



ELSEVIER

Journal of Power Sources 4687 (2002) 1–8

 JOURNAL OF
**POWER
 SOURCES**

www.elsevier.com/locate/jpowersour

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

Whitney Colella*

Department of Engineering Sciences, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

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 Published by Elsevier Science B.V.

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 ratios

* Fax: +1-530-869-7676.

E-mail address: wcolella@alumni.princeton.edu (W. Colella).

Table 1
Comparison of CHP and conventional generation technologies against 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 Electricity and Boiler	Advanced Grid Electricity and Boiler
Key Success Factors	Financial	Cost Competitive						
		Suitability for Micro-Cogeneration						
		Matching Heat to Power Ratio						
		High Overall Efficiency						
		Advanced Development Stage						
	Technical	Long Lifetime						
		Straightforward Grid Interconnection						
		Low Maintenance Requirements						
	Environmental	Low Carbon Dioxide Emissions						
		Low SOx, NOx, HC and CO Emissions						
		Low Noise Impact						

	High Performance
	Moderate Performance
	Low Performance
	Not Applicable

75 than an engine based system can at low temperatures, it can
 76 operate over a larger range of heat-to-power ratios. (The heat-
 77 to-power ratio of a CHP system is not as limited on the high
 78 end because electrical energy can always be converted to heat
 79 with 100% efficiency via electrical resistance heating.)
 80 This relativity inimitable technical characteristic of fuel
 81 cells can be used as a competitive economic advantage. An
 82 inimitable characteristic can be used to extract additional

83 economic rent by enabling a product to provide a unique
 84 service. The competitive advantage that a new technology
 85 gains by providing a new unique service is one of the
 86 primary mechanisms via which new technologies dislodge
 87 incumbents [9]. Given the important financial, environmen-
 88 tal, and competitive benefits, a rapidly variable heat-to-
 89 power ratio should be one of the primary technical goals
 90 that shape the design of a CHP FCS.

**At Low Temperatures, Fuel Cells Can Achieve Lower
Minimum Heat to Power Ratios**

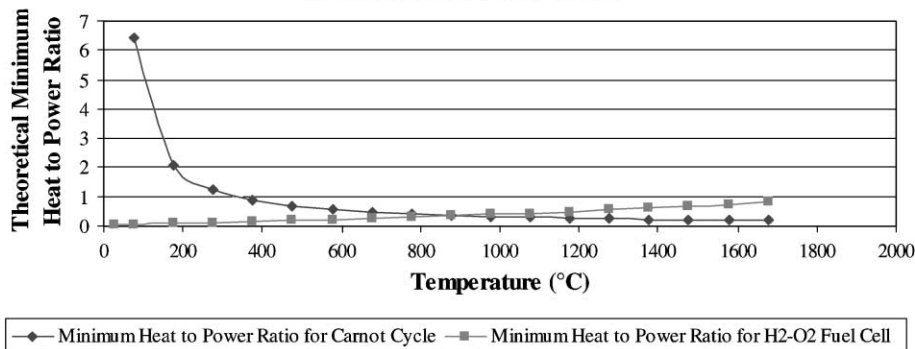


Fig. 1. The fuel cell's heat-to-power ratio advantage over an engine is in achieving low heat-to-power ratios at low temperatures. The figure is based on the theoretical Carnot cycle efficiency of an engine operating between 30 and 1700 °C and the maximum theoretical electrical efficiency of a hydrogen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

