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Journal of Power Sources 106 (2002) 397–404

JOURNAL OF POWER SOURCES

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Implications of electricity liberalization for combined heat and power (CHP) fuel cell systems (FCSs): a case study of the United Kingdom

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Abstract

Globally electricity markets are heading in the direction of the United Kingdom's liberalized model, in which transactions are increasingly transparent such that prices more closely reflect their underlying costs. Increased transparency in the structure of electricity markets augurs to have both negative and positive effects for embedded generators such as combined heat and power (CHP) fuel cell systems (FCSs). Embedded generators are decentralized generators in close proximity to consumers that feed part of their electricity directly into a local low-voltage distribution network and, in some cases, part to a direct source of demand onsite. First, this article analyses the negative consequences that the UK's liberalized model has had on current embedded generators. Second, it discusses the potential positive effects that the liberalizing trend could have on future embedded generators. Finally, based on these lessons, it draws conclusions about design strategies for CHP FCSs as future embedded generators. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fuel cell system (FCS); Combined heat and power (CHP); Electricity market structure; Embedded generator; New Electricity Trading Arrangements (NETA)

1. Introduction

Electricity markets around the world are increasingly heading in the direction of the UK's liberalized model. In the UK and increasingly in other countries, governments that previously supported state-regulated (or state-owned) monopolies for their electricity markets are now liberalising these markets to create more competition [1]. To create competition, the UK experimented with two different market based systems: (1) the Pool system (1990–2001) and more recently (2) the New Electricity Trading Arrangements (NETA) system (2001). The Pool system created a liberalized market based on centralized competitive bidding among generators [2]. In contrast, NETA creates a liberalized market based on private contracts between buyers and sellers [3]. These two systems are compared with the former state-monopoly in Fig. 1. As the UK's experience with these systems shows, increased transparency in the structure of electricity markets promises to have both negative and positive effects for embedded generators. First, this article analyzes the negative consequences that the UK's liberalized model has had on current embedded generators. Second, it discusses the potential positive effects that the liberalizing trend could have on future embedded generators. Finally, based on these lessons, it draws conclusions about design strategies for combined heat and power fuel cell systems (CHP FCSs) as future embedded generators.

An embedded generator differs from a conventional, large-scale generator in its physical configuration in an electricity network. This physical contrast is shown in Fig. 2. Embedded generators are decentralized generators in close proximity to consumers that feed part of their electricity directly into a local low-voltage distribution network and, in some cases, part to a source of local onsite demand. By contrast, conventional large-scale generators deliver their electricity to consumers more remotely from long distances first by transforming their electrical output up to a high voltage, then by transmitting it across a high-voltage distribution network, and finally by transforming it back down to a lower voltage. Embedded generators include most power plants under 1 MW, such as a CHP FCS.

First this article analyses the reasons that many embedded generators have suffered under the UK's most liberalized model. On the negative side, embedded generators are on average less profitable under the UK's NETA system than they were under the previous Pool system [4]. In the worst instances, they must *pay* to export their electricity to the grid. Many embedded generators have faired worse under NETA because they lack two technical characteristics:

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PII: S0378-7753(01)01062-X

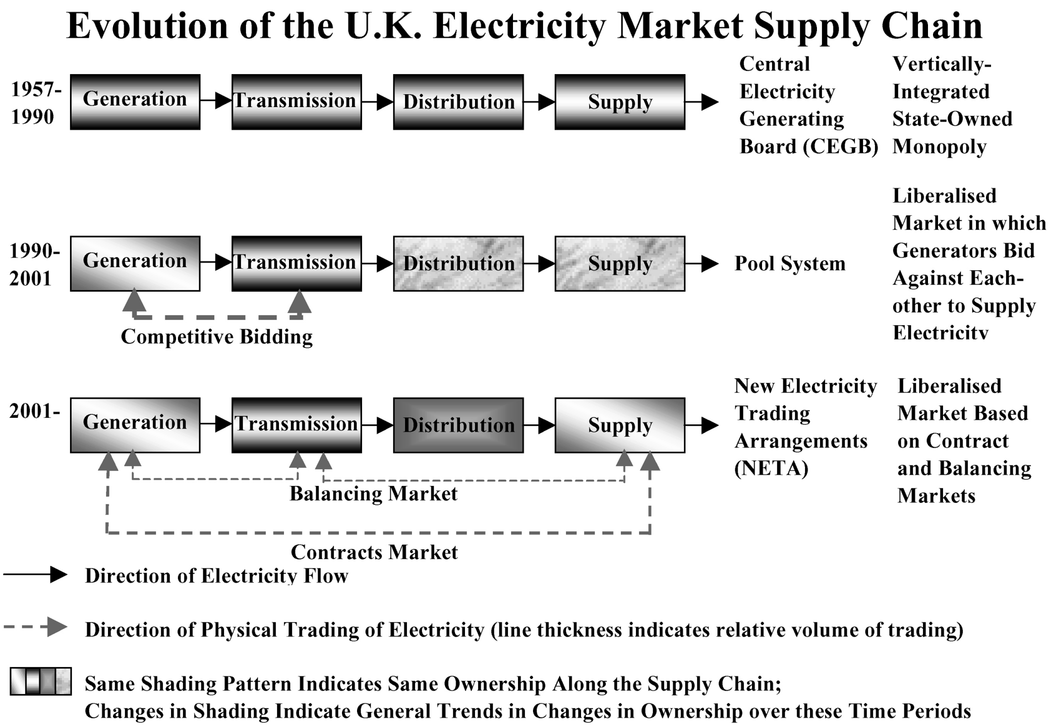

Fig. 1. The UK's electricity supply chain transformed in 1990 from a vertically-integrated state monopoly to a liberalized market based on centralized competitive bidding among generators (The Pool System). Again in 2001, the market transformed into another type of liberalized market based on private contracts between buyers and sellers in advance to delivery (Contracts Market) and a bidding market for unresolved demand and supply close to real time (Balancing Market).

- reliability (the ability to deliver electricity in a predictable manner to the local source of demand and to the distribution network); and
- flexibility (the ability to rapidly change the amount of electricity delivered in response to changes in demand from the local source of demand and from the distribution network).

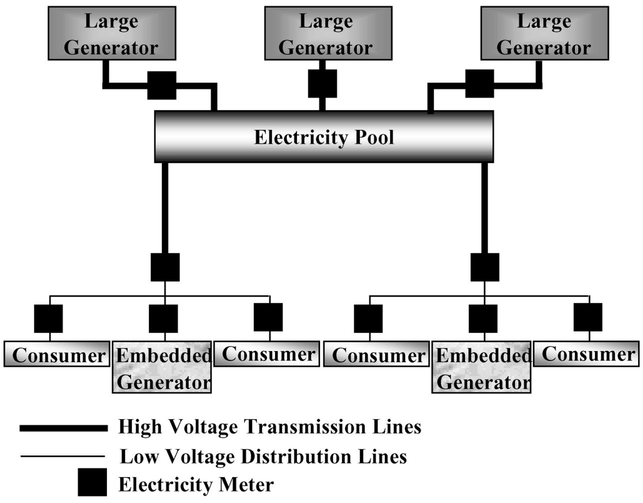

Fig. 2. Contrasts between embedded and large centralized generators. Embedded generators provide electricity to the customer locally over the low-voltage distribution network. Large generators provide electricity remotely over high-voltage transmission lines.

Reliability is rewarded in a *Contracts Market*, in which generators strike contracts directly with electricity suppliers to sell a fixed amount of electricity at a point in the future. Flexibility is rewarded in a *Balancing Market*, in which generators resolve differences between their contracted amount and the amount of electricity they actually delivered.

