

# **Use of Mixed Combustion/Electrochemical Energy Conversion to Achieve Efficiencies in Excess of 70% for Transportation-Scale Engines**

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## **Abstract**

In order to achieve efficiencies in excess of 70% in transportation-scale engines, a mixed combustion/electrochemical strategy was developed in which a piston engine is coupled to a downstream fuel cell by way of a catalytic reformer. The piston engine serves to reform the fuel and extract some work by operating in a fuel-rich regime, the catalytic reformer serves to catalytically reform the exhaust gas, with additional fuel and water, into a hydrogen-rich syngas, and the fuel cell serves to extract the majority of the remaining chemical exergy in the form of electrical work. Heat exchangers and turbomachinery are also employed to manage the thermomechanical exergy effectively within the system. Modeling results suggest that this strategy can reach the goal of 70% efficiency on an LHV basis. The modeled system that achieves this employs a high-temperature strategy in which a thermally insulated, compression-ignition engine is coupled to a downstream solid oxide fuel cell through a high-temperature reformer. This strategy relies on the capability of the constituent devices (i.e. the engine, the reformer, and the fuel cell) to perform their modeled function, however. Regarding the engine, it must be verified that fuel-rich operation without forming significant non-equilibrium products (soot and hydrocarbons) is possible in a direct-injection, compression-ignition (DI-CI) combustion strategy. Regarding the reformer, it must be verified that commercial catalysts are active and stable in the environment modeled in the system and produce the required product stream for the downstream fuel cell. These two areas are the focus of experimental research efforts. The investigation of the rich DI-CI combustion strategy consists of the operation of single-cylinder research engine to measure the rich combustion products as well as the work output, optical access experiments in both a single-cylinder optical-access engine as well as an extreme compression device to observe physical phenomena associated with this rich combustion strategy, and the development of a phenomenological model to help interpret the experimental results. The investigation of the reformer consists of experiments in which synthetic exhaust gas is passed through a catalyst testbed, and the reformed products are measured by way of gas chromatography. The combined results of these efforts serve to refine expectations of the performance of the proposed system as well as begin to address the more practical concerns associated with the operation of the system.

## **Introduction**

This project investigates using a mixed combustion/electrochemical energy conversion strategy to achieve the goal of 70% engine efficiency at transportation scale (~100 kW). The research is reported in detail in the PhD theses of Dr. John Fyffe and Dr. Mark Donohue, cited

in the Publications. A summary of the overall scheme is provided here for the sake of brevity. Complete results—including the details of the supporting experimental work—can be found in those references.

The mixed strategy uses both combustion and electrochemical energy conversion techniques to accomplish fuel oxidation. Specifically, the strategy employs an internal combustion (IC) engine as a fuel reformer that supplies hot, pressurized, H<sub>2</sub>-containing reformat to a fuel cell. From this basis, two system architectures are developed that provide the balance of plant required to achieve efficient exergy extraction.

This strategy was developed to take advantage of the strengths of both IC engines and fuel cells while mitigating their weaknesses through informed system design. IC engines are high-power, small-scale devices that can use almost any fuel and are efficient gas-compression and -expansion devices. Unfortunately, they are combustion based devices that suffer a roughly 20% exergy loss due to combustion, and they typically have similarly high heat transfer losses. Fuel cells are extremely efficient at converting chemical energy to work, however they use very particular fuels (typically H<sub>2</sub>), fail to utilize ~10% of their fuel, and also have heat transfer losses in the 20% range.

Using the IC engine as a fuel reformer (by operating grossly rich) reduces the amount of chemical energy conversion that occurs in an engine thereby reducing combustion losses while simultaneously producing work and a high-temperature, high-pressure, H<sub>2</sub>-containing fuel stream for the fuel cell. The fuel cell fuel utilization is addressed by careful system design. Heat transfer losses are reduced through thermal barrier coatings in the engine and by regeneratively using thermal energy instead of rejecting it to the environment.

Two system architectures—a low-temperature and high-temperature system—were developed and modeled to determine the merit of this general strategy. Detailed thermodynamic models were used to further refine the designs and explore the performance space of the mixed system approach. The low-temperature strategy employs an efficient, low-temperature combustion strategy for IC engines (HCCI) combined with a high-temperature proton exchange membrane (HT-PEM) fuel cell that operates near HCCI exhaust temperatures. The high-temperature strategy leverages a high-temperature Diesel-style combustion strategy combined with a solid-oxide fuel cell (SOFC).