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

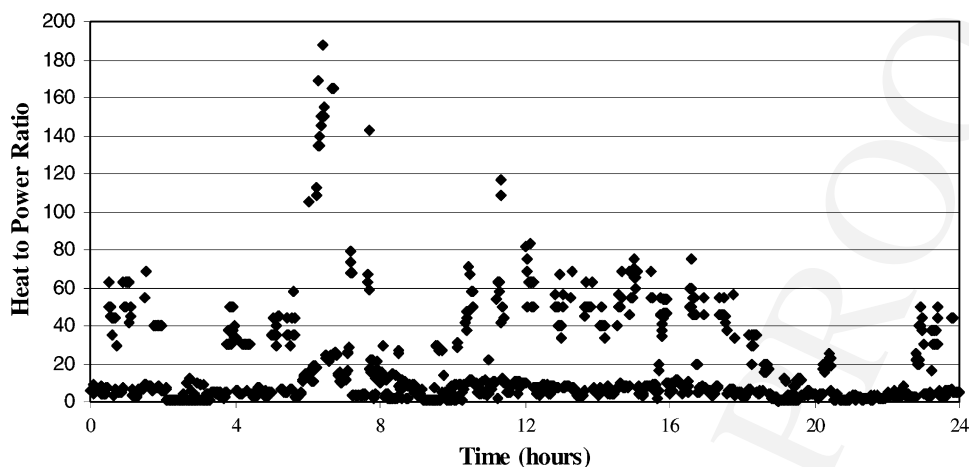


Fig. 2. Fig. 2 shows that the heat-to-power ratio varies rapidly over a large magnitude between 0 and 200 for this detached house in the UK over a single day. Much of this variation is not predictable.

91 Matching the heat-to-power ratio demanded from an
 92 individual building (and/or local network) with that supplied
 93 from a small-scale CHP system is a formidable task. On the
 94 demand side, the heat and power demanded in a home or
 95 office varies rapidly and sporadically over a large range.
 96 Fig. 2 illustrates the significant and rapid variation in the
 97 heat-to-power ratio of a detached house in the UK over a
 98 single day [10]. If a homeowner significantly changes the
 99 electrical demand of a house by switching on or off electrical
 100 appliances (i.e. between 0.3 kWe base load to 9 kWe peak in
 101 a fraction of a second), even if the heat demand remains
 102 constant, the heat-to-power ratio varies dramatically (i.e. by
 103 a factor of at least 30 in this example). On the supply side, in
 104 most electricity systems, electricity is supplied at the same
 105 instant in which it is demanded, because electrical storage
 106 costs are seen as prohibitive in most cases. The same holds to
 107 a lesser extent for heat. In cases in which changing the
 108 electrical load quickly results in a temporary mismatch with
 109 heat demand, a system can be designed to use hot water
 110 tanks or the thermal mass of the building as a heat buffer, but
 111 only temporarily. Alternatively, surplus electricity can
 112 always be transformed to heat via resistance heating, but
 113 potentially at much higher cost. One can assume that, in a
 114 FCS, the most expensive component is the fuel cell itself,
 115 and its lifetime depends on the number of hours it produces
 116 electricity. Since the fuel cell is the most expensive compo-
 117 nent of the system, using it to transform chemical energy to
 118 electrical energy and then to thermal energy is likely to be
 119 less economical than using another system component (or
 120 configuration) to convert chemical energy directly to ther-
 121 mal energy. Also a separate resistance-heating device
 122 reduces the compactness of the system. To achieve a match
 123 between the heat-to-power ratio demanded and that sup-
 124 plied, a CHP FCS must incorporate several unique design
 125 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 arrange-
 ment 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 effi-
 ciency, 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 proces-
 sing sub-system, shown in green in Fig. 3, reforms a
 hydrocarbon fuel into a hydrogen rich gas [12]. The five
 most commercially advanced types of fuel cells consume
 either hydrogen or a hydrogen rich mixture containing
 carbon monoxide and in some cases methane. A fuel pro-
 cessing sub-system produces a hydrogen rich mixture either