Second, this article discusses the potential positive effects that the liberalizing trend could have for future embedded generators. On the positive side, future embedded generators such as CHP FCSs may benefit more from the trend towards increased transparency under a few conditions. Future embedded generators are likely to benefit from a greater degree of transparency than under NETA if (1) the more transparent market directly incorporates electricity transmission and distribution costs into electricity price and (2) the more transparent market conveys real-time prices to all members along the electricity market supply chain (including domestic consumers). With regard to the first point, since embedded generators sell their electricity directly to a local source of demand, they avoid transmission costs entirely, along with the majority of distribution costs, and therefore, appear marginally more profitable on this point. With regard to the second point, generators that can rapidly respond to market signals can garner significant profits by quickly reducing their output in periods of excess supply and increasing their output in periods of excess demand. To effectively respond to these market signals, future embedded generators must be both flexible and reliable.

Finally, based on these lessons, this article draws conclusions about design strategies for CHP FCSs as future embedded generators. Generators can achieve both flexibility and reliability if they develop the technical ability to achieve a variable heat to power ratio on an individual unit level. They can also achieve flexibility and reliability if several generators operate in concert to achieve a variable heat to power ratio for a network. If both strategies are pursued simultaneously, such a network of generators, each with individually rapidly variable heat to power ratios, can achieve an even greater degree of flexibility and reliability than either strategy alone. A high degree of flexibility and reliability at high efficiency over a large range of heat to power ratios may be an inimitable technical characteristic of a CHP FCS. Competing power generation technologies may not be as suited to develop this ability.

2. Experimental

2.1. Negative aspects of transparent markets for embedded generators

As the UK's experience shows, embedded generators have proven less profitable in liberalized markets similar to NETA than in ones similar to the Pool. Since the UK electricity system transitioned from the centralized Pool system based on nation-wide bidding by generators to the decentralized NETA system based on confidential contracts between buyers and suppliers in 2001, embedded generators have appeared less profitable. Embedded generators received an average price under NETA in 2001 that is 17% lower than that under the Pool in 2000. Over the same period, their export volume also declined by 44%. Hardest hit have been industrial CHP generators, which have almost altogether canceled new builds.

Under NETA, most generators strike contracts directly with suppliers. Generators agree in advance to sell suppliers a certain amount of electricity for a certain period of time in the future [5]. This direct exchange between electricity generators and customer suppliers is referred to as the Contracts Market, shown in Fig. 2. In the Contracts Market, generators bargain directly to sell their electricity to an abundance of potential suppliers and can therefore negotiate a good price for it. However, to successfully deliver on their contracts in the Contracts Market, generators must be reliable, i.e. able to deliver electricity in a predictable manner at a point in the future. If generators are not reliable, and therefore, cannot predictably deliver on their contracts, they are exposed to less amenable prices in the Balancing Market.

Unlike most generators, embedded generators have difficulty in delivering on contracts in advance to sell their electricity (via the Contracts Market) because their net electrical output to the grid is less reliable. Their electrical output to the grid is less reliable than other generators for two possible reasons. First, their net electrical export may be less reliable because their source of electricity may be less reliable (as in the case of wind, wave, and solar power). Second, and more commonly, their net export may be less reliable because they may send part of their gross electrical supply to a volatile source of local demand (as in the case of CHP generators). Although, an embedded generator's gross output may be entirely reliable, the net amount that it exports to the grid may be much less reliable. Net export to the grid is the difference between the gross output and the local electrical demand that the unit immediately serves that is often volatile. As the difference between these two profiles, the embedded generator's net electrical output to the grid is also volatile. Fig. 3 illustrates this unpredictability for an embedded generator supplying electricity to a detached house in the UK [6]. The embedded generator produces a constant 5 kW output. At any one point in time, part of this output meets the immediate local demand of the household and the remaining is fed to the grid. As a result, embedded generators that serve unpredictable sources of immediate local demand feed electricity to the grid in an unpredictable manner. (A recent study by Ofgem falsely concluded that "embedded generators are no more or less reliable than stationary generators", because it failed to note the difference between the gross electrical output of embedded generators and their net output to the grid [7]).

Because their electricity is less reliable, embedded generators often cannot fully deliver on their contracts in the Contracts Market. They are therefore exposed to less amenable prices in the Balancing Market. (Only 3% of generators must trade via the less profitable Balancing Market). In the Balancing Market, generators who either exported too much or too little relative to their contracted amount must either sell or buy the difference, respectively. In this market, excess generators receive a very low and sometime negative price for their excess electricity; deficit generators pay a very high price to buy their electricity shortfall. These out-of-balance generators essentially pay a fine via a lower net electricity sale price [8]. For example, in the Balancing Market, the average price paid to excess generators for their out-of-balance surplus electricity was five times less than that paid in the Contracts Market over the same period [9].