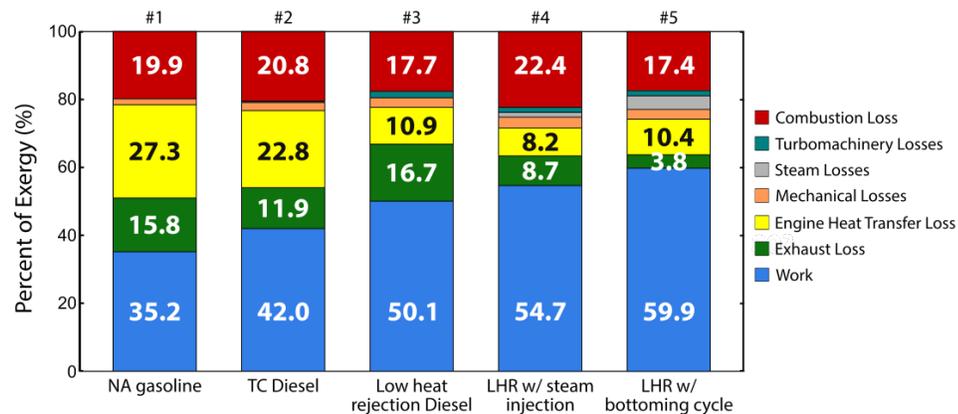
## **Background**

70% efficiency was the project's target. 70% was chosen because the most-efficient modern systems are now exceeding 60%, with GE's HA-class combined cycle system recently setting a combined-cycle world record of 62.2% LHV efficiency [1]. 70% is clearly the next milestone and provides a clear benchmark for progress.

Two recent research developments have contributed significantly to the conceptual basis of this work. The first is work by Johnson and Edwards that demonstrated an IC engine using in-cylinder thermal barrier coatings capable of achieving 60% exergy efficiency [2, 3]. In Johnson's work, exergy loss due to heat transfer—typically around 30%—was reduced by nearly half using thermal barrier coatings. The reduced heat transfer increased the exergy

transferred out of the engine in the exhaust, where some of the exergy was then extracted using a combination of geometric over-expansion, turbo-compounding, and thermal energy recovery.

Figure 1 shows the exergy distribution for various engine architectures modeled by Johnson. The first two engines shown in Figure 1 are for comparison: a naturally aspirated (NA) gasoline engine (system #1) and a turbo-charged (TC) Diesel engine (#2). The next result shown is a TC Diesel with in-cylinder thermal barrier coatings on the piston face, head, and valve faces and stems, and this engine is called the low heat rejection (LHR) Diesel. After that, mechanical extraction through in-cylinder geometric over-expansion was included and two thermal energy recovery techniques were explored: steam injection #4 and a Rankine bottoming cycle #5. After the improvements, the largest single remaining loss in the system was the combustion loss at 17.4%. Therefore, the mixed system strategy can be thought of as the next iteration of Johnson’s work, as likely the only way to increase the efficiency from 60% to 70% would be to meaningfully reduce the combustion loss. Note that the numbering convention will be continued in the high-temperature architecture results to reinforce the view of the LHR strategy as the conceptual predecessor.



**Figure 1:** Exergy distribution comparison of traditional engines (#1 and #2) with a low heat rejection (LHR) Diesel engine (#3) and LHR Diesel engine with steam injection (#4) and a bottoming cycle (#5) [2].

The second development that has played a significant role in informing this work is recent work by Pass and Edwards, as well as the work that Pass built upon by Ramakrishnan, Miller, Teh, and Edwards [4–7]. Their combined efforts highlight the role restrained reactions play in increasing the maximum achievable efficiency in ideally optimized energy systems by utilizing electrochemical energy conversion in place of combustion. In summary, prior work concludes that a solid-oxide fuel cell/gas turbine hybrid system with optimized thermal integration is theoretically capable of 79% LHV efficiency (~75% exergy efficiency) [8]. The prior work assumes grid-scale device performance and that the fuel cell provides the majority of the work extraction, necessitating a very large (relative to the system) fuel cell. Such a large fuel cell suggests that economies of scale must be used for economic viability. In their research, the contributions to understanding how a hybrid fuel cell system operates, the theoretical basis for why it achieves such high efficiencies, and the limitations of such systems, was invaluable in the development of this work.

### *Limiting reaction-related exergy destruction*

This project was conceived because the only path to 70% efficiency that could be envisioned required the combustion exergy losses to be significantly reduced. Therefore, the first task was to determine if it was possible to mitigate the reaction-related loss. If the combustion loss cannot be reduced below 20% of the input exergy, it is improbable that the combination of heat transfer, exhaust, and other parasitic losses add up to less than the 10% of the input exergy that would be required to achieve 70%. Knowing electrochemical energy conversion significantly reduces reaction-related losses, fuel cells were the clear candidate device to build a new energy system architecture around. However, fuel cells have issues that must be addressed; primarily, they have strict fuel requirements (again, typically H<sub>2</sub>), consume at most 90% of the inlet fuel, and are net exothermic, requiring non-negligible amounts of heat transfer to maintain operating temperature.

The first issue of fuel cells noted above is that they have strict fuel requirements and cannot be used directly with natural energy resources like natural gas. Hence, fuel transformations are a necessary enabling technology. The incomplete conversion of fuel in a fuel cell presents another challenge, with at least 10% of the inlet fuel being exhausted. The significant chemical exergy in the fuel cell exhaust must be properly recovered by downstream devices. In the case of high-temperature fuel cells, the exhaust gas also contains significant thermal exergy, compounding the exhaust exergy problem. Finally, any heat-transfer out of the fuel cell that is not utilized is another major source of exergy loss, and must be handled appropriately.