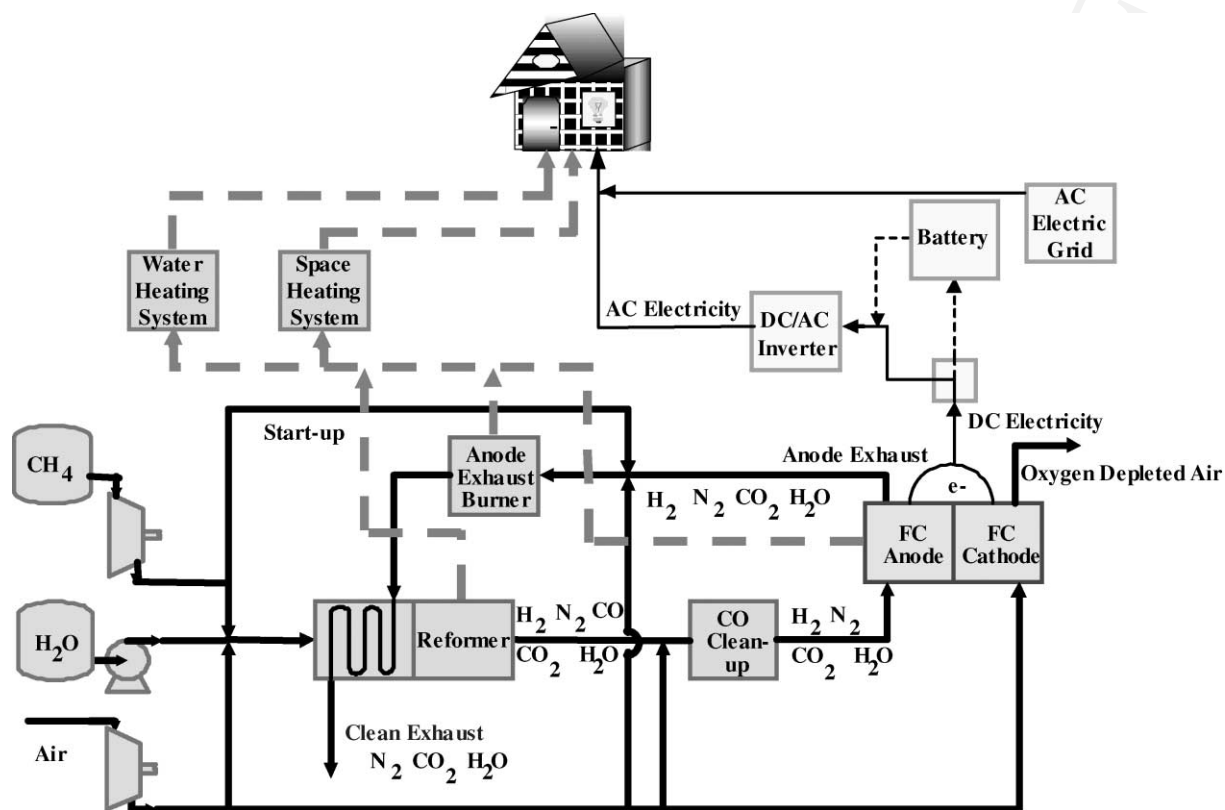


Fig. 3. shows a schematic diagram of one type of combined heat and power (CHP) fuel cell system (FCS) using a proton exchange membrane (PEM) fuel cell and a fuel processing system for the delivery of hydrogen fuel. The thick solid line represents gas flow of products and reactants; the thin solid line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

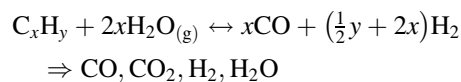
158 in an external chemical reactor (external reforming) as
 159 shown in Fig. 3 or at the fuel cell's anode (internal reforming).
 160 Second, the fuel cell sub-system, shown in blue in
 161 Fig. 3, converts the hydrogen rich mixture into direct current
 162 (dc) electricity. Third, the power electronics sub-system,
 163 shown in yellow in Fig. 3, converts the dc electric power into
 164 alternating current (ac) power and manages the electrical
 165 current draw from the system against that drawn from an
 166 external electricity source (such as the grid). Fourth, the
 167 thermal management sub-system, shown in red in Fig. 3,
 168 captures waste heat from the fuel processing sub-system and
 169 from the fuel cell sub-system for space heating, hot water,
 170 and other types of thermal demand. Through these four sub-
 171 systems, a CHP FCS provides power and heat for a home,
 172 office, or other building.

