

Design options for achieving a rapidly variable heat-to-power ratio in a combined heat and power (CHP) fuel cell system (FCS)

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Abstract

This article calls for a change in paradigm within the fuel cells industry such that it focuses less on solely maximizing a fuel cell's electrical efficiency, and more on a fuel cell system's (FCS) overall combined thermal and electrical efficiency, as defined in relation to the instantaneous demand for heat and electricity. Based on market needs in the power generation sector, it emphasizes the need to develop FCSs such that they can achieve a heat-to-power ratio that can be rapidly varied. This article then delineates engineering methods to achieve a rapidly variable heat-to-power ratio for a combined heat and power (CHP) FCS. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fuel cell system (FCS); Combined heat and power (CHP); Variable heat-to-power ratio; Proton exchange membrane (PEM); Thermal and electrical efficiency

1. Introduction

Engineers are more likely to succeed in developing a successful commercial product if they incorporate the results of a thorough market analysis into the first stage of their design efforts. An extensive analysis of power generation markets concludes that one of the most important engineering characteristics of a power plant is flexibility, i.e. the ability to change the amount of electricity supplied rapidly in response to changes in demand [1]. On an individual power plant level, one of the only ways to achieve this without significantly sacrificing overall (combined thermal and electrical) efficiency is to design a plant with a rapidly variable heat-to-power ratio [2]. The heat-to-power ratio is defined as the rate of useful thermal energy production to that of electrical energy production. This article delineates various engineering methods to achieve a rapidly variable heat-to-power ratio for a combined heat and power (CHP) fuel cell system (FCS).

For stationary power generation, a variable heat-to-power ratio has compelling advantages over a fixed one. Firstly, the more closely a CHP unit can match the instantaneous supply of heat and electricity with the instantaneous demand for heat and electricity, the more fuel efficient it will be. In the case of power generation technologies, since fuel is the dominant source of marginal running costs, higher fuel efficiency is concomitant to lower marginal costs. Secondly,

a variable heat-to-power ratio that leads to higher fuel efficiency also results in lower emissions. Finally, and most importantly, a variable heat-to-power ratio enables a power plant to achieve both (1) reliability (the ability to deliver electricity in a predictable manner) and (2) flexibility (the ability to rapidly change the amount of electricity delivered in response to rapid changes in demand). Reliability and flexibility are two of the most important characteristics for power generators in emerging liberalized electricity markets [3].

The ability to achieve a rapidly variable heat-to-power ratio over a large range is a relatively inimitable characteristic that fuel cells have over competing technologies. Table 1 summarizes the results of a competitor analysis of power generation technologies, which show that one of the only power generation technologies that may be able to realistically achieve a rapidly varying heat-to-power ratio is a CHP FCS (shown in the third row). Data compiled from [4–7]. Any type of engine, operating alone, is limited in its ability to achieve a rapidly variable heat-to-power ratio because its heat to work ratio is a fixed quantity. In comparison with an engine-based CHP system, a fuel cell CHP system can achieve a larger range of heat-to-power ratios. The fuel cell's heat-to-power ratio advantage over an engine is that, at low temperatures, unlike the engine, it can achieve low heat-to-power ratios. Fig. 1 compares the minimum theoretical heat-to-power ratio of a fuel cell and an engine at various temperatures [8]. At temperatures below approximately 850 °C, the fuel cell can achieve a lower heat-to-power ratio. Because the fuel cell can achieve lower heat-to-power

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Table 1
Comparison of CHP and conventional generation technologies against key success factors

| Key Success Factors | | Combined Heat and Power (CHP) | | | | | Conventional Generation | |
|---------------------|---------------|--------------------------------------|-----------------------|----------------------|----------------------------|-----------------------|-------------------------|---------------------------------|
| | | PEM Fuel Cell | Solid Oxide Fuel Cell | Micro-turbine | Reciprocating Engine (Gas) | Stirling Engine (Gas) | Grid Electric & Boiler | Superior Grid Electric & Boiler |
| Key Success Factors | Financial | Cost Competitive | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Low Performance | Low Performance |
| | | Suitability for Micro-Cogeneration | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Not Applicable | Not Applicable |
| | | Matching Heat to Power Ratio | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Not Applicable | Not Applicable |
| | | High Overall Efficiency | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |
| | | Advanced Development Stage | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |
| | Technical | Long Lifetime | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |
| | | Straightforward Grid Interconnection | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Not Applicable | Not Applicable |
| | | Low Maintenance Requirements | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |
| | Environmental | Low Carbon Dioxide Emissions | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |
| | | Low SOx, NOx, HC and CO Emissions | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |
| | | Low Noise Impact | High Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance | Moderate Performance |

ratios than an engine based system can at low temperatures, it can operate over a larger range of heat-to-power ratios. (The heat-to-power ratio of a CHP system is not as limited on the high end because electrical energy can always be converted to heat with 100% efficiency via electrical resistance heating.)

