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Integration of Fuel Cells into Combined Power Cycles

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Abstract

Integrated and Combined Cycles (ICC) traditionally involve only gas and steam turbines. This can be broadened to the integration of high-temperature fuel cells (FC) having electrical efficiency up to 40-60 %, compared to 30-35 % for most gas turbines [1]. The previous research on FC hybrids indicates achieving high efficiencies [2] and economic viability [3] is possible. The ICC of various FC types, their performance and the potential for utilisation of renewables are analysed considering also power generation capacity and site integration context. Further research and development with industrial relevance are outlined, giving priority to CO_2 emissions reduction.

Keywords: Energy Efficiency, High-temperature Fuel Cells, CHP, Integrated and Combined Cycle, Power Cycle Integration, Heat Integration

1. Introduction

Regarding the atmosphere, there are three main CO_2 pathways through fuel-based energy systems, including FC: recycling, build-up and sequestration (Fig 1). Their significance is influenced by the energy efficiency and the CO_2 recycled/sequestered. There is an extensive research on efficiency improvement of FC systems [3] by varying the FC types and the operating conditions.

Another promising option is FC integration with bottoming cycles to design dedicated power generation or combined heat-and-power (CHP) applications.

2. Efficiency of FC and combined cycles

2.1 Operating temperature and fuel cell efficiency

Most FC use H_2. An exception is the direct-methanol FC. The primary fuel – mostly natural gas or biogas, is used to generate the required H_2 through reforming and shift reactions.

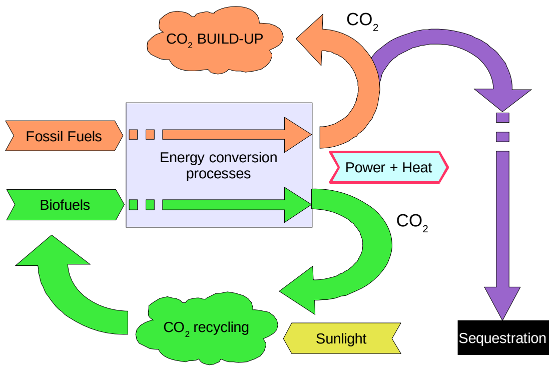


Fig 1. CO_2 pathways for energy systems

High-temperature FCs (HTFCs) allow heat integrating the fuel conversion and power generation, while low-temperature FCs (LTFCs) do not and additional fuel is burnt [4], resulting in efficiencies around 35% for LTFC against 41% for HTFC. Similar estimates result from MCFC integration [3] (Table 1).

Table 1. MCFC properties from Varbanov et al. [3] (2,320 MW power generation)

Fuel for power generation	5,002 MW	MCFC Efficiency	35.09 %
Additional fuel (no integration)	1,610 MW	FCCC Efficiency	46.38 %

2.2 Combinations with bottoming cycles

Integrating HTFCs with steam and the gas turbines can utilise the fuel even better. A summary of the interesting works in this area is given in Table 2.

2.2.1 Fuel Cell - Steam Cycle hybrids

The simplest way for FC integration is with steam cycles [3]. The sensitivity analysis in this work for a wide range of FC capital costs indicates that the FCCC systems can achieve power prices as low as 40-47 $/MWh.

Table 2. Sources on cycle integration of FC

Source	**System / Notes**	η_E *(%)*	$\eta_{CHP.MAX}$*(%)*
Uechi et al. [5]	SOFC + μGT. Integrated GT compressor.	66.5	93.0
Gunes and Ellis [6]	PEM FC. Residential CHP	31.0	80.0
Oyarzábal et al [7]	PEM FC + GT. Considers CHP.	39.0	73.0
Lunghi and Ubertini [8]	MCFC + GT. No cogeneration.	59.2	59.2
Bedont et al. [9]	MCFC + GT. Integrated GT compressor	59.7	83.5
Massardo and Bosio [2]	MCFC + GT+ST. 1- and 2-level HRSG	69.1	82.7
Campanari [10]	SOFC + μGT.	64.9	71.9

2.2.2 Fuel Cell – GT hybrids

The FC+GT ICC configurations [2, 5, 7-10] can be classified as:

(a) **With indirect heated GT.** They have gas-gas heat exchangers (large) for recovering FC exhaust heat and separate FC and GT air compressors.

(b) **With an integrated air compressor.** The GT compressor is used by the FC cathode compartment. After that, the stream passes through a post-combustor and through the GT expander, where it generates torque.

Option (a) has the advantage that the working pressures in the FC and the GT are independent, while in option (b) the GT pressure must be lower than that in the FC, resulting in lower compression ratios and GT efficiencies. However, in this case the very large and costly gas-gas heat exchanger is avoided.

2.2.3 Fuel Cell – GT – Steam Cycle hybrids

These systems haven't been much investigated so far due to their relative complexity and the small marginal efficiency increase they offer. From the sources in Table 2, only Massardo and Bosio [2] investigate such a system with a 100 kW MCFC. They report best electrical efficiency 67.4% and 69.1% for the cases of single-level and two-level steam cycles respectively.

3. Fuel options and renewable energy

3.1. Major trade-offs

The fuels for FC-based systems influence the electrical efficiencies, carbon emissions and economics significantly. H_2-rich feedstocks as natural gas are more advantageous for lower emissions. Biofuels lower the emissions too, but fossil fuels are still cheaper. A study on CH_4-CO_2 fuel mixtures for SOFC [4] indicates maximum efficiency at around 45% CH_4 - within the usual range of biogas compositions. The main reason is that H_2 is produced by dry reforming, where CO_2 and CH_4 are consumed in equimolar quantities. Thus, waste treatment plants can employ SOFC for CHP from biogas at top efficiency. Siemens, GE and others have started developing FCs using coal synthesis gas. Combined biomass and coal gasification may also be attractive.