While the Balancing Market penalizes less reliable generators, it highly rewards flexible generators. Flexible generators have the opportunity to either increase or decrease their electricity production in real time to balance unresolved differences in demand and supply. Flexible generators received very high prices for their electricity in this market because they have a great deal of market power due to the low number of available flexible participants and the inelastic demand for their service. Flexible generators more easily appropriate oligopolistic rent because their market is a repeating auction with few players, an environment that breeds tacit collusion. Flexible generators receive high prices for compensating for imbalances. These high prices are paid for by the less reliable generators who have been unable to precisely meet portions of their contracted supply. (As a caveat, the

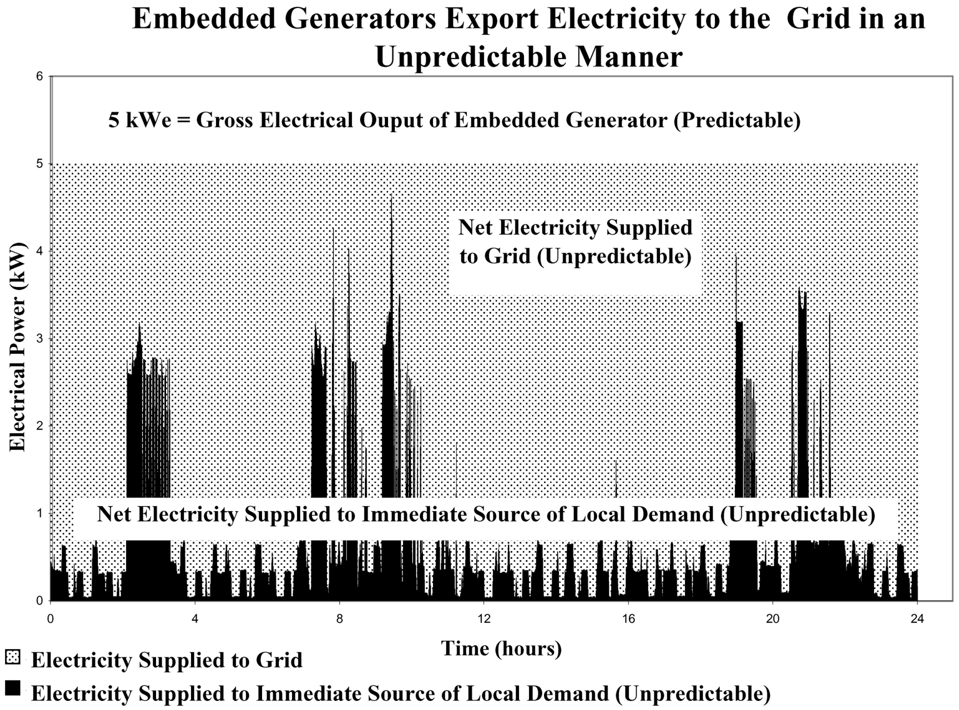

Fig. 3. The embedded generator produces a predictable gross electrical output, in this example, at a constant 5 kW. Part of this output meets the immediate local demand of the household, which is, to a large extent, unpredictable. The embedded generator delivers its remaining electricity to the grid. Therefore, the electricity it feeds to the grid is also delivered in an unpredictable manner. For this reason, embedded generators exhibit low reliability, as defined by the ability to deliver electricity to a network in a predictable manner.

extremely high imbalance prices encountered in the first few months of NETA are likely to dampen down as the market for flexible generation becomes more competitive).