This relatively inimitable technical characteristic of fuel cells can be used as a competitive economic advantage. An inimitable characteristic can be used to extract additional economic rent by enabling a product to provide a unique service. The competitive advantage that a new technology

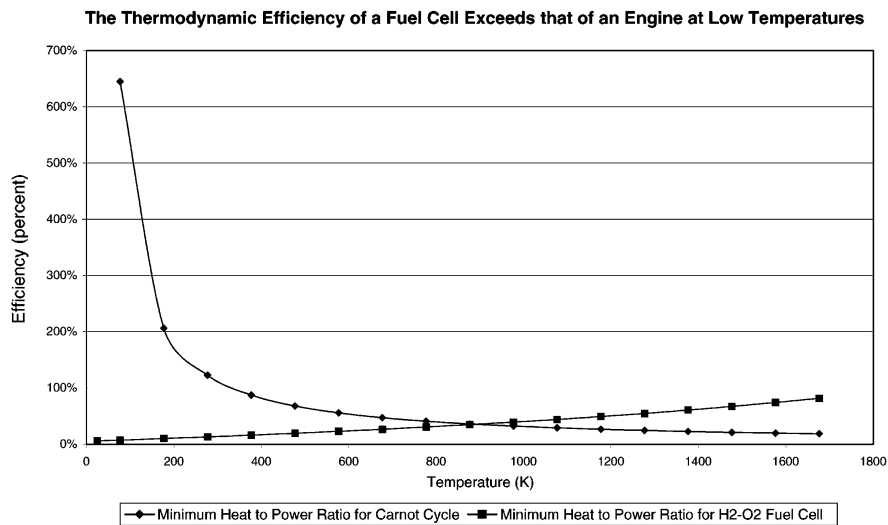


Fig. 1. The fuel cell's heat-to-power ratio advantage over an engine is in achieving low heat-to-power ratios at low temperatures. The figure is based on the theoretical Carnot cycle efficiency of an engine operating between 30 and 1700 °C and the maximum theoretical electrical efficiency of a hydrogen oxygen fuel cell.

The Ratio of Heat to Power Demanded in a House Rapidly Varies Over a Large Range in a Single Day

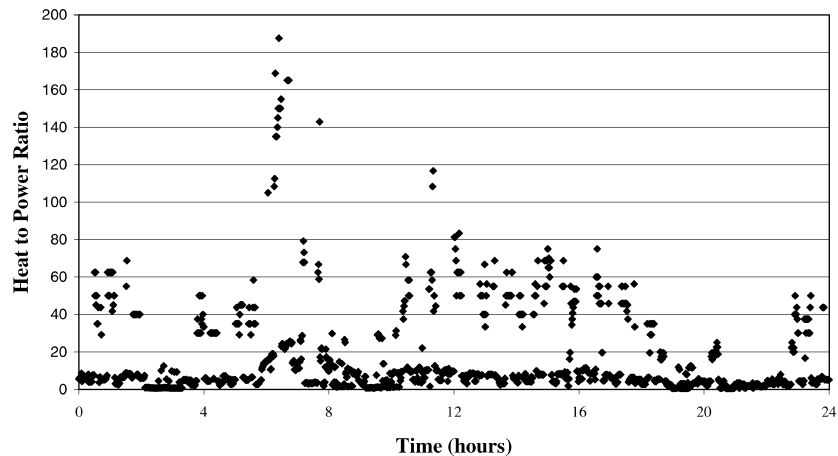


Fig. 2. It shows that the heat-to-power ratio varies rapidly over a large magnitude between 0 and 200 for this detached house in the UK over a single day. Much of this variation is not predictable.

gains by providing a new unique service is one of the primary mechanisms via which new technologies dislodge incumbents [9]. Given the important financial, environmental, and competitive benefits, a rapidly variable heat-to-power ratio should be one of the primary technical goals that shape the design of a CHP FCS.

Matching the heat-to-power ratio demanded from an individual building (and/or local network) with that supplied from a small-scale CHP system is a formidable task. On the demand side, the heat and power demanded in a home or office varies rapidly and sporadically over a large range. Fig. 2 illustrates the significant and rapid variation in the heat-to-power ratio of a detached house in the UK over a single day [10]. If a homeowner significantly changes the electrical demand of a house by switching on or off electrical appliances (i.e. between 0.3 kWe base load to 9 kWe peak in a fraction of a second), even if the heat demand remains constant, the heat-to-power ratio varies dramatically (i.e. by a factor of at least 30 in this example). On the supply side, in most electricity systems, electricity is supplied at the same instant in which it is demanded, because electrical storage costs are seen as prohibitive in most cases. The same holds to a lesser extent for heat. In cases in which changing the electrical load quickly results in a temporary mismatch with heat demand, a system can be designed to use hot water tanks or the thermal mass of the building as a heat buffer, but only temporarily. Alternatively, surplus electricity can always be transformed to heat via resistance heating, but potentially at much higher cost. One can assume that, in a FCS, the most expensive component is the fuel cell itself, and its lifetime depends on the number of hours it produces electricity. Since the fuel cell is the most expensive component of the system, using it to transform chemical energy to electrical energy and then to thermal energy is likely to be less economical than using another system component (or configuration) to convert chemical energy directly to ther-

mal energy. Also a separate resistance-heating device reduces the compactness of the system. To achieve a match between the heat-to-power ratio demanded and that supplied, a CHP FCS must incorporate several unique design features.