### *Internal combustion engine as fuel reformer*

Fuel cells were chosen as the core fuel reacting device and the system was designed with the intent of using commercially available energy carriers like natural gas (i.e., not assuming it can access a reservoir of pure hydrogen). Therefore, an integrated fuel transformation is required to supply the fuel cell with a fuel stream it can react. This is done in a non-traditional way in this work, with an IC engine. Instead of using a standard catalytic steam methane reforming approach to produce syngas, an IC engine is used as a fuel reformer by operating it grossly rich. The concept of using the IC engine as a fuel reformer provides a few theoretical benefits over traditional reforming methods. The engine performs the primary task—producing H<sub>2</sub> for the fuel cell—but also produces work and increases the pressure and temperature of H<sub>2</sub>-containing fuel stream. Therefore, it combines the functions of a heater, compressor, and fuel reformer while producing net work. Detailed analysis was done to confirm whether or not these advantages are a net positive. Before proceeding however, it is worth discussing the feasibility of operating an IC engine grossly rich, which is—to say the least—atypical.

Homogeneous charge compression ignition (HCCI) is a combustion strategy that combines the premixed fuel and air approach of standard spark ignition (SI) engines with compression ignition (CI) typically seen in direct injection (DI or Diesel-style) engines. This approach is well suited to rich combustion because it is not limited by flame propagation issues in a grossly rich fuel/air mixture like an SI engine would be. Additionally, HCCI engines require significant dilution in the form of EGR or lean operation to reduce the large and rapid pressure increases that result from the near-instantaneous combustion. In grossly rich HCCI operation the extra fuel acts both as a diluent and a thermal energy sink because of the endothermic reforming reactions, which might entirely eliminate the need for dilution. Finally, HCCI is suitable for natural gas combustion, the target fuel for this research.

Less obvious is how a direct-injection, compression-ignition (i.e., CI-DI or Diesel) engine could be operated grossly rich without significant challenges. Additionally, natural gas is not traditionally thought of as a potential Diesel fuel because of its very low cetane number. However, recent research by Oliver indicates that it is actually possible to not only use natural gas as a Diesel fuel, but in fact it can be advantageous when coupled with a low-heat rejection strategy [9]. This work shows that using in-cylinder thermal barrier coatings and reduced turbocharger aftercooling sufficiently increases gas temperatures at the time of injection such that natural gas autoignites readily and produces orders of magnitudes less soot than Diesel #2 fuel, even with stoichiometric operation. Therefore, leveraging Oliver's work, this strategy is used in the high-temperature architecture.

## Results

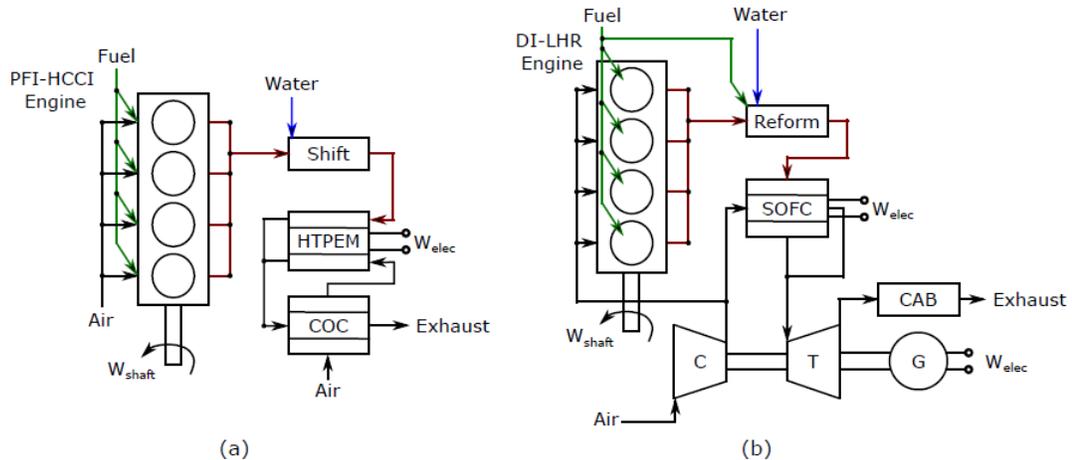
There are many ways one could construct a mixed combustion/electrochemical energy conversion system. Here we propose two illustrative systems—a low-temperature architecture and a high-temperature architecture—that demonstrate the tradeoffs of moving some of a system's chemical energy conversion from combustion in an IC engine to electrochemical conversion in a fuel cell.

The low-temperature architecture uses a homogeneous charge compression ignition (HCCI) engine to perform the fuel reforming. HCCI engines have moderately low temperature exhaust which is well matched to water-gas shift reactors and lower temperature fuel cells that operate around 150-200°C (such as HT-PEM or phosphoric acid fuel cells). This architecture was expected to be capable of operating over a wide load range with quick start-up while achieving a high efficiency (but was expected to be lower in efficiency than the high-temperature architecture).