Fig. 4 summarizes the winners and the losers in a liberalized NETA system. Fig. 4 shows examples of different types of generators that either meet the reliability (predictability) requirement or the flexibility (rapid response) requirement. Those generators that meet the requirement of flexibility are highly rewarded in the Balancing Market because they are paid high out-of-balance prices for immediately supplying electricity during periods of undersupply and reducing their electricity supply during periods of excess. Those generators that meet the requirement of reliability are not penalized in the Balancing Market by having to pay out-of-balance prices. Those types of generators that are both flexible and reliable are both rewarded in the Balancing Market and avoid penalties in this market. An example of a type of flexible generator that is not reliable is a small diesel generator, which can rapidly vary its power level, but which requires periodic maintenance. An example of a type of reliable generator that is not flexible is a nuclear power plant, which operates without interruption for extended periods but which cannot rapidly alter its power output due to technical bottlenecks such as moving control rods. An example of a type of generator that is both reliable and flexible is a natural gas turbine, which ramps up and down its power level easily and malfunctions less frequently than internal combustion engine systems. Examples of generators that are neither reliable nor flexible include most renewable energy technologies, including wind, wave, and solar power, and conventional CHP generators.

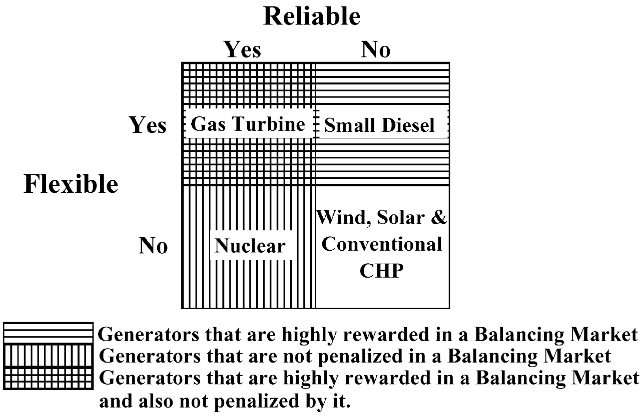

Fig. 4. Different types of generators that are either reliable (predictable) or flexible (respond rapidly), or both. Flexible generators are highly rewarded in the Balancing Market. Reliable generators avoid penalty in the Balancing Market.

By contrast, under the Pool (1990–2001) system, embedded generators were more profitable because all generators received the same price for their electricity at a given moment. Under the Pool system, generators around the country bid against each other in advance on a half-hourly basis to export to the grid. All generators that bid below the highest successful bid received the same highest bid price. Generators were not severely punished for less reliable supply. As a result of these two factors, embedded generators garnered higher profits.

As the UK's experience seems to indicate, CHP FCSs are likely to be less profitable in liberalized markets similar to NETA than in ones similar to the Pool. Embedded generators that were profitable under the Pool are no longer profitable under NETA. These two systems are structured slightly differently such that the economic rent that was previously allocated under the Pool to less reliable and less flexible generators via their receipt of the highest bid price is now allocated more under NETA to reliable and flexible generators. It is important to note that both the Pool and NETA are transparent, market based systems, yet, because of their specific economic structures, embedded generators are more profitable in one than in the other.

3. Discussion

3.1. Positive aspects of transparent markets for combined heat and power fuel cell systems—two mechanisms

As the UK electricity market grows increasingly transparent such that prices reflect costs, embedded generators such as CHP FCSs may benefit from this trend via at least two mechanisms:

- the direct incorporation of transmission and distribution costs into price; and
- real time pricing in combination with the technical ability of these embedded generators to provide reliable, flexible supply.

The later fundamentally relies on the technical development of future embedded generators such that they operate reliably and flexibly.

3.1.1. The incorporation of transmission and distribution costs

One way in which the general trend towards greater transparency may benefit embedded generation is via the incorporation of transmission (high-voltage) and distribution (low-voltage) costs into price. Since embedded generators avoid these costs, with regard to this point, they appear marginally more profitable. Transmission and distribution costs include the costs of maintaining the physical, economic, and informational infrastructures around electricity networks. Physical infrastructure costs include the costs of cables, equipment, transformers, maintenance, and electricity created at the generation site but lost as heat via the wires. Information infrastructure costs include the costs of communicating information about the network to buyers and sellers. Economic infrastructure costs include the costs of running the trading mechanisms and governmental supervisory agencies.