This article briefly outlines design options for achieving the goal of a variable heat-to-power ratio. Some design suggestions require significant research and development to introduce them in practice. Others simply affect arrangement of the balance of plant. They include the following:

- I. Vary the ratio of reactants, the temperature, and/or the pressure in the fuel processing sub-system to alter the amount of fuel flowing to the fuel cell and the enthalpy of the reforming reaction;
- II. Vary the fuel flow rate to the anode off-gas burner;
- III. Vary the system's electrical configuration;
- IV. Change the shape and/or position of the polarization curve during operation.

The development of these ideas requires a change in paradigm in the fuel cell industry, which has traditionally focused on maximizing only the fuel cell's electrical efficiency, not its overall (thermal and electrical) efficiency [11].

2. Discussion: engineering methods to achieve a variable heat-to-power ratio

2.1. System overview

A CHP FCS converts natural gas, liquid petroleum gas (LPG), or another readily accessible fuel into electrical and thermal energy via four sub-systems. First, the fuel processing sub-system, shown in light grey in Fig. 3, reforms a hydrocarbon fuel into a hydrogen rich gas [12]. The five most commercially advanced types of fuel cells consume

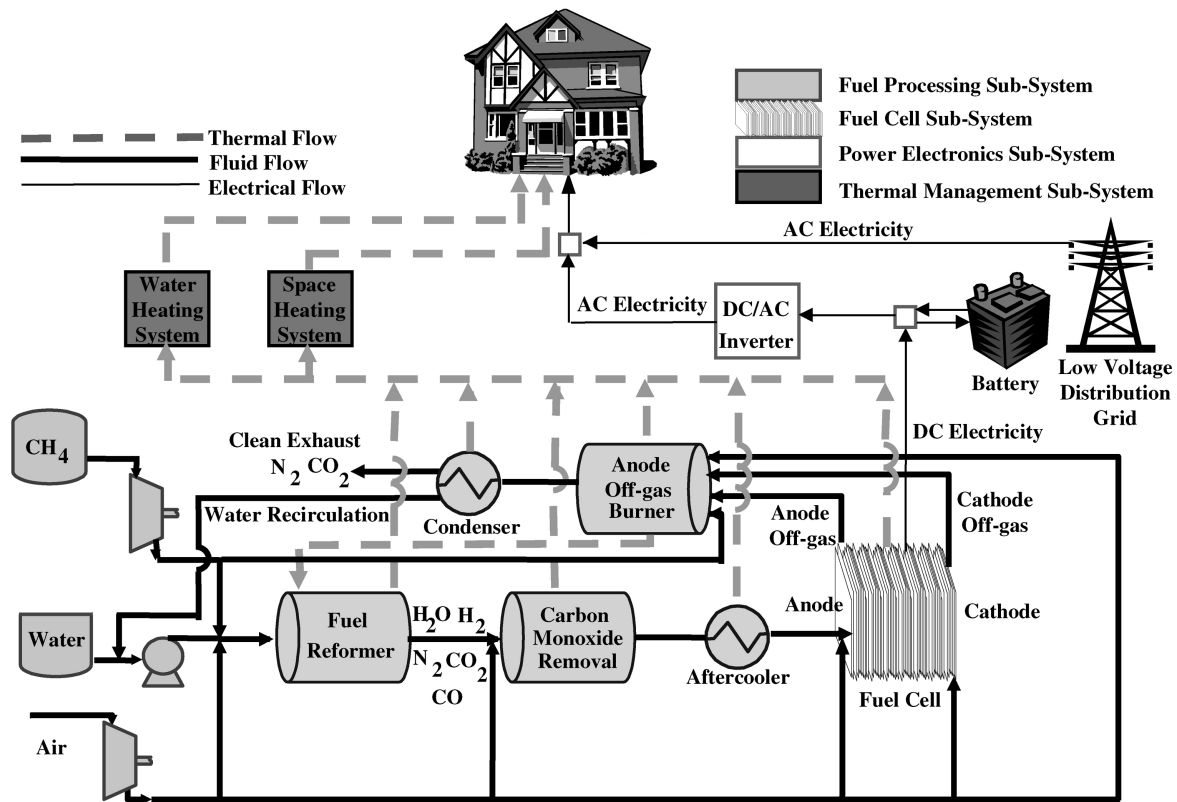


Fig. 3. Shows a schematic diagram of one type of combined heat and power (CHP) fuel cell system (FCS) using a proton exchange membrane (PEM) fuel cell and a fuel processing system for the delivery of hydrogen fuel. The thick solid line represents gas flow of products and reactants; the thin solid line represents electricity flow; and the thick dashed line indicates heat flow.