3.2. Implications for carbon capture and sequestration

Burning biogas is carbon-neutral (Fig 1). Using fossil fuels causes CO_2 build-up and the need for CO_2 capture and sequestration. FCs keep the path of the air stream apart from that of the fuel and its products. Stoichiometrically CO_2 and water are the only anode-side products. In practice some fuel is present in the anode exhaust prompting post-combustion and introducing a some air into the exhaust. There is an opportunity for efficient CO_2 capture and subsequent sequestration. SOFC systems take this advantage to the extreme since they can oxidise both H_2 and CO [5]. Cheaper SOFCs with maximum fuel utilisation, producing mixtures of water and CO_2 only, may eliminate the need for CO_2 capture.

4. Application of FC-based energy conversion

4.1 Types of applications and power-to-heat ratio

Energy users differ widely by the scale and the power-to-heat ratio (PHR) of the demands. Residential applications feature daytime $PHR_{DAY} > 10$ and $PHR_{NIGHT} \approx 1$. PHRs of industrial energy demands vary too. An EC report [12] quotes the range 0.4-0.6. Grid supply power stations are another promising application, where district heating CHP (PHR = 0.10-0.49 [13]) are put at strong advantage by the legislation in most industrialised countries. The CHP efficiencies for the systems reviewed are also given in Table 2. They can serve applications with any practical PHR. For PHR > 1 (e.g. mechanical processing, grid-dedicated power plants), FC hybrids can be directly applied. For smaller PHR some components such as GT can be discarded. For very small values – PHR < 0.2, a

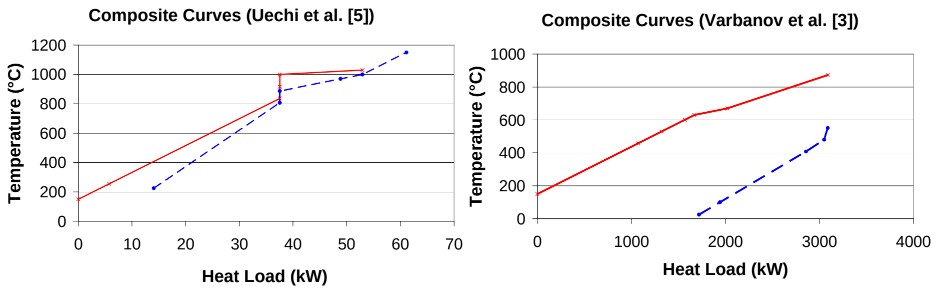
CHP plant with PHR > 0.2 may be designed and the excess power can be sold to the grid, if this is contractually and physically possible. An interesting direction is the design and operation of FC-based CHP systems for large industrial sites. In oil refineries and petrochemical plants there are large amounts of chemically low-quality hydrocarbon feedstocks (currently burned) suitable for reforming/gasification and further use as FC fuels.

4.2 Heat integration and its cost implications

Heat recovery inside FC systems has been analysed for different arrangements. Fig 2 shows the Composite Curves (CCs) for two representative cases – (a) integration of a SOFC with GT and (b) a MCFC with a steam cycle. The comparison of the cases in Fig 2 leads to two conclusions:

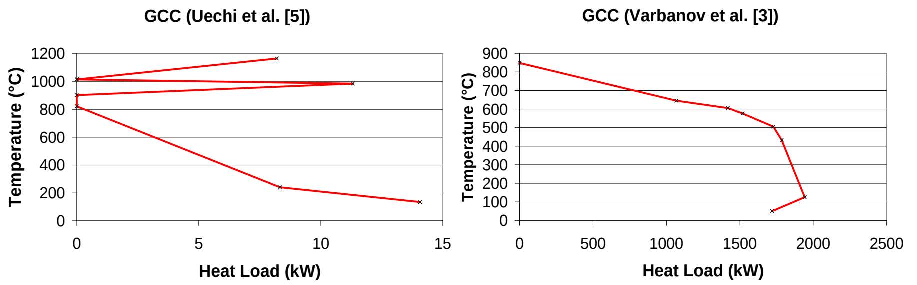
(i.) In the SOFC+GT arrangement [5] the components are more tightly integrated. These results in high efficiency, but also in smaller driving forces, which would tend to increase the capital costs.

(ii.) For MCFC+ST [3], higher efficiency is still possible, but the driving forces are much larger which indicates potentially smaller capital costs.



(a) SOFC+GT by Uechi et al. [5] (b) MCFC+ST by Varbanov et al. [3]

Fig 2. Composite curves (CC) of FC integration



(a) SOFC+GT by Uechi et al. [5] (b) MCFC+ST by Varbanov et al. [3]

Fig 3. Grand Composite Curves (GCC) of FC integration

The GCC (Fig.3) indicate that the MCFC+ST arrangement allows significant generation of any level steam for heating (to be used on-site or sold for profit).

5. Conclusions and future work

The paper studies benefits of FC integration. It has been found that the focus should be on high-temperature FC. Combining FC with either GT or ST is very efficient. Integration with both bottoming cycles provides no significant benefits in terms of efficiency. Lowering the FC cost while preserving their high efficiency is needed. The emphasis should be put on the CHP rather than electrical efficiency. Waste treatment and biogas plants can be suitable fuel suppliers for FC-based CHP systems. Gasified biomass or coal can be attractive too. Clean coal power plants should be based on SOFC with CO_2 sequestration.

Acknowledgements

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