The high-temperature architecture leverages the LHR engine concept from Johnson's work. The LHR engine has very high exhaust temperature which is well suited to the high temperature used in methane steam reforming and SOFCs. SOFCs are slow to start because of their high operating temperature (>800°C), and are more difficult to adapt to a wide load range. The hybrid architecture potentially enables quick-start power generation and a wider operating range via use of the engine at stoichiometric or even lean equivalence ratios. During system startup, the engine could produce power by operating at a stoichiometric equivalence ratio and heat the SOFC to operating temperatures with the high-temperature exhaust gas. Once the SOFC was up to temperature, the engine could then be switched to rich operation to produce syngas. Another potential operating mode would be a high power, lower efficiency case where the engine was used closer to stoichiometric operation at high speed to deliver similar amounts of fuel to the fuel cell but increase the engine power output. These transient considerations are interesting but ultimately outside the scope of this work. The high-temperature architecture shows promise as the more efficient system, but it is more complicated and probably more costly.

A schematic of the low-temperature architecture is shown in Figure 2(a). In this system, the products of rich combustion from a port fuel injected (PFI) HCCI engine exit the engine at a temperature of approximately 175°C. This is followed by a water-gas shift reactor (labeled Shift in Fig. 2(a)) that operates at 190°C. In a shift reactor, a catalyst promotes water-gas shift equilibration, increasing H<sub>2</sub> and decreasing CO concentrations in the syngas. Downstream of

the shift reactor, the reformed syngas enters a high-temperature polymer electrolyte membrane (HT-PEM) fuel cell. The HT-PEM fuel cell oxidizes the majority of the  $H_2$  in the syngas. The remaining fuel is oxidized in a conventional oxidation catalyst (COC) to avoid emitting fuel to the atmosphere. The COC also functions as heat exchanger, preheating the fuel cell air supply.



**Figure 2:** Simplified system schematics for the two proposed configurations for mixed combustion/electrochemical engines. Shown in (a) is the low-temperature architecture that uses a rich HCCI engine in combination with a high-temperature PEM fuel cell. Shown in (b) is the high-temperature architecture that uses a direct injection, low heat rejection engine in combination with a solid-oxide fuel cell and a turbocharger/generator. Some elements such as heat exchangers and heat transfers are left off for clarity.

The high-temperature architecture is shown in Figure 2(b). The IC engine in this system is a direct injection, compression ignition, low-heat rejection (LHR) engine. The exhaust from this engine exits at around  $600^{\circ}\text{C}$  when operating at grossly rich equivalence ratios ( $\phi \gg 1$ ,  $\sim 900^{\circ}\text{C}$  at  $\phi = 1$ .) The engine exhaust must be heated to reach the reformer operating temperature of  $800\text{--}1000^{\circ}\text{C}$ . Downstream of the engine is the fuel reformer (Reform in Figure 2(b)), where a catalyst promotes the steam reforming reaction, converting steam, unburned fuel in the engine exhaust, and additional fuel to syngas for the SOFC.

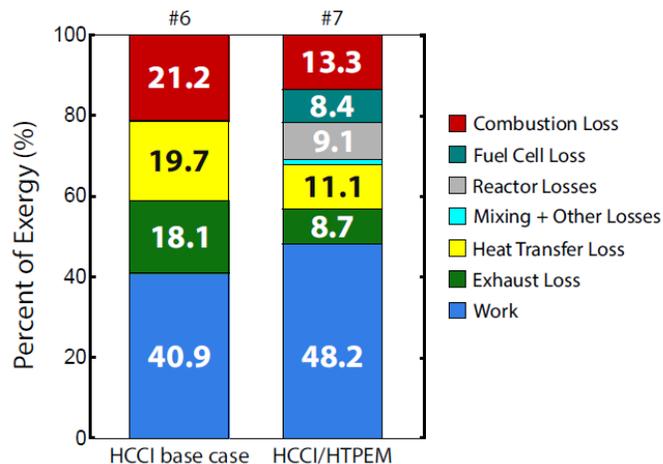
Modern turbochargers have material constraints that limit maximum turbine inlet temperatures (TIT) to around  $1000^{\circ}\text{C}$ . Therefore, the SOFC exhaust is already at or near the maximum TIT and is expanded through the turbine. Following expansion, the remaining fuel is oxidized in the catalytic afterburner (CAB). The post-CAB gas is at a high temperature and so it is used to preheat reforming reactants (engine exhaust and any additional fuel or water) and the SOFC air input.

The low-temperature architecture of the mixed system strategy was investigated first. The model of mixed system was compared to an analysis of a baseline HCCI engine. In the mixed system, the HCCI engine equivalence ratio was chosen to be two, with an overall (system) equivalence ratio of one. For the baseline HCCI engine comparison, the equivalence ratio was also set to unity. In both cases, the excess fuel and residual were used for charge dilution in place of excess air. This allows us to compare a system where all fuel oxidation occurs via

combustion to the mixed combustion/electrochemical approach at the same overall equivalence ratio.