either hydrogen or a hydrogen rich mixture containing carbon monoxide and in some cases methane. A fuel processing sub-system produces a hydrogen rich mixture either in an external chemical reactor (external reforming) as shown in Fig. 3 or at the fuel cell's anode (internal reforming). Second, the fuel cell sub-system, shown in a pattern fill in Fig. 3, converts the hydrogen rich mixture into direct current (dc) electricity. Third, the power electronics sub-system, shown in white in Fig. 3, converts the dc electric power into alternating current (ac) power and manages the electrical current draw from the system against that drawn from an external electricity source (such as the grid). Fourth, the thermal management sub-system, shown in dark grey in Fig. 3, captures waste heat from the fuel processing sub-system and from the fuel cell sub-system for space heating, hot water, and other types of thermal demand. Through these four sub-systems, a CHP FCS provides power and heat for a home, office, or other building.

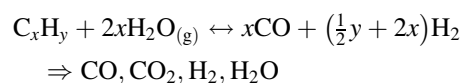
2.2. Vary the ratio of reactants, the temperature, and/or the pressure in the fuel processing sub-system to alter the amount of fuel flowing to the fuel cell and the enthalpy of the reforming reaction

One method for achieving a rapidly variable heat-to-power ratio is to vary the ratio of reactants, the temperature,

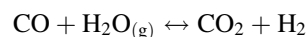
and/or the pressure in the fuel processing sub-system to alter the amount of fuel flowing to the fuel cell and the enthalpy of the reforming reaction. For the five most commercially advanced types of fuel cell, the hydrocarbon fuel must either be reformed first before being consumed at the fuel cell's anode or it must be oxidized at the anode (as in the case of solid oxide and molten carbonate fuel cells). In the case of reforming, the hydrocarbon fuel is converted into a hydrogen rich gas via one of three methods: (1) steam reforming (an endothermic reaction), (2) partial oxidation reforming (an exothermic reaction), or (3) a combination of the first two.

2.2.1. Steam reforming (SR) endothermically

Steam reforming endothermically combines a vaporized hydrocarbon with steam over a catalyst via,



During steam reforming, the water-gas shift (WGS) reaction also takes place, thereby converting the hydrogen in water directly to hydrogen gas.



The primary reactions of the SR process for methane gas are listed as the first three equations of Table 2 [13]. For the

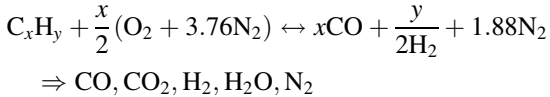
Table 2
Reactions for steam reforming (1–3) and partial oxidation (4–9) of methane gas

| S. no. | Autothermal reforming reactions | | |
|--------|---------------------------------|---|-----------------------------|
| | Reaction type | Stoichiometric formula | ΔH_r° (kJ/mol) |
| 1 | Steam reforming | $\text{CH}_4 + 2\text{H}_2\text{O}(\text{g}) \rightarrow \text{CO}_2 + 4\text{H}_2$ | +165.2 |
| 2 | Water-gas shift reaction | $\text{CO} + \text{H}_2\text{O}(\text{g}) \rightarrow \text{CO}_2 + \text{H}_2$ | -41.2 |
| 3 | Evaporation | $\text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_2\text{O}(\text{g})$ | +44.1 |
| 4 | Partial oxidation | $\text{CH}_4 + 1/2\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2$ | -35.7 |
| 5 | Partial oxidation | $\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2$ | -319.1 |
| 6 | Thermal decomposition | $\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$ | +75.0 |
| 7 | Methane combustion | $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}(\text{g})$ | -803.5 |
| 8 | CO combustion | $\text{CO} + 1/2\text{O}_2 \rightarrow \text{CO}_2$ | -283.4 |
| 9 | Hydrogen combustion | $\text{H}_2 + 1/2\text{O}_2 \rightarrow \text{H}_2\text{O}(\text{g})$ | -242.2 |

steam reforming of natural gas, the hydrogen rich outlet stream typically contains in thermodynamic equilibrium at atmospheric pressure 76% hydrogen, 9% carbon dioxide, 15% carbon monoxide (with a steam-to-carbon ratio S/C of 3), and traces of methane, sulphur, and ammonia [14]. However, after the shift-reaction stage described below, the concentration of hydrogen increases to about 80%.