173 *2.1.1.1. Vary the ratio of reactants, the temperature, and/or*
 174 *the pressure in the fuel processing sub-system to alter the*
 175 *amount of fuel flowing to the fuel cell and the enthalpy of*
 176 *the reforming reaction*

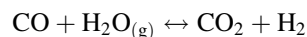
177 One method for achieving a rapidly variable heat-to-
 178 power ratio is to vary the ratio of reactants, the temperature,
 179 and/or the pressure in the fuel processing sub-system to alter
 180 the amount of fuel flowing to the fuel cell and the enthalpy of
 181 the reforming reaction. For the five most commercially
 182 advanced types of fuel cell, the hydrocarbon fuel must either

183 be reformed first before being consumed at the fuel cell's
 184 anode or it must be oxidized at the anode (as in the case of
 185 solid oxide and molten carbonate fuel cells). In the case of
 186 reforming, the hydrocarbon fuel is converted into a hydro-
 187 gen rich gas via one of three methods: (1) steam reforming
 188 (an endothermic reaction), (2) partial oxidation reforming
 189 (an exothermic reaction), or (3) a combination of the first
 190 two.

191 *2.1.1.1. Steam reforming.* Steam reforming endothermically
 192 combines a vaporized hydrocarbon with steam over a catalyst
 193 via,



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



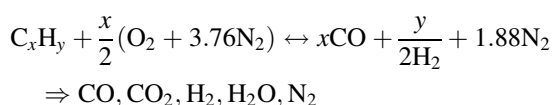
201 The primary reactions of the SR process for methane gas are
 202 listed as the first three equations of Table 2 [13]. For the
 203 steam reforming of natural gas, the hydrogen rich outlet
 204 stream typically contains in thermodynamic equilibrium at
 205 atmospheric pressure 76% hydrogen, 9% carbon dioxide,

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

206 15% carbon monoxide (with a steam-to-carbon ratio S/C of
207 3), and traces of methane, sulphur, and ammonia [14].
208 However, after the shift-reaction stage described below,
209 the concentration of hydrogen increases to about 80%.

210 *2.1.1.2. Partial oxidation reforming.* In a partial oxidation
211 (POX) reaction, the hydrocarbon fuel reacts with less than
212 stoichiometric oxygen for incomplete combustion in the
213 presence of a catalyst:



215
216 The primary reactions of the POX reforming process for
217 methane gas are listed as Eqs. 4–9 in Table 2. Fig. 4 shows
218 the manner in which the temperature of the partial oxidation
219 reaction of methane can be varied to achieve varying levels
220 of hydrogen yield, and therefore fuel cell electrical output
221 and system heat-to-power ratio [15]. Although Fig. 4 shows
222 operating points that are thermodynamically possible, the

practical operating region is much narrower due to the limits
of catalytic activity.

2.1.1.3. 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 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

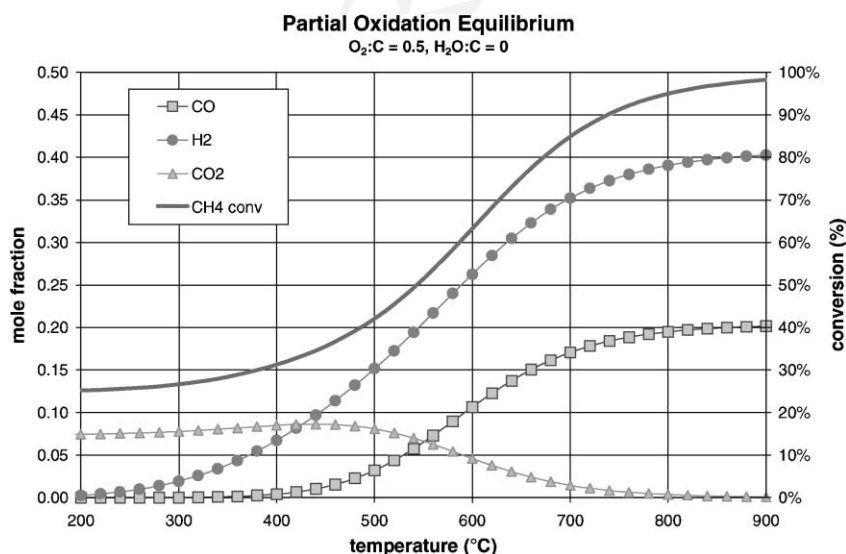


Fig. 4. shows the increase in hydrogen composition for the partial oxidation reaction of methane with increasing reactor outlet temperature. This analysis assumes the Gibbs free energy of the products is minimized.