Figure 4 shows the exergy breakdown of the base case HCCI engine (#6) vs. the low-temperature architecture (#7). The exergy efficiency increases from 40.9% (42.3% LHV) to 48.2% (49.9% LHV), and the combustion exergy destruction decreases from 21.2% to only 13.3%. However, if the combustion, reaction (COC and WGS reactors), and fuel cell losses are summed together as reaction-related losses, they total 30.8%—with 13.3% from combustion, 5.1% from the shift reactor, 4% from the conventional oxidation catalyst, and 8.4% from the fuel cell. Therefore, in this architecture the mixed combustion/electrochemical energy conversion strategy actually increases reaction-related losses by 45%. Unfortunately, despite significant fuel oxidation occurring in the fuel cell there is not a net reduction in exergy destruction due to chemical reactions. In this case, the combination of the reactor losses and fuel cell losses are too large to offset the reduction in combustion destruction.

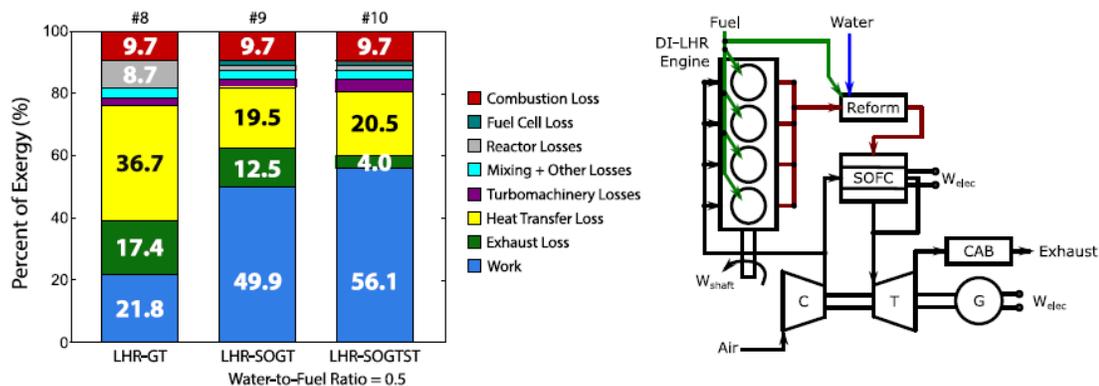
While this system has a higher efficiency, the greater reaction-related losses mean further system optimization to reduce other losses could not yield 70% efficiency. The combustion losses were indeed reduced by operating rich and shifting the fuel oxidation away from combustion. However, the large reactor losses result from the same mechanism as combustion exergy destruction. The input reactants are far from chemical equilibrium. Any time a step is taken towards equilibrium without work being extracted, exergy is destroyed. A larger step towards equilibrium means more exergy destruction. The large fuel cell loss is primarily due to the cathode activation loss with the large electrochemical potential required to drive the oxygen dissociation half-reaction at relatively low operating temperature. Unfortunately, without significant improvements to HT-PEM performance or another viable fuel cell alternative at these temperatures, there is no chance of reducing reaction-related losses by even marginal amounts, making extremely high efficiencies with this architecture unreachable. Hence, there was no need for further exploration of this architecture.



**Figure 4:** Exergy distributions of the HCCI base-case system #6 and the HCCI/HT-PEM system #7.

A progressive approach was taken in developing the high-temperature architecture. First, a model of an LHR engine followed by a catalytic after burner and a gas turbine was used to provide a starting point system (#8 in Figure 5). This system was used for comparison with the simplest high-temperature system where the catalytic afterburner was replaced with a reformer and SOFC (#9 in Fig. 5). This comparison was conducted to determine if in fact the reaction-related losses can be reduced by a meaningful amount using the electrochemical energy conversion strategy.

The best case LHR engines from Johnson’s research fell just shy of 60% exergy efficiency, primarily due to the large combustion loss. To push past 60%, the basic LHR engine/gas turbine (GT) was used as the starting point, but instead of starting with an engine operating at an equivalence ratio of unity, the engine is operated grossly rich ( $\phi=2$ ) to shift the fuel oxidation away from combustion and into the fuel cell. Figure 5 shows the exergy analysis of the baseline rich LHR engine with turbo-compounding (LHR-GT, #8). The system was kept at an overall equivalence ratio of unity by adding air into the engine exhaust upstream of the catalytic afterburner. Keeping the overall equivalence ratio at unity is done for two reasons: (1) it enables the use of a relatively simple and inexpensive three-way catalyst as an emissions abatement strategy, and (2) it requires the least amount of parasitic load for air pressurization while providing enough air to fully oxidize the fuel in the system.



**Figure 5:** Exergy breakdown for a base-case turbo-compounded rich LHR Diesel- style engine with a catalytic afterburner (system 8) as well as two rich LHR engine- SOFC configurations: LHR-SOFT (system 9) and LHR-SOFTST (system 10) with a water-to-fuel molar ratio of 0.5. The ratio of fuel directly input into the reformer to the fuel input into the engine was 0.5 for system 8 and 9. System schematic shown again for reference.