2.2.2. Partial oxidation reforming

In a partial oxidation (POX) reaction, the hydrocarbon fuel reacts with less than stoichiometric oxygen for incomplete combustion in the presence of a catalyst:



The primary reactions of the POX reforming process for methane gas are listed as Eqs. 4–9 in Table 2. Fig. 4 shows the manner in which the temperature of the partial oxidation

reaction of methane can be varied to achieve varying levels of hydrogen yield, and therefore fuel cell electrical output and system heat-to-power ratio [15]. Although Fig. 4 shows operating points that are thermodynamically possible, the practical operating region is much narrower due to the limits of catalytic activity.

2.2.3. Combining steam reforming and partial oxidation to achieve a variable heat-to-power ratio

The first two main types of reforming processes can be combined in series or in parallel, and in different ratios to create other types of reforming process. By changing the ratio, order, temperature, or pressure of these reactions, one can alter (1) the final composition of the hydrogen rich mixture so as to alter the amount of fuel flowing to the fuel cell and (2) the amount of waste heat from the reformer (and hence the system). For example, during periods of high thermal demand, a greater percentage of the fuel may be intentionally oxidized, to produce less hydrogen fuel (and

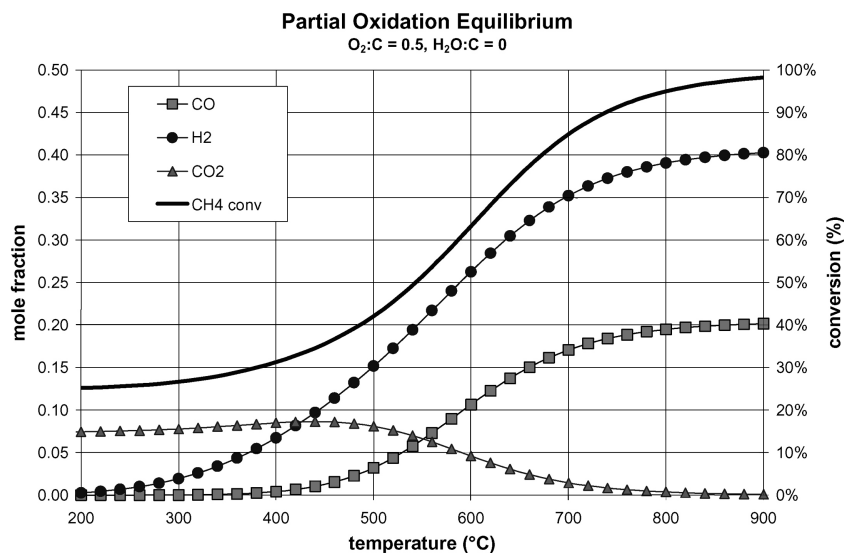


Fig. 4. Shows the increase in hydrogen composition for the partial oxidation reaction of methane with increasing reactor outlet temperature. This analysis assumes the Gibbs free energy of the products is minimized.

carbon monoxide and/or methane depending on the type of fuel cell) for consumption at the anode and a higher enthalpy of reaction at the reformer. The heat-to-power ratio can be varied across a wide spectrum by changing the ratio of reactions because the steam reforming reaction is endothermic and the partial oxidation reaction is exothermic. During the extreme periods of the highest thermal demand, the same fuel processing sub-system may operate in a mode that achieves complete combustion. The hydrogen content of the outlet gas and the enthalpy of reaction are obviously interdependent variables. In this way, by varying the ratio of reactants, the temperature, and/or the pressure in the fuel processing sub-system, one can alter the heat-to-power ratio of the system. (With more practical considerations in mind, if the system runs catalytically, the operating temperature window of the reformer is constrained by the catalyst, which is limited on the low side by the level of activity and on the high side by durability. As a result, the process of choosing effective operating points for altering the heat-to-power ratio is more complex than simply altering the relative amounts of steam reforming versus partial oxidation).

2.3. Vary the fuel flow rate to the anode off-gas burner

A second method for achieving a variable heat-to-power ratio is to vary the flow rate of fuel (natural gas, LPG, etc.) to the anode off-gas burner to produce a varying level of heat relative to the total energy output of the system. Some FCSs use an anode off-gas burner, as shown in Fig. 3, to combust any residual hydrogen and hydrocarbons that have not been consumed at the fuel cell's anode. The burner may also be used to combust fuel directly, for example, to heat the system up under start-up. To integrate this device into a variable heat-to-power strategy for a system, the fuel source is directly connected to the anode off-gas burner by a valve that can be opened or closed, as shown in Fig. 3 as the central, solid, horizontal line on the left side. To achieve this operating mode, it is necessary to use a catalytic burner that is highly versatile. The burner must have (i) a large turndown ratio to allow a wide variance in inlet flow rates and (ii) a high tolerance to a wide variety of gas compositions (from 30% hydrogen from the fuel cell anode off-gas to 100% natural gas from the fuel source). Ideally, the off-gas burner would have a large enough turndown ratio so as to be able to replace a boiler, an unnecessary additional piece of equipment. The primary advantages of this strategy for controlling the heat-to-power ratio are that (i) the unit can deliver heat at high temperature, and (ii) this strategy does not require extensive research and development, but rather only modifications to the balance of plant, re-sizing the burner, and testing appropriate catalysts. The primary disadvantage of this strategy is that this operating mode achieves lower system efficiency than other methods for altering the heat-to-power ratio. In typical burners, 30% of the fuel energy may be lost as heat.