242 reaction is exothermic. During the extreme periods of the
 243 highest thermal demand, the same fuel processing sub-system
 244 may operate in a mode that achieves complete combustion.
 245 The hydrogen content of the outlet gas and the enthalpy of
 246 reaction are obviously interdependent variables. In this way,
 247 by varying the ratio of reactants, the temperature, and/or the
 248 pressure in the fuel processing sub-system, one can alter the
 249 heat-to-power ratio of the system. (With more practical
 250 considerations in mind, if the system runs catalytically, the
 251 operating temperature window of the reformer is constrained
 252 by the catalyst, which is limited on the low side by the level of
 253 activity and on the high side by durability. As a result, the
 254 process of choosing effective operating points for altering the
 255 heat-to-power ratio is more complex than simply altering the
 256 relative amounts of steam reforming versus partial oxidation).

257 *2.1.2. Vary the fuel flow rate to the anode off-gas burner*

258 A second method for achieving a variable heat-to-power
 259 ratio is to vary the flow rate of fuel (natural gas, LPG, etc.) to
 260 the anode off-gas burner to produce a varying level of heat
 261 relative to the total energy output of the system. Some FCSs
 262 use an anode off-gas burner, as shown in Fig. 3, to combust
 263 any residual hydrogen and hydrocarbons that have not been
 264 consumed at the fuel cell's anode. The burner may also be
 265 used to combust fuel directly, for example, to heat the system
 266 up under start-up. To integrate this device into a variable
 267 heat-to-power strategy for a system, the fuel source is
 268 directly connected to the anode off-gas burner by a valve
 269 that can be opened or closed, as shown in Fig. 3 as the
 270 uppermost horizontal line on the left side. To achieve this
 271 operating mode, it is necessary to use a catalytic burner that
 272 is highly versatile. The burner must have (i) a large turndown
 273 ratio to allow a wide variance in inlet flow rates and (ii) a
 274 high tolerance to a wide variety of gas compositions (from
 275 30% hydrogen from the fuel cell anode off-gas to 100%
 276 natural gas from the fuel source). Ideally, the off-gas burner
 277 would have a large enough turndown ratio so as to be able to
 278 replace a boiler, an unnecessary additional piece of equip-
 279 ment. The primary advantages of this strategy for controlling
 280 the heat-to-power ratio are that (i) the unit can deliver heat at
 281 high temperature, and (ii) this strategy does not require

282 extensive research and development, but rather only mod-
 283 ifications to the balance of plant, re-sizing the burner, and
 284 testing appropriate catalysts. The primary disadvantage of
 285 this strategy is that this operating mode achieves lower
 286 system efficiency than other methods for altering the
 287 heat-to-power ratio. In typical burners, 30% of the fuel
 288 energy may be lost as heat.

289 *2.1.3. Vary the system's electrical configuration*

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

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

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

307 *2.1.4. Change the shape and/or position of the polarization
 308 curve during operation*

309 A polarization curve, shown by the uppermost dashed line
 310 in Fig. 5, describes the decrease in the electrical efficiency of
 311 a fuel cell with an increase in current density. On the current
 312 versus voltage plot, if one can change the shape or position
 313 of the polarization curve during operation, one necessarily
 314 changes the system's heat-to-power ratio (useful thermal to
 315 electrical energy). For a given polarization curve, Fig. 5
 316 shows the resulting heat-to-power ratio curve, as indicated
 317 by the solid line. As the polarization curve shifts upwards,
 318 the fuel cell's heat-to-power ratio declines, and, as it shifts
 319 downwards, it increases. Thus, by changing the shape or
 320

