Overview

Design of fuel-cell micro-cogeneration systems through modeling and optimization

Sheila Mae C. Ang,[1,2] Daniel J. L. Brett,[1] Iain Staffell,[3] Adam D. Hawkes,[4] Eric S. Fraga,[1] Nouri J. Samsatli[1] and Nigel P. Brandon[5]*

Micro-cogeneration is a promising technology that has the potential to lower energy costs and CO2 emissions in the residential housing sector. Among the different micro-cogeneration technologies, fuel cells offer the potential benefits of the highest electrical efficiency, lowest emissions, and a heat-to-power ratio that is well suited for residential applications. The design of fuel-cell micro-cogeneration systems involves decision making in which trade-offs are made between conflicting objectives. This paper illustrates the use of modeling and optimization in informing system design by generating different design alternatives that contain these trade-offs, thus allowing the design engineers to make decisions in a quantitative and rational way.

How to cite this article:
WIREs Energy Environ 2012, 1: 181–193 doi: 10.1002/wene.39

INTRODUCTION

The inefficiencies and the pollution associated with centralized power generation and conventional heating systems have motivated new developments in distributed (decentralized or on-site) power generation. One such emerging technology is micro-cogeneration, which has the potential to replace grid electricity and conventional home space heating and hot-water systems.[1–3] Among the different micro-cogeneration technologies, fuel cells, specifically solid oxide fuel cells (SOFCs) and polymer electrolyte fuel cells (PEFCs), offer the promising benefits of high electrical efficiency, low emissions, and a low heat-to-power ratio that is well suited for residential applications.[4,5]

Fuel cells have been under development for the past 50 years.[6] However, they are less mature and more expensive than other micro-cogeneration technologies. Further research and development are necessary to improve their durability and technical performance and reduce their system cost. Despite this, an increasing number of fuel-cell products are becoming available commercially. For instance, there are nearly 4000 domestic fuel-cell micro-cogeneration units already operating in Japan,[7] with a further 8000 pre-ordered by domestic customers.[8]

The use of modeling and computer-based optimization in fuel-cell systems design is receiving increasing interest. This has been motivated by the increasingly commercial nature of fuel cells and has been facilitated by the increase in computational resources along with the availability of new and effective methods for solving numerical problems. A benefit of this approach is that it often leads to substantial savings in design cycle time and cost, as well as better design and operation.[9]

*Correspondence to: n.brandon@imperial.ac.uk

[1]Department of Chemical Engineering, University College London, London, United Kingdom

[2]Department of Chemical Engineering, University of the Philippines, Quezon City, Philippines

[3]Department of Chemical Engineering, University of Birmingham, Birmingham, United Kingdom

[4]Centre for Energy Policy and Technology, Imperial College London, London, United Kingdom

[5]Department of Earth Science and Engineering, Imperial College London, London, United Kingdom

DOI: 10.1002/wene.39

The design of a fuel-cell system involves multiple objectives such as efficiency, size, fuel consumption, power output, emissions, and cost, among others. These objectives are inherently conflicting, which means achieving an optimum for one objective requires compromise on one or more other objectives. The determination of a set of trade-off solutions is a multi-objective optimization problem.[10–13] The solution of such a problem is not a single solution but a complete nondominated or Pareto set, which includes the alternatives representing the trade-offs among the objectives. This provides a range of choices available to the design engineers, which allows them to make decisions quantitatively and rationally.

This paper gives an overview of the role of modeling and optimization in the design of fuel-cell micro-cogeneration systems. Modeling requires understanding of the system, and so sections *Micro-Cogeneration* and *Fuel Cells for Micro-Cogeneration* provide the fundamentals of micro-cogeneration and fuel cells. Section *Overview of the Design Process* discusses a typical fuel-cell system design process and how modeling and optimization are used to generate design alternatives and identify good designs. In the design process, identifying the critical criteria and the ones that can be compromised is a crucial step; thus, section *Criteria for Design* presents the key issues for some of the most important criteria in fuel-cell micro-cogeneration systems design. Finally, section *Design of a Fuel-Cell Micro-Cogeneration Plant* illustrates the use of modeling and optimization in generating different design alternatives that contain trade-off information about the conflicting design objectives. In the presented case study, a specific model suitable for multi-objective optimization of stack size, efficiency, power output, and fuel consumption was considered. In other situations, a different model may be more appropriate. A large number of fuel-cell models with different complexity, level of detail, and scope are available in the literature. An extensive review and classification of these models are presented by Ang et al.[14]

MICRO-COGENERATION

Micro-cogeneration is the decentralized and simultaneous generation of heat and power for residential and small commercial applications. It is sometimes referred to as micro-combined heat and power (micro-CHP) or residential cogeneration.[3,15] The EU Cogeneration directive defines an upper limit on capacity of 50 kWe,[16] whereas others define 'domestic' micro-cogeneration as being under 3 kWe.[17]

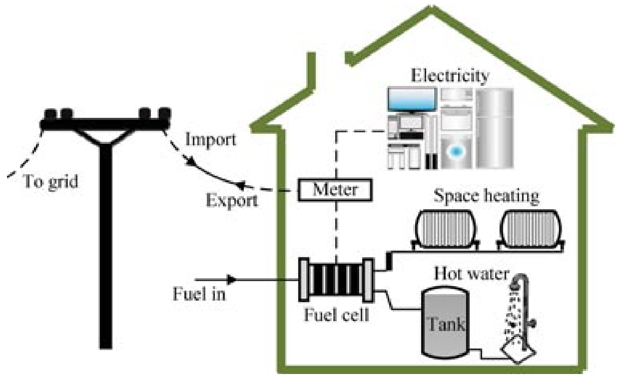

FIGURE 1 | The micro-cogeneration concept showing the import/export of electricity.

A micro-cogeneration system can be thought of as a small-scale power station generating energy in the home. The by-product heat that would otherwise be wasted is instead captured and utilized for space and water heating. It is anticipated that micro-cogeneration may provide an installed generation capacity of a similar order of magnitude to the nuclear industry.[18] A micro-cogeneration system can also be looked at as an effective replacement for the gas central heating boiler. It can supply heat and hot water as usual but additionally provides the majority of the home's electricity needs. The potential success of micro-cogeneration lies in the large number of systems that may ultimately be installed in the millions of homes in the United Kingdom and other European countries where natural gas is currently the dominant heating fuel.

Figure 1 illustrates the micro-cogeneration concept applied to a home. Natural gas enters the building from the gas distribution network; the fuel cell (or other cogeneration technology) generates heat to service the space and water heating loads and electrical power for lights and other appliances. Electricity can be exported to the grid at times of excess production, and imported at times of high electrical load. Net or 'smart metering' allows the balance of export and import to be logged. Similarly, excess production or demand for heat can be accommodated by a hot-water storage tank.

There are several different micro-cogeneration technologies including the internal combustion engine, the Stirling engine, and the fuel cells.[2,3,15,17] All of them consume fuel to produce heat and electricity simultaneously. In the case of internal combustion and Stirling engines, an engine drives a generator to produce electricity. A fuel cell, on the contrary, generates direct current electric power by consuming fuel within electrochemical cells.

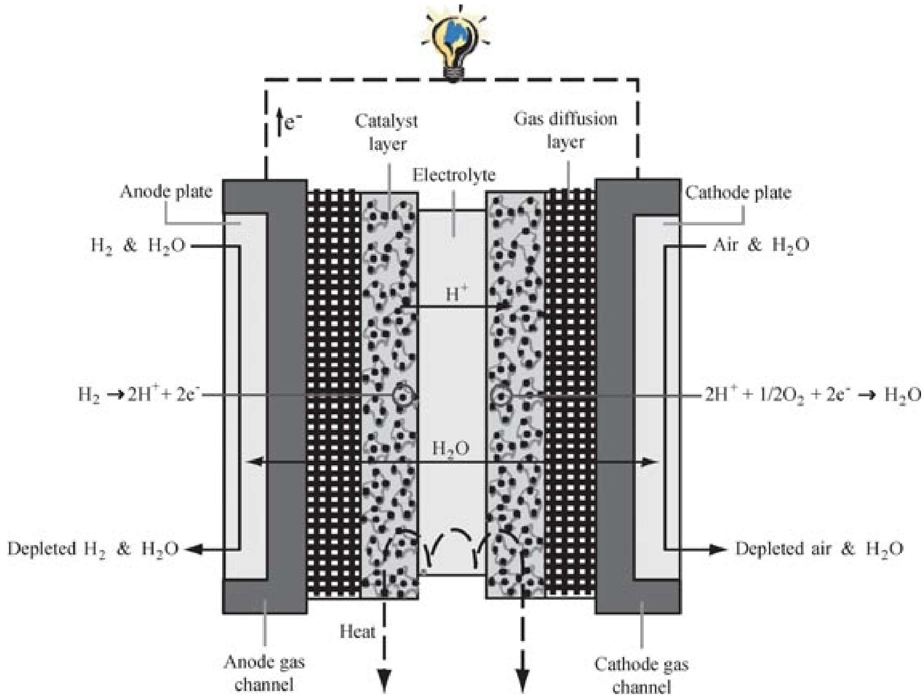

FIGURE 2 | Illustration of fuel cell operation taking the hydrogen-fuelled polymer electrolyte fuel cell (PEFC) as an example.

FUEL CELLS FOR MICRO-COGENERATION

Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into electricity (and heat), without involving the process of combustion. A simplistic view of a fuel cell is that it is a cross between a battery (chemical energy converted directly into electrical energy) and a heat engine (a continuously fuelled air breathing device); this is why fuel cells are sometimes referred to as electrochemical engines. There are a number of fuel-cell technologies with very different designs, each suited to different applications. However, they all share the characteristics of high efficiency, no moving parts, quiet operation, and low (compared with heat engines) or zero emissions at the point of use. In addition, modular stack design means that there are no technical limitations on minimum capacity, which is a problem for mechanical heat engines.

Several types of fuel cells are under development. The classification is primarily by the kind of electrolyte,[19] which determines the chemical reaction that takes place in the cell, the catalyst required, the operating temperature range, and the fuel required. For micro-cogeneration, two particular types of fuel cell have received the most interest and development time: the low-temperature PEFC that typically operates around 80°C and the high-temperature SOFC, operating in the range of 500–1000°C.

Taking the hydrogen-fuelled PEFC as an example, Figure 2 shows the basic operation of a fuel cell. A single cell consists of a negatively charged electrode (anode), a positively charged electrode (cathode), an electrolyte membrane, catalyst and gas diffusion layers, gas channels, and end plates. Hydrogen is channeled to the anode wherein the catalyst separates the hydrogen's negatively charged electrons from the positively charged protons. The membrane allows only the protons to pass through the cathode; the electrons must flow around the membrane through an external circuit. This flow of electrons forms an electric current. At the cathode, the electrons and hydrogen ions (protons) combine with oxygen to form water and heat. The exact reactions that occur depend on the type of fuel cell, but for hydrogen-fuelled cells, the reactions are as follows:

$$\text{Anode}: \quad H_2;:: \; 2H^+ + 2e^-$$

$$\text{Cathode}: \quad \frac{1}{2}O_2 + 2H^+ + 2e^-;:: \; H_2O$$

$$\text{Overall}: \quad H_2 + \frac{1}{2}O_2;:: \; H_2O + \text{electricity} + \text{heat}$$

The amount of power produced by a fuel cell depends on several factors, including the type of fuel cell, the fuel used, the cell size, the temperature and pressure at which it operates, etc. The current output is proportional to the active area of the individual cells, and the voltage is proportional to the number of cells connected together. As with solar photovoltaic cells and batteries, a single fuel cell produces voltage barely enough for even the smallest applications (1