2.4. Vary the system's electrical configuration

Another method to vary the system's heat-to-power ratio is to vary the FCS's electrical configuration. Three methods for achieving this include the following:

- (i) Operate the system with multiple stacks that can be attached either in series or in parallel, so as to achieve a large turndown ratio (ratio of maximum to minimum electrical output);
- (ii) Vary the number of cells electrically connected in series in a stack to match the desired voltage;
- (iii) Operate the FCS in series or in parallel with an electrical storage device (such as batteries, capacitors, or a local distribution grid) [16].

Although varying the electrical system configuration is unlikely to be a viable option in the immediate future due to current technical limitations, it does nonetheless need to be considered, especially in the context of future research and development efforts.

2.5. Change the shape and/or position of the polarization curve during operation

A polarization curve, shown by the uppermost dashed line in Fig. 5, describes the decrease in the electrical efficiency of a fuel cell with an increase in current density. On the current versus voltage plot, if one can change the shape or position of the polarization curve during operation, one necessarily changes the system's heat-to-power ratio (useful thermal to electrical energy). For a given polarization curve, Fig. 5 shows the resulting heat-to-power ratio curve, as indicated by the solid line. As the polarization curve shifts upwards, the fuel cell's heat-to-power ratio declines, and, as it shifts downwards, it increases. Thus, by changing the shape or position of polarization curve on the current versus voltage graph, one can alter the heat-to-power ratio of the fuel cell stack, and therefore, that of the system. The shape of the polarization curve can be changed both through indirect methods (such as altering temperature, pressure, and reactant concentrations) and direct methods (such as altering a cell's Ohmic polarization), as described below.

2.5.1. Vary the temperature

One way to change the shape and position of the polarization curve on the current versus voltage plot during operation is to alter a fuel cell's operating temperature. A fuel cell's polarization curve depends strongly on temperature. For most types of fuel cells (AFC, PAFC, MCFC, SOFC), as their temperature increases, their polarization curve shifts upwards [17]. For the proton exchange membrane (PEM) fuel cell, as the temperature increases, its polarization curve increases up until a point (about 0.85 V at open circuit and 130 °C), where it begins to decline with further increase in temperature.

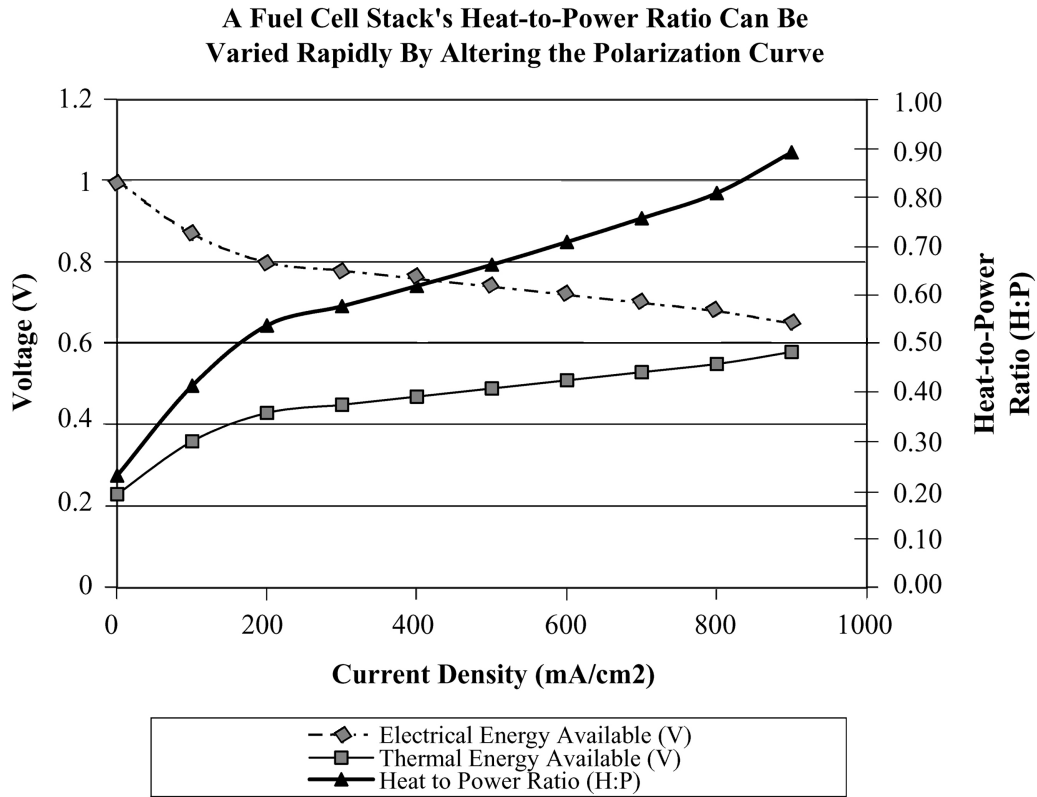


Fig. 5. It shows the polarization curve for a fuel cell, which indicates the electrical energy available from a fuel cell at any current draw. The heat available from the fuel cell is the mirror image of this curve. The heat-to-power ratio is the ratio of these curves.