The baseline system (#8) has a low exergy efficiency of 21.8% because a large portion of the fuel is being reacted downstream of the engine, and while there is also a turbine to extract work, it operates over a small pressure ratio. Essentially, this is a terribly designed hybrid of an IC engine and a Brayton cycle, but is useful to track how the exergy distribution changes throughout the system design process. The large heat transfer loss is a result of the rich engine exhaust passing through a catalytic afterburner and reaching 1700°C, much higher than the turbine inlet temperature (TIT) for small-scale turbines. The model cools the stream to the TIT before the turbine and rejects this thermal energy to the environment, contributing a significant

portion of the heat transfer exergy destruction. This system is clearly not representative of anything that would be implemented, but it is a useful starting point to illustrate the benefits of using the mixed strategy. This simple case also illustrates the difficulty of managing thermal energy within a system where the engine exhaust is not only hot but also contains significant chemical exergy. The engine combustion destruction is reduced compared to the LHR engines operating at stoichiometric (9.7% for System 8 compared to 17–22% for Systems #1–5). However, when the exergy destroyed in the catalytic afterburner is included, the overall reaction-related losses remain high at 18.4%. This is unsurprising, however, since all chemical reactions are still occurring in an entirely unrestrained manner (i.e. there is no coupling between the chemical reaction and work extraction).

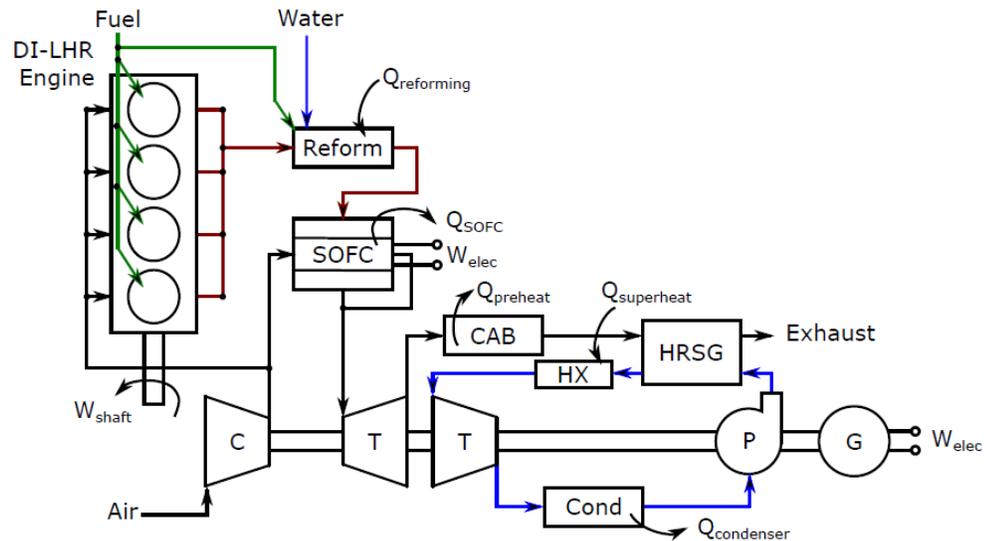
The next system in Figure 5 (#9) is the first incarnation of the high-temperature architecture (with the simplified system schematic shown in Figure 5 as well). In this system, the catalytic afterburner is replaced by a reformer and SOFC. It is labeled the LHR-SOGT system as an abbreviation of LHR engine/SOFC/gas turbine. Finally, the goal of the mixed combustion/electrochemical energy conversion strategy is realized, with the combination of the combustion (9.7%), fuel cell (1.4%), and reactor (1.5%) losses summing to only 12.6%. This is an improvement of 32% compared to the baseline rich LHR-GT case, and between a 28% and 44% improvement over the stoichiometric LHR engine cases #2–5. With a roughly 1/3rd reduction in the reaction-related losses through the use of the mixed system strategy, the goal was then to identify a path to converting the preserved exergy to work and achieving 70% efficiency.

After confirming that reaction-related losses were decreased, the next step was to identify the largest remaining exergy losses and develop means of reducing those to increase the work output. The two major losses in case #9 are heat transfer (19.5%) and exhaust (12.5%). The exhaust is at ambient pressure which means there is no more potential for mechanical extraction and only thermal exergy and a small amount of chemical exergy remains. Bottoming cycles are commonly used for thermal exergy recovery from exhaust. Figure 6 shows the schematic of the system with a steam bottoming cycle that first uses exhaust to generate steam followed by a superheat stage that uses thermal energy from the SOFC to bring the steam to the steam turbine inlet temperature (550°C). Figure 5 shows the modeling result of this System (#10, LHR-SOGTST). The added Rankine bottoming cycle recovers 6.2 percentage points from the exhaust and SOFC heat transfer to increase the system efficiency to 56.1%. The slight net increase in heat transfer losses are from the steam cycle heat transfer steps (steam generation, superheat, and condensation).