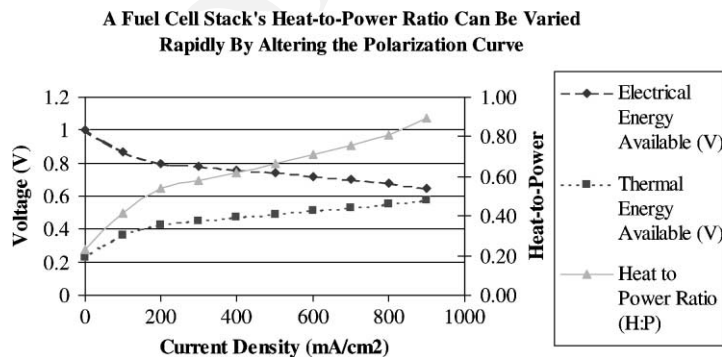


Fig. 5. Fig. 5 shows the polarization curve for a fuel cell, which indicates the electrical energy available from a fuel cell at any current draw. The heat available from the fuel cell is the mirror image of this curve. The heat-to-power ratio is the ratio of these curves.

322 position of polarization curve on the current versus voltage
323 graph, one can alter the heat-to-power ratio of the fuel cell
324 stack, and therefore, that of the system. The shape of the
325 polarization curve can be changed both through indirect
326 methods (such as altering temperature, pressure, and reactant
327 concentrations) and direct methods (such as altering a
328 cell's Ohmic polarization), as described below.

329 *2.1.4.1. Vary the temperature.* One way to change the shape
330 and position of the polarization curve on the current versus
331 voltage plot during operation is to alter a fuel cell's operating
332 temperature. A fuel cell's polarization curve depends strongly
333 on temperature. For most types of fuel cells (AFC, PAFC,
334 MCFC, SOFC), as their temperature increases, their
335 polarization curve shifts upwards [17]. For the proton
336 exchange membrane (PEM) fuel cell, as the temperature
337 increases, its polarization curve increases up until a point
338 (about 0.85 V at open circuit and 130 °C), where it begins to
339 decline with further increase in temperature.

340 The polarization curve changes in shape and position as
341 the cell's temperature changes due to changes in the nature
342 of polarizations. In general, as temperature rises, activation
343 polarization decreases due to the higher reaction rate, Ohmic
344 polarization decreases due to a decrease in the resistance in
345 the electrodes and electrolyte, and concentration polariza-
346 tion decreases due higher mass diffusion rates. Also, as
347 temperature rises, low temperature fuel cells have a higher
348 tolerance to carbon monoxide. On the other hand, as tem-
349 perature rises, polarizations may increase due to material
350 constraints.

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

361 *2.1.4.2. Vary the pressure.* Another way to change the shape
362 of the polarization curve during operation is to alter the stack
363 pressure. Pressure has a similar effect as temperature; an
364 increase in pressure shifts the polarization curve up, and vice
365 versa. An increase in pressure increases the partial pressure
366 of reactants and the rate of mass diffusion. The drawbacks to
367 increasing pressure include thicker piping, the need for a
368 compressor with a higher rating and turndown ratio, and
369 potential materials problems, such as reactant leakage
370 through the electrolyte and seals. Also, the gains in fuel
371 cell electrical efficiency from increasing the pressure are
372 partly offset by the increase in parasitic power losses via the
373 compressor.

374 As with temperature, the response time of this control
375 method is a few minutes or less. Most of this lag time

depends on the time it takes to increase system pressure, 376
rather than the time it takes to decrease system pressure 377
(which can be quite quick with a purge valve) or the time it 378
takes for the pressure increase to affect the shape of the 379
curve. As a result, changing the system pressure is one 380
method for responding to some short demand changes in the 381
order of minutes, and certainly hourly to seasonal changes. 382

383 *2.1.4.3. Vary the reactant concentration at the fuel cell*
384 *inlet.* The reactant concentration at the inlet to the fuel cell
385 can be varied so as to get a more appropriate heat-to-power
386 ratio. For example, in a PEM FCS the hydrogen content of
387 the reformat stream can be varied in a variety of ways:

- (i) Bypass the shift reactor to reduce hydrogen content of 390
the inlet gas stream to the fuel cell (assuming a high 391
level of carbon monoxide tolerance at the fuel cell 392
anode);
- (ii) Recycle the anode off-gas to dilute the hydrogen 394
content of the fuel cell inlet gas or store it for later use 395
in dilution;
- (iii) Change the degree of partial oxidation versus steam 397
reforming in the autothermal reformer to either dilute 398
or magnify hydrogen content, respectively. 399

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

411 *2.1.4.4. Vary Ohmic polarization.* Changing the temperature
412 or pressure of a system are two ways to indirectly alter
413 polarizations to affect the heat-to-power ratio. Polarizations
414 can also be directly altered—via changing some aspect of
415 activation, Ohmic, or concentration polarization. Some direct
416 methods are complicated enough as to require a few stages of
417 research and development activity before they can be
418 practically implemented.

419 One method to enable one to vary the heat-to-power ratio
420 is to vary the fuel cell's Ohmic polarization during opera-
421 tion. By choosing materials with desired resistance proper-
422 ties, the electrical resistance of the flow field plates,
423 electrolyte, flow field plates, or wiring could be designed
424 to change in response to a certain stimuli. For example, the
425 resistance of some materials is a strong function of current,
426 and, for other materials, temperature. In the case of a
427 hydrogen-fuelled fuel cell (with no reformer system), a flow
428 field plate's Ohmic resistance might be designed to increase
429 at lower current draw so as to dissipate more heat to the inlet
430 hydrogen and air to preheat them. This enables the chemical 430

431 reaction of hydrogen and oxygen to proceed at higher
 432 temperatures, achieve a higher extent of reaction, and pro-
 433 duce a large percentage of electricity in comparison to waste
 434 heat (lower heat-to-power ratio). Although varying the
 435 Ohmic polarization of a fuel cell is very similar to using
 436 an external electrical resistance heater, its primary benefits
 437 over the later are that it saves space and presents an
 438 opportunity for a more passive control method.

439 3. Conclusion

440 Although fuel cell research has traditionally focused on
 441 increasing electrical efficiency, for some fuel cell applica-
 442 tions, a different research focus is perhaps more appropriate.
 443 The goal of fuel cell developers has traditionally been to
 444 maximize a fuel cell's electrical efficiency (or minimize its
 445 polarization) so that its experimentally observed cell voltage
 446 approaches its ideal open circuit cell voltage [18]. For
 447 example, one of Ballard Power Corporation's five principal
 448 development strategy goals for its fuel cell stacks has been to
 449 increase its stack operating voltage [19]. As this article
 450 attempts to highlight, after fuel cells have reached a certain
 451 level of electrical efficiency, the goal of increasing their
 452 electrical efficiency even further is not necessarily synon-
 453 ymous with the technology's economical application. One of
 454 the best examples of this kind of application is the CHP
 455 market, which depends on the useful application of both a
 456 power plant's thermal and electrical power. In such cases, for
 457 the purpose of meeting market requirements, it may be less
 458 technically important to focus engineering efforts on refining
 459 the fuel cell stack electrical efficiency and more important to
 460 focus efforts on meeting the system's combined electrical
 461 and thermal needs, not just at a system design level but also at
 462 a fundamental research and development level.

463 Acknowledgements

464 The author wishes to thank the following organizations
 465 for their support: The Marshall Scholarship Trust Fund; The
 466 United States (US) National Science Foundation (NSF); The
 467 United Kingdom's (UK) Department of Trade and Industry
 468 (DTI); The Johnson Matthey Technology Center (JMTC).