The polarization curve changes in shape and position as the cell's temperature changes due to changes in the nature of polarizations. In general, as temperature rises, activation polarization decreases due to the higher reaction rate, Ohmic polarization decreases due to a decrease in the resistance in the electrodes and electrolyte, and concentration polarization decreases due to higher mass diffusion rates. Also, as temperature rises, low temperature fuel cells have a higher tolerance to carbon monoxide. On the other hand, as temperature rises, polarizations may increase due to material constraints.

The response time of this control method is in the order of minutes. Depending on the type of cell, the degree of temperature change, and the stack heat transfer design, a cell's temperature can be altered in a few minutes or less. These temperature changes are, for the most part, instantaneously reflected in the cell's polarization curve and hence its heat-to-power ratio. Therefore, a FCS can be operated in such a way that it changes its stack temperature to alter its heat-to-power ratio to respond to changes in electricity demand on a per minute or greater basis.

2.5.2. Vary the pressure

Another way to change the shape of the polarization curve during operation is to alter the stack pressure. Pressure has a similar effect as temperature; an increase in pressure shifts the polarization curve up, and vice versa. An increase in

pressure increases the partial pressure of reactants and the rate of mass diffusion. The drawbacks to increasing pressure include thicker piping, the need for a compressor with a higher rating and turndown ratio, and potential materials problems, such as reactant leakage through the electrolyte and seals. Also, the gains in fuel cell electrical efficiency from increasing the pressure are partly offset by the increase in parasitic power losses via the compressor.

As with temperature, the response time of this control method is a few minutes or less. Most of this lag time depends on the time it takes to increase system pressure, rather than the time it takes to decrease system pressure (which can be quite quick with a purge valve) or the time it takes for the pressure increase to affect the shape of the curve. As a result, changing the system pressure is one method for responding to some short demand changes in the order of minutes, and certainly hourly to seasonal changes.

2.5.3. Vary the reactant concentration at the fuel cell inlet

The reactant concentration at the inlet to the fuel cell can be varied so as to get a more appropriate heat-to-power ratio. For example, in a PEM FCS the hydrogen content of the reformat stream can be varied in a variety of ways:

- (i) Bypass the shift reactor to reduce hydrogen content of the inlet gas stream to the fuel cell (assuming a high level of carbon monoxide tolerance at the fuel cell anode);

- (ii) Recycle the anode off-gas to dilute the hydrogen content of the fuel cell inlet gas or store it for later use in dilution;
- (iii) Change the degree of partial oxidation versus steam reforming in the autothermal reformer to either dilute or magnify hydrogen content, respectively.

For example, in the summer, the fuel reformer can be run such that a greater percentage of the reaction is via steam reforming so as to produce a larger hydrogen yield (and therefore a lower heat-to-power ratio), since heat does not have a useful outlet in summer. The converse of this is simply that in the winter, when heat demand is higher, the reformer is run such that a greater percentage of the reaction is via partial oxidation or autothermal reforming. To implement this, a particular reactor design must be characterized for performance at different percentages of partial oxidation versus steam reforming reaction.

2.5.4. Vary Ohmic polarization

Changing the temperature or pressure of a system are two ways to indirectly alter polarizations to affect the heat-to-power ratio. Polarizations can also be directly altered—via changing some aspect of activation, Ohmic, or concentration polarization. Some direct methods are complicated enough as to require a few stages of research and development activity before they can be practically implemented.

One method to enable one to vary the heat-to-power ratio is to vary the fuel cell's Ohmic polarization during operation. By choosing materials with desired resistance properties, the electrical resistance of the flow field plates, electrolyte, flow field plates, or wiring could be designed to change in response to a certain stimulus. For example, the resistance of some materials is a strong function of current, and, for other materials, temperature. In the case of a hydrogen-fuelled fuel cell (with no reformer system), a flow field plate's Ohmic resistance might be designed to increase at lower current draw so as to dissipate more heat to the inlet hydrogen and air to preheat them. This enables the chemical reaction of hydrogen and oxygen to proceed at higher temperatures, achieve a higher extent of reaction, and produce a large percentage of electricity in comparison to waste heat (lower heat-to-power ratio). Although varying the Ohmic polarization of a fuel cell is very similar to using an external electrical resistance heater, its primary benefits over the later are that it saves space and presents an opportunity for a more passive control method.