The system schematic in Figure 6 also shows the option to add fuel and/or water to the reformer along with the rich engine exhaust. Adding fuel and water downstream of the engine shifts even more of the fuel oxidation into the fuel cell, reducing the combustion loss contribution even further. The amount of fuel and water added to the reformer was specified using a fuel ratio and a molar water-to-fuel ratio. The fuel ratio was defined as the ratio of the fuel added to the reformer to the fuel used in the piston engine. In Cases #9 and #10 the fuel ratio was zero (i.e., no fuel was added to the reformer). The water-to-fuel ratio was defined as the molar ratio of water to the total fuel input to the system. In Cases #9 and #10 the water-to-fuel ratio was 0.5.

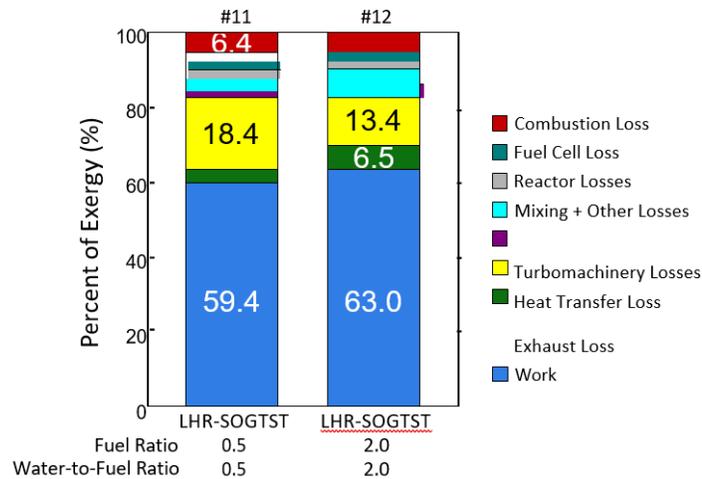
Increasing the amount of water and fuel added to the reformer provides two benefits: 1) It increases thermal regeneration, acting as a high-temperature sink for heat transfer from the SOFC. 2) It shifts more chemical energy conversion to the fuel cell. Case #11 has the same water-to-fuel ratio as Cases #9 and #10 and has a fuel ratio of 0.5 (i.e., 2/3rd of the fuel passes through the engine while 1/3rd is added at the reformer inlet). Case #12 increases both the fuel ratio and the water-to-fuel ratio to 2.0 as an extreme example of pushing as much chemical conversion into the fuel cell as possible. Exergy breakdowns for these cases are shown in Figure 7.

As expected, shifting more of the fuel oxidation to the fuel cell reduces the combustion-related destruction while increasing the fuel cell and reactor losses. However, the net change for Cases #10, #11, and #12 is an overall reduction in reaction related losses from 12.6% to 11.3% to only 9.9%, respectively. The net result of the fuel and water addition was an increase in exhaust losses, a decrease in heat transfer losses, and an increase in exergy efficiency from 56.1% to 59.4% to 63.0% for Cases #10, #11, and #12.



**Figure 6:** Conceptual system diagram of the high-temperature architecture with an added steam bottoming cycle.

The tradeoff between increasing exhaust losses and decreasing heat transfer losses indicates that the added fuel and water are effectively used for thermal regeneration from the SOFC heat transfer, providing a sink for heat transfer at fuel reforming temperatures (1000°C). However, it exacerbates the exhaust losses in two ways: 1) because more H<sub>2</sub> enters the fuel cell, more H<sub>2</sub> is exhausted from the fuel cell, increasing the exhaust exergy and 2) because the exhaust mass flow rate is increased. The increased H<sub>2</sub> in the SOFC exhaust increases the post-CAB gas temperature. However, while adding fuel and water to the reformer increases exergy in the exhaust, redesigning the system for this operating condition is likely to result in further increases in efficiency.

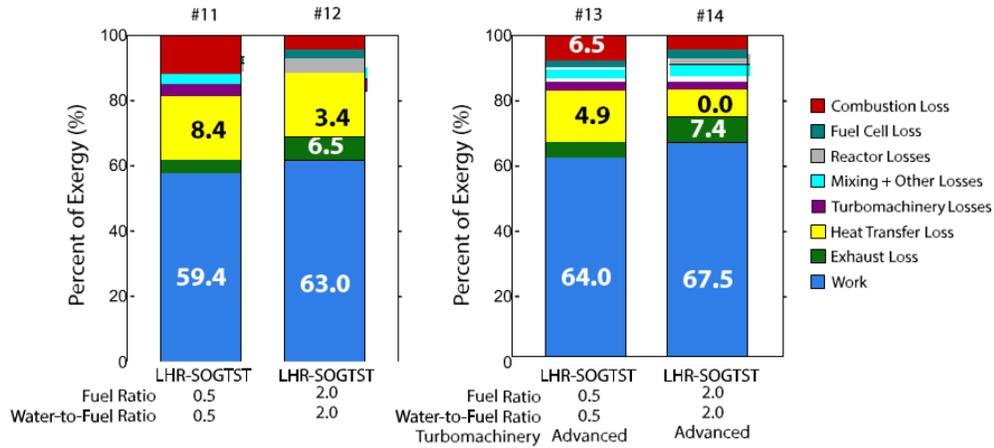


**Figure 7:** Exergy breakdown for the LHR-SOGTST system with increased fuel and water-to-fuel ratios.

Finally, the sensitivity to turbomachinery assumptions was explored. As mentioned previously, the model included turbomachinery parameters applicable to small-scale devices. To determine what effect improvements in small-scale turbomachinery might have on mixed combustion/electrochemical systems, two cases were analyzed with “improved” turbomachinery (Cases #13 and #14 in Figure 8).