References

470 [1] D. Bauknecht, European Electricity Market Analyst, PowerInk Ltd.,
 471 Brighton, UK.
 530

- [2] W. Colella, Combined heat and power fuel cell systems, doctoral
 472 thesis transfer report, Department of Engineering Sciences, Uni-
 473 versity of Oxford, Oxford, June 2001. 474
- [3] W. Colella, Implications of electricity liberalization for combined
 475 heat and power (CHP) fuel cell systems (FCS): a case study of the
 476 UK, Elsevier, London, UK, J. Power Sources, 2002. 477
- [4] P. Gray, Solid Polymer Fuel Cell Prototype System for Micro-CHP
 478 Phase 1: Market, Technical and Economic Study, Department of
 479 Trade and Industry, London, UK, 1999. 480
- [5] J. Cotton, The Potential for Economic Manufacture of Solid
 481 Oxide Fuel Cells, Department of Trade and Industry, London, UK,
 482 1995. 483
- [6] Combined Power Systems Ltd., A Technical and Economic
 484 Assessment of Small Stirling Engines for Combined Heat and
 485 Power, Department of Trade and Industry, London, UK, 1993. 486
- [7] S.R. James, Stirling Engines, Moriya Press, River Falls, WI, 1993. 487
- [8] S.N. Carnot, Réflexions sur la puissance motrice du feu et sur les
 488 machines propres à développer cette puissance, Reflections on the
 489 Motive Power of Fire, Paris, 1824. 490
- [9] J.A. Schumpeter, The Theory of Economic Development, 1911. 491
- [10] Electricity and Heat Demand Data for a UK. Detached House on the
 492 Weekend of 6 May 1996, Advantica (formerly BG Technology),
 493 Ashby Rd, Loughborough, Leicestershire LE 11 3GR [www.lattice-
 494 group.com](http://www.lattice-group.com). 495
- [11] J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, M.G. Klett, Fuel
 496 Cells Handbook, 4th Edition, DOE/FETC-99/1076, Table 2-2, US
 497 Department of Energy, Washington, DC, 1998, p. 2–8. 498
- [12] Adapted From a Figure Courtesy of the Johnson Matthey
 499 Technology Center (JMTC), UK, 2001. 500
- [13] R.M. Felder, R.W. Rousseau, Elementary Principles of Chemical
 501 Processes, Table B.1 Selected Physical Property Data: Heat of
 502 Formation and Heat of Combustion, 3rd Edition, Wiley, New York,
 503 NY, 2000, p. 635. 504
- [14] M.V. Twigg, Catalyst Handbook, Manson Publishing, London, UK,
 505 1996. 506
- [15] J. Sun, Hydrogen Generation for PEM Fuel Cells, Fuel Cell
 507 Today, September 2001. [http://www.fuelcelltoday.com/FuelCellTo-
 510 day/FCTFiles/FCTArticleFiles/article_319_jamessunfuelprocessing
 511 0901.pdf](http://www.fuelcelltoday.com/FuelCellTo-

 508 day/FCTFiles/FCTArticleFiles/article_319_jamessunfuelprocessing

 509 0901.pdf). 512
- [16] The following study concluded that, under the assumption of both
 513 mass-produced fuel cells and batteries, adding a peaking battery
 514 storage system would increase the cost of electricity from a proton
 515 exchange membrane (PEM) FCS, in: C.E. Thomas (Ed.), Utility
 516 Sector Hydrogen System Analysis with Battery Augmentation, Task
 517 4 Final Report, Subcontract No. ACG-8-18012-01, For the National
 518 Renewable Energy Laboratory, US DOE, Washington, DC, US
 519 DOE, 1999. 520
- [17] S.N. Simons, R.B. King, P.R. Prokopius, in: E.H. Camera (Ed.),
 521 Symposium Proceedings on the Fuel Cells Technology Status and
 522 Applications, Institute of Gas Technology, Vol. 45, Fig. 1, Chicago,
 523 IL, 1982, p. 46. 524
- [18] J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, M.G. Klett, Fuel
 525 Cells Handbook, 4th Edition, DOE/FETC-99/1076, Table 2-2, US
 526 Department of Energy, Washington, DC, 1998, p. 2–8. 527
- [19] K. Washington, Development of a 250 kW Class Polymer
 528 Electrolyte Fuel Cell Stack at Ballard Power Systems Inc., 2000
 529 Fuel Cell Seminar Abstracts: Fuel Cells—Powering the 21st Century,
 530 Portland, Oregon, US DOE, 2000, p. 468. 528