The costs of transmission and distribution are being more accurately incorporated into price via a variety of mechanisms. For example, under a new policy proposed for NETA, generators would pay "capacity charges" to have access to a certain percentage of the transmission and distribution network [10]. Generators bid for a limited amount of wire capacity. If three 100 MW generators each want to send electricity through one 100 MW capacity wire, they will bid amongst each other for access to this wire. Since embedded generators provide electricity directly into a local distribution network and thereby avoid more of these costs, they appear marginally more economical on this point.

3.1.2. Real time pricing combined with rapid response

A second way that the general trend towards greater transparency may benefit future CHP FCSs is via real time pricing. Future CHP FCSs benefit from increased transparency the more that (a) the market openly conveys real-time prices to members of the electricity-distribution supply chain and (b) these devices develop the ability to respond rapidly either individually (on a per unit basis) or in concert (as a network) to price signals. A more transparent market, such as that exemplified by the UK's NETA, moves increasingly towards real-time pricing of electricity on a half-hourly or per minute basis. Real-time pricing allows buyers and suppliers to know the instantaneous price of electricity, which fluctuates dramatically (up to 1000 times the average price). In the most transparent market, price fluctuations on a per second basis are communicated even to residential consumers. Domestic consumers make purchase decisions based not on an average daily price for electricity (as is the case in the UK in 2001) but rather on real time, instantaneous prices. (Electricity markets that have demonstrated real time pricing include the UK's Pool and the Pennsylvania, New Jersey, Maryland, US wholesale electricity network, albeit not yet for end-consumers [11]).

In response to real-time price information, consumers will react to limit their vulnerability to price fluctuations via a variety of mechanisms, one of which could potentially be the use of a CHP FCS specifically designed to be both flexible and reliable. Such a system can achieve an arbitrage opportunity between the sale of electricity and natural gas. This arbitrage opportunity exists in part because price spikes in the gas market do not tend to be as severe as those in the electricity market due to the ability to store gas but not electricity [12]. Generators that can quickly respond to market signals garner significant profits from arbitrage opportunities by quickly decreasing their generation in periods of excess supply and by quickly increasing their generation in periods of excess demand.

A few caveats are necessary with regard to this arbitrage opportunity between electricity and gas. First, such an arbitrage opportunity requires the development of technically sophisticated metering and pricing systems. However, various countries are currently adopting the use of more sophisticated pricing systems that operate in real time and convey pricing information instantaneously to the full length of the electricity supply chain. Furthermore, France, Italy, Germany, and some regions of the US are implementing either sophisticated metering or pricing systems, or both, even for domestic customers. Second, the extent of the arbitrage opportunity between electricity and gas is likely to wane over time in the UK. In the UK's context, the profit potential is likely to decrease over time because (1) these two separate markets are expected to converge as a result of parties taking advantage of this arbitrage opportunity and (2) consumers may reduce the extent of the electrical price spikes by engaging in peak shaving (reducing demand during price spikes). As a result, the profit margins that a very flexible embedded may be able to garner in five years time in the UK are likely to be less than they are now. Finally, other types of both embedded generators and centralized generators may be able to take advantage of an arbitrage opportunity in natural gas and electricity.

4. Conclusion

4.1. Design implications for CHP FCS—achieving flexibility and reliability

If the UK's NETA system is an archetype for liberalized electricity markets of the future, embedded generators such as CHP FCSs will prove more profitable if designed to be both flexible and reliable. Embedded generators that deliver combined heat and power can achieve both flexibility and reliability in at least two ways. These two methods include (1) designing an individual embedded generator to achieve a rapidly variable heat to power ratio and (2) designing a network of embedded generators to achieve a system-wide rapidly variable heat to power ratio by controlling the dispatch of steady-state generators in concert. These two methods are shown in Fig. 5 as achieving both reliability and flexibility, unlike other methods that achieve only one or the other.

