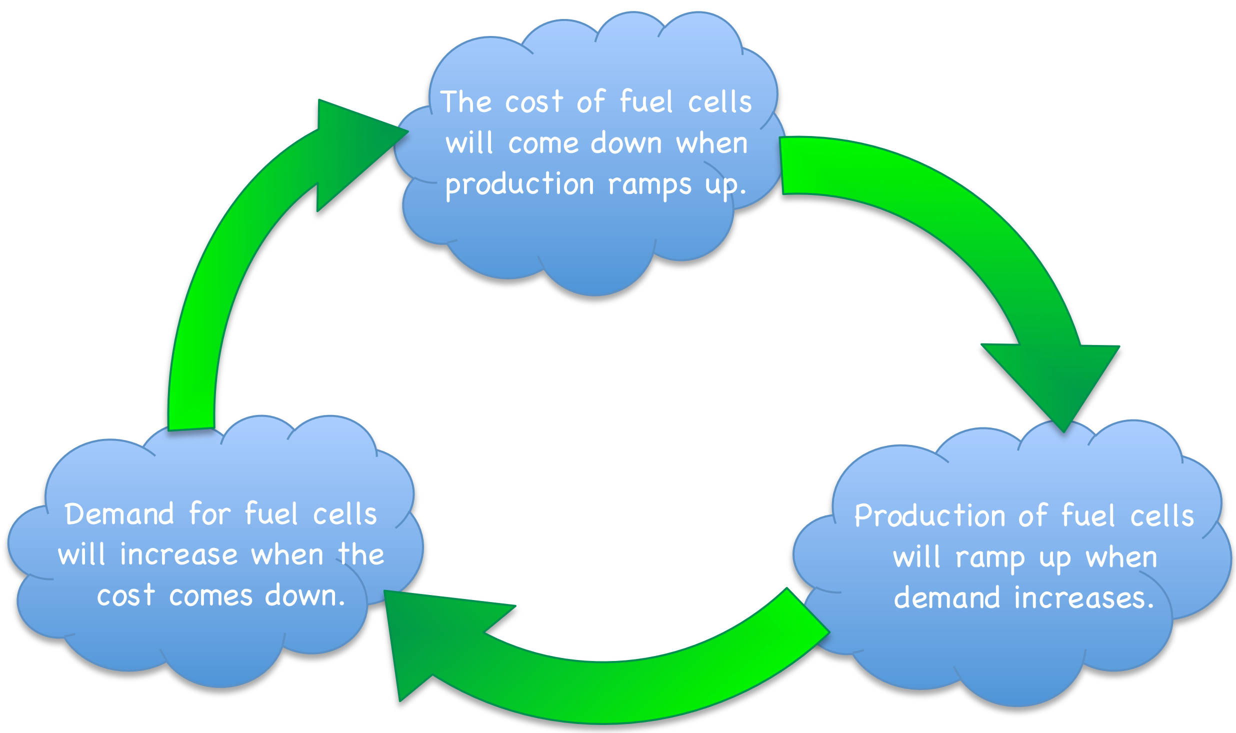
Estimates of System Efficiency and Cost of Energy

Cost of Fuel Cells

In all fuel cell systems, the “elephant in the room” is the cost of the fuel cell. Fuel cells are expensive. The fuel cell can represent 50% to 75% of plant cost.

However, fuel cells do not need to be expensive. Flat panel TVs and cell phones are much more complex than fuel cells, but both of these products are very affordable. This is because of industry investment in highly efficient production processes that drove down the cost of cell phones and flat panel TVs in just a few years. There is potential for similar reductions in the cost of fuel cells.

A circular dilemma that is common to new technologies has hindered fuel cell cost reduction.



Breaking out of this cycle usually requires an external shock – either economic or technological. We believe the Split Fuel Stream System will create the external shock that breaks this cycle and leads to a reduction in fuel cell prices.

To date, there has been no clear technology development path that would lead to fuel cells having long lives with highly efficient operation. We believe the SFS will provide a path to fuel cell viability, leading to industry investment in production processes that drive down fuel cell costs.

The present order-of-magnitude cost for fuel cell systems is between $1M and $3M for a 1MW system.[11] EnergYield believes that with efficient production techniques, plus commercialization of some technology advances currently under development in industry and academia, the cost of fuel cell energy systems can drop to $500k for a 1MW system.

Estimate of SFS Energy Efficiency and Cost of Energy

Working prototypes of the Split Fuel Stream System have not yet been built and tested.[12] We can estimate the efficiency of the SFS by reviewing published data on efficiency and cost of similar systems, and then factoring in efficiency and cost savings that should be attained in the SFS.

A report from the Department of Energy Fuel Cells Program[13] (the “DOE Report”) states that as of 2010, CHP fuel cell systems attained efficiency levels in the range of 70% to 90%.[14] The DOE report looks at systems in the power range of 100kW to 3MW.

A report from the National Renewable Energy Laboratory[15] (the “NREL Report”) estimates CHP efficiency of 85% in year 2012 for PEM and SOFC systems, rising to 87% to 90% CHP efficiency by year 2020. The NREL report focuses on smaller systems, in the power range of 1-10kW.

A report from Mitsubishi Heavy Industries[16] (the “MHI Report”) on SOFC-GT CHP systems states that an 800MW system fueled by LNG has 70% efficiency and a 700MW system fueled by coal has 60% efficiency.

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[11] There is a broad price range that depends on the specific fuel cell technology and the design of the plant.