Lists of the input parameters are shown in Table 1 for the small-scale device Cases #7-12 and the improved turbomachinery Cases #13 and #14. In Case #7–12, the gas turbine maximum inlet temperature was chosen to be 1000°C and a polytropic efficiencies of 75% and 80% were used for turbines and compressors/pumps, respectively. For ease of comparison, Case #13 has the same input parameters as Case #11 except with the improved turbomachinery parameters. Similarly, Case #14 is the improved turbomachinery version of Case #12.

The improved device parameters result in a roughly 4.5 percentage-point increase for both cases analyzed. Overall, adjusting the device parameters not only reduces the turbomachinery losses, but allows for more efficient thermal integration within the system since the maximum turbine inlet temperatures for both the gas and steam turbine are increased. The 67.5% exergy efficiency for Case #14 corresponds to an LHV efficiency of 69.9%, which is close to the SOGTST system from Mitsubishi Heavy Industries analyzed by Pass [20], who also showed the optimal SOFC-GT architecture can reach 79% LHV efficiency [6]. This is very illustrative, in the limit of pushing most of the chemical conversion to the fuel cell and using large-scale turbomachinery, the mixed combustion/electrochemical energy conversion strategy approaches the Mitsubishi SOGTST system. It is clear that by using small-scale devices the maximum efficiency is reduced, but the model suggests it is plausible to achieve extremely high efficiencies that are usually considered unapproachable for small-scale systems. Additionally, Pass’ work shows how optimal system architectures can improve performance as well (at the likely cost of system complexity and cost), further evidence that 70% efficiency is possible using this strategy.



**Figure 8:** Exergy breakdown for the LHR-SOGTST Cases #13 and #14, which are the same as Cases #11 and #12 (also shown for comparison) but with improved turbomachinery device parameters, specifically higher turbine inlet temperatures and increased polytropic efficiencies.

Cases	7-12	13-14
Gas turbine inlet temperature (°C)	1000	1427
Steam turbine inlet temperature (°C)	550	600
Gas turbine polytropic efficiency (%)	75	82
Steam turbine polytropic efficiency (%)	75	75
Air compressor polytropic efficiency (%)	80	86
Fuel compressor polytropic efficiency (%)	80	86
Water pump polytropic efficiency (%)	80	85

Table 1: Turbomachinery parameters

## Conclusions

The results of this work showed that the low-temperature architecture can achieve efficiencies in excess of 50% but likely has fundamental barrier's to achieving 70%. The high-temperature architecture was successful in reducing reaction-related losses and indicated there is a plausible path to 70%. These results suggest that the high-temperature architecture should be explored further to bring the concept closer to deployment. The largest uncertainties that pose a risk to the development of this system are the Diesel-style rich combustion strategy and the use of rich engine exhaust in a catalytic reformer and fuel cell. Experimental investigation of both of these processes were conducted to understand if the modeling results are valid. The first, Diesel-style rich combustion, was explored experimentally by Mark Donohue and the results are reported in his dissertation [10]. The basic conclusion from the experiments was that there is no real bar to pursuing this approach. The second, catalytic reforming of reactants containing rich engine exhaust, was explored experimentally by John Fyffe and is discussed in his dissertation [11]. Similar to the work of Donohue, the conclusion is that there is no

fundamental barrier to pursuing this approach, and although further work is required, the results of the analysis reported here appear to be achievable.

## **Publications and Presentations**

### **Publications**

1. J. R. Fyffe et al. [Mixed combustion–electrochemical energy conversion for high-efficiency, transportation-scale engines](#). *Int. J. of Engine Res.*, 1468087416665936, Mar. 2016.
2. J. R. Fyffe, “Exploration of integrated fuel transformations for high efficiency energy systems,” Ph.D. dissertation, Dept. Mech. Eng., Stanford Univ., Stanford, CA, 20018.
3. M. A. Donohue, “In-cylinder fuel reforming for small-scale mixed combustion/electrochemical engines,” Ph.D. dissertation, Dept. Mech. Eng., Stanford Univ., Stanford, CA, 20019.

### **Presentations**

1. M. A. Donohue, “Mixed combustion/electrochemical energy conversion for high-efficiency, transportation-scale engines,” technical presentation at *ASME International Mechanical Engineering Congress & Exposition, Phoenix, AZ, USA, November 11-17, 2016*.

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