4.1.1. Designing a rapidly variable heat to power ratio into an individual generator

Flexibility and reliability can be achieved by designing an individual embedded generator to achieve a rapidly variable heat to power ratio. For an individual embedded generator, a rapidly variable heat to power ratio has compelling advantages over the more conventional fixed one. If an individual embedded generator is designed to have a rapidly variable heat to power ratio, it can more closely match the instantaneous supply of heat *and* electricity with the instantaneous demand for heat *and* electricity. A rapidly variable heat to power ratio enables a generator to follow the high levels of variation in electricity demand from an unpredictable local source (in Fig. 3 for a house) and heat demand much more closely. For a hypothetical embedded generator with a *perfect* ability to rapidly vary its heat to power ratio, at any instant, the generator supplies (1) the immediate source of unpredictable local demand, (2) a prearranged amount of electricity to the local distribution network, and (3) an amount of heat that contributes to meeting the slightly more longer term thermal demand of the immediate source (not necessarily the instantaneous thermal demand). A variable heat to power ratio enables a power plant to achieve both (1) reliability (the ability to deliver electricity in a predictable manner to the local source of demand and to the distribution network) and (2) flexibility (the ability to rapidly change the amount of electricity delivered in response to rapid changes in demand from the local source of demand and from the distribution network).

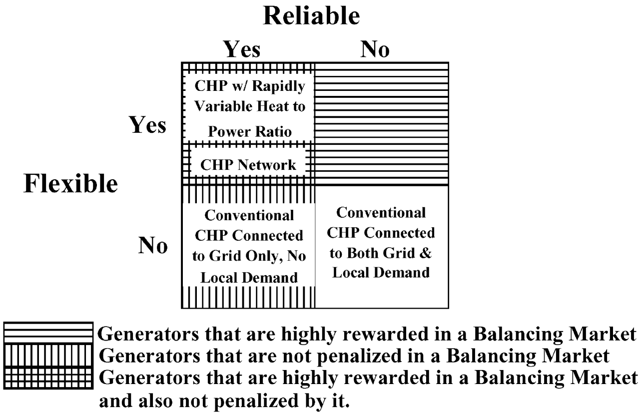

Fig. 5. Embedded generators that deliver combined heat and power (CHP) can achieve both flexibility and reliability if they either develop the technical ability to achieve a variable heat to power ratio on an individual unit level, or if they operate in concert as a network to achieve a variable heat to power ratio for a network, or both.

For developing a rapidly variable heat to power ratio for within a FCS, the primary development challenge remains with the FCS engineer. There are various methods for technically configuring a FCS such that it achieves a rapidly variable heat to power ratio. Although one of the most technically simplistic options is to convert electricity from the fuel cell directly to heat via electrical resistance heating, other options also exist that tax the fuel cell less and avoid the additional spatial requirements of the external heater. While these methods present a more complex development challenge, viable solutions have begun to be delineated in the literature [13,14].

A high degree of flexibility and reliability at high efficiency over a large range of heat to power ratios may be an inimitable technical characteristic of a CHP FCS. Competing power generation technologies may not be as suited to develop this characteristic. Any engine is constrained in its ability to operate with a rapidly variable heat to power ratio on its own because its ratio of heat to work is a constant [15]. Compared to an engine-based system, a fuel cell combined heat and power 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. Because the fuel cell can operate at lower heat to power ratios than an engine at low temperatures, it can achieve a larger range of heat to power ratios. (All CHP units have a heat to power ratio that is not as limited on the high end because electricity always can be efficiently converted to heat with an external electrical resistance-heating device).

4.1.2. *Designing a rapidly variable heat to power ratio into a network*

Via a second method, flexibility and reliability can be achieved by designing a network of embedded generators to achieve a system-wide rapidly variable heat to power ratio by controlling the dispatch of steady-state generators in concert. For this second method, the primary development challenge lies with the distribution network engineer in developing a flexible and reliable distribution network. Each individual unit need not respond rapidly on an individual basis and, for example, could operate at a few steady state values. A network can achieve flexibility by activating or deactivating individual units rapidly. Reliability can be achieved because of the low probability of several units failing simultaneously and because of the opportunity to smooth out changes in demand from each immediate source across the network. In this way, several of these units operating in concert emulate an extremely flexible and reliable large generator. For these units to become viable in networks, the network must incorporate associated technologies such as smart metering and dispatching.

This second method poses an advantage in that, in operating the units in this manner, it may be possible to achieve a higher capacity utilization of the decentralized units. If the individual CHP units are electrically (and perhaps thermally) connected in a local network, the load factor of any individual unit can increase. The crucial factor impacting the economics of these systems is not the load factor of any individual unit operating stand-alone, but the load factor of a system composed of a network of these generators. One of the primary benefits of operating these units as part of a system is that the heat and power demand profiles smooth with a larger number of users. For this reason, large generators serving a regional network of customers achieve a high load factor. In a similar manner, small generators serving a local network of customers can achieve the same high load factor. If the relative sizes of the network and its average power plant are similar, according to

$$\frac{\sigma_S}{\rho_S} = \frac{\sigma_L}{\rho_L} \tag{1}$$

where σ_S is the size of a small local network of small-scale generators, ρ_S is the average size of a small-scale power plant within the local network, σ_L is the size of a large regional network of large-scale generators, and ρ_L is the average size of a large-scale power plant within the regional network, then one can achieve the same economies of scale in generation with a localized network of small generators as with a regional network of large-scale generators. One example of such a local network operating off of small generators is that of the UK town of Woking, administered by the local Borough Council [16].

In summary, embedded generators that deliver combined heat and power can achieve both flexibility and reliability if they either develop the technical ability to achieve a variable heat to power ratio on an individual unit level, or if several operate in concert to achieve a variable heat to power ratio for a network. If both strategies are pursued simultaneously, such a network of generators, each with individually rapidly variable heat to power ratios, can achieve an even greater degree of flexibility and reliability than either strategy alone.

4.2. *Other strategies*

Other strategies shown in Fig. 5 achieve a lesser degree of flexibility or reliability. For example, a conventional combined heat and power embedded generator can be configured to deliver electricity only to the distribution network, such that it is disconnected from a local source of demand. Such a generator can achieve reliability, but not flexibility. By disconnecting from the local source of demand, the embedded generator removes the source of unpredictability in its electrical export to the distribution network. In this way, the generator can feed a predictable electrical supply to a local distribution network. However, this generator is still not, in and of itself, able to rapidly respond to changes in electrical demand, i.e. flexible. Conversely, a conventional combined heat and power embedded generator can be configured to deliver electricity only to a local source of demand, such that it is disconnected from the distribution network. Such a generator achieves low reliability and flexibility, similar to that of a conventional generator connected to both the local source and the network. Under this last scenario of grid disconnection, it becomes even more crucial for the embedded generator to be capable of a rapidly variable heat to power ratio.

4.3. *The link between generator design and the choice of electricity market to enter*

Depending on their design, CHP FCSs are likely to be more economical in certain types of electricity markets than in others. The attractiveness of a system to market entry depends on the electricity network's regional characteristics, the characteristics of the chosen market segment within that region, and the FCS's technical characteristics. For example, as the evolution of the UK's electricity market supply chain shows, conventional embedded generators that lack a high degree of flexibility and reliability are likely to be more profitable in liberalized markets that follow the Pool model rather than ones that follow the NETA model. The Pool model is based on centralized competitive bidding among generators, in which the contracted price to all generators is the same predetermined value for all generators. By contrast, NETA is based on a Contracts Market composed of private contracts between buyers and sellers and a Balancing Market for resolving close to real time imbalances in demand and supply. To achieve the most economic success in electricity markets similar to NETA, a CHP FCS must be designed to achieve (1) reliability (the ability to deliver electricity in a predictable manner to both a distribution grid and an independent source of demand) and (2) flexibility (the ability to rapidly change the amount of electricity delivered in response to rapid changes in demand). Under an electricity market similar to NETA, embedded generators that achieve flexibility are highly rewarded in a Balancing Market. Reliable generators avoid penalty in the Balancing Market. As the examples set forth in this article show, to increase the likelihood of viable market entry, the chosen electricity market segment must directly impact the engineer's approach to designing the CHP FCS and its surrounding network.

Acknowledgements

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

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