3. Conclusion

Although fuel cell research has traditionally focused on increasing electrical efficiency, for some fuel cell applications, a different research focus is perhaps more appropriate. The goal of fuel cell developers has traditionally been to maximize a fuel cell's electrical efficiency (or minimize its

polarization) so that its experimentally observed cell voltage approaches its ideal open circuit cell voltage [18]. For example, one of Ballard Power Corporation's five principal development strategy goals for its fuel cell stacks has been to increase its stack operating voltage [19]. As this article attempts to highlight, after fuel cells have reached a certain level of electrical efficiency, the goal of increasing their electrical efficiency even further is not necessarily synonymous with the technology's economical application. One of the best examples of this kind of application is the CHP market, which depends on the useful application of both a power plant's thermal and electrical power. In such cases, for the purpose of meeting market requirements, it may be less technically important to focus engineering efforts on refining the fuel cell stack electrical efficiency and more important to focus efforts on meeting the system's combined electrical and thermal needs, not just at a system design level but also at a fundamental research and development level.

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References

- [1] D. Bauknecht, European Electricity Market Analyst, PowerInk Ltd., Brighton, UK.
- [2] W. Colella, Combined heat and power fuel cell systems, doctoral thesis transfer report, Department of Engineering Sciences, University of Oxford, Oxford, June 2001.
- [3] W. Colella, Implications of electricity liberalization for combined heat and power (CHP) fuel cell systems (FCS): a case study of the UK, Elsevier, London, UK, J. Power Sources, 2002.
- [4] P. Gray, Solid Polymer Fuel Cell Prototype System for Micro-CHP Phase 1: Market, Technical and Economic Study, Department of Trade and Industry, London, UK, 1999.
- [5] J. Cotton, The Potential for Economic Manufacture of Solid Oxide Fuel Cells, Department of Trade and Industry, London, UK, 1995.
- [6] Combined Power Systems Ltd., A Technical and Economic Assessment of Small Stirling Engines for Combined Heat and Power, Department of Trade and Industry, London, UK, 1993.
- [7] S.R. James, Stirling Engines, Moriya Press, River Falls, WI, 1993.
- [8] S.N. Carnot, Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance, Reflections on the Motive Power of Fire, Paris, 1824.
- [9] J.A. Schumpeter, The Theory of Economic Development, 1911.
- [10] Electricity and Heat Demand Data for a UK. Detached House on the Weekend of 6 May 1996, Advantica (formerly BG Technology), Ashby Rd, Loughborough, Leicestershire LE 11 3GR www.lattice-group.com.
- [11] J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, M.G. Klett, Fuel Cells Handbook, 4th Edition, DOE/FETC-99/1076, Table 2-2, US Department of Energy, Washington, DC, 1998, p. 2–8.

- [12] Adapted From a Figure Courtesy of the Johnson Matthey Technology Center (JMTC), UK, 2001.
- [13] R.M. Felder, R.W. Rousseau, *Elementary Principles of Chemical Processes*, Table B.1 Selected Physical Property Data: Heat of Formation and Heat of Combustion, 3rd Edition, Wiley, New York, NY, 2000, p. 635.
- [14] M.V. Twigg, *Catalyst Handbook*, Manson Publishing, London, UK, 1996.
- [15] J. Sun, Hydrogen Generation for PEM Fuel Cells, *Fuel Cell Today*, September 2001. http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/article_319_jamessunfuelprocessing0901.pdf.
- [16] The following study concluded that, under the assumption of both mass-produced fuel cells and batteries, adding a peaking battery storage system would increase the cost of electricity from a proton exchange membrane (PEM) FCS, in: C.E. Thomas (Ed.), *Utility Sector Hydrogen System Analysis with Battery Augmentation*, Task 4 Final Report, Subcontract No. ACG-8-18012-01, For the National Renewable Energy Laboratory, US DOE, Washington, DC, US DOE, 1999.
- [17] S.N. Simons, R.B. King, P.R. Prokopius, in: E.H. Camera (Ed.), *Symposium Proceedings on the Fuel Cells Technology Status and Applications*, Institute of Gas Technology, Vol. 45, Fig. 1, Chicago, IL, 1982, p. 46.
- [18] J.H. Hirschenhofer, D.B. Staugger, R.R. Engleman, M.G. Klett, *Fuel Cells Handbook*, 4th Edition, DOE/FETC-99/1076, Table 2-2, US Department of Energy, Washington, DC, 1998, p. 2–8.
- [19] K. Washington, Development of a 250 kW Class Polymer Electrolyte Fuel Cell Stack at Ballard Power Systems Inc., 2000 Fuel Cell Seminar Abstracts: Fuel Cells—Powering the 21st Century, Portland, Oregon, US DOE, 2000, p. 468.