[12] The final section of this paper summarizes the state of development of the SFS

[13] Medium-scale CHP Fuel System Targets. US Department of Energy Fuel Cells Program Record #11014. Spendlow, et al. Sept 30, 2011

[14] All energy efficiency data are LHV unless otherwise noted.

[15] 1-10 kW Stationary Combined Heat and Power Systems Status and Technical Potential, Independent Review. Report number NREL/BK-6A10-48265. Nov 2010.

[16] Development of SOFC-GT Combined Cycle System with Tubular Type Cell Stack. Tomida, et al. October 19, 2010

All of these efficiency reports have impressive numbers and would suggest that hybrid fuel cell CHP systems are commercially viable. Details that underlie the efficiency estimates explain why fuel cell systems have not yet caught on.

All of the reports acknowledge, directly or implicitly, that there are problems with declining efficiency over the life of the system. The reported levels of efficiency seem to refer to the first hours of operation when the fuel cell is at peak efficiency. (A possible exception is the MHI report, which appears to reflect average efficiency over longer-term operation.)

Also, most of the reports state that the entire fuel cell stack needs to be replaced, typically after 30,000 to 40,000 hours of operation. Finally, in most of the CHP systems, the captured heat is transferred to a steam power generation system. This is a significant addition to plant cost, which affects the total cost of energy. These two points (stack replacement and plant cost) affect the total cost of energy of fuel cell systems.

Ultimately, the commercial viability of any energy generation system hinges on the levelized cost of energy (LCOE) of the system. Data on LCOE of fuel cell systems is limited, and there is a lot of variability in the data. There are several reasons for this:

- Limited number of fuel cell systems in operation
- Limited number of hours of operation of *in situ* fuel cell systems
- Variation in the formulas used to estimate LCOE of fuel cell systems[17]

A recent report from the DOE[18] appears to have a broad base of underlying data and a minimum of bias in the calculations. The report estimates the LCOE of several different kinds of energy generation technologies in the year 2020. Of all the systems analyzed in the DOE report, medium-sized (500kW) fuel cell CHP systems have the lowest estimated LCOE, in a range of $0.07 to $0.09 per kWh.[19]

A report by Lazard[20] on current costs of energy also appears to be based on broad and unbiased data. This report estimates the current LCOE of basic fuel cell systems (i.e. not hybrid systems, and not CHP systems) is $0.109 to $0.206 per kWh.

[17] Reports on LCOE of fuel cell systems are often prepared by stakeholders in the system, and this can sometimes induce a stakeholder's bias in the calculations.

[18] Levelized Costs of Electricity from CHP and PV. Offices of Solar Energy Technologies & Fuel Cell Technologies Program Record # 14003. Nguyen, et al. Feb 27, 2014

[19] All LCOE estimates assume no government subsidies unless otherwise noted.

[20] Lazard's Levelized Cost of Energy Analysis – Version 7.0. August 2013

How would the SFS compare to existing fuel cell systems in terms of efficiency and cost of energy?

Energy Efficiency

We estimate that the energy efficiency of the SFS system is on par with the energy efficiencies currently reported for hybrid fuel cell systems at the beginning of system life. I.e. we estimate 80% to 90% energy efficiency of the SFS. A key difference between the SFS system and prior systems is that the SFS is designed to maintain this efficiency over much longer operational life, compared to existing fuel cell systems which degrade in performance and efficiency.

LCOE

We estimate that the LCOE of the SFS system will be at or slightly below the low-end of the range in the DOE LCOE report. I.e. we estimate LCOE of $0.05 to $0.07 per kWh for the SFS. The rationale behind this estimate is:

1. The inherently high efficiency of the SFS will keep operating costs at the low end of the range.
2. Longer life of the fuel cell will reduce maintenance costs – specifically, the cost of stack replacement.
3. Integrated CHP (feeding the steam and heat back into the system) eliminates the need for an external steam power generator, which reduces plant cost.
4. The efficiency and long life of the SFS system will trigger the development of efficient production processes for fuel cell energy systems. I.e. cost of fuel cells and related components will come down.

Summary

Energy efficiency of the Split Fuel Stream System is estimated at 80% to 90% over the life of the system. LCOE is estimated at $0.05 to $0.07 per kWh. If the SFS achieves this level of performance, we believe it will initiate the era of commercial viability of fuel cell energy systems.

Status of Intellectual Property

Table 3: Summary of patents

Country	**Status**
United States	Patent numbers 7,818,969 and 8,047,006 Continuation applications on file
Canada	Patent number 2,720,193
Japan	Patent number 5,570,614
Germany	Published patent application pending
United Kingdom	Published patent application pending

Status of Product Development

The Split Fuel Stream Hybrid Energy System is at concept stage.

The principals of EnergYield have done extensive research on the components in the SFS, on the chemical and physical processes within the system, and on the challenges associated with hybrid fuel cell/turbine systems. Our research supports the two key postulates underlying the SFS:

1. The SFS will provide the highest lifetime energy efficiency of any fuel cell system designed and developed to date

2. The SFS will maximize the operational life of the fuel cell

The next step is to develop a test bed for the SFS. The test bed will allow mixing and matching different technologies (reformers, filters and separators, fuel cells, turbines and engines) to collect performance data. The goals of the test bed are to validate the SFS concept and to fine tune performance of the system.

Given the extensive development work already performed on hybrid fuel cell systems, we feel that the costs and risks associated with building the test bed and validating the concept are low.

EnergYield is looking for development partners to collaborate in designing and building the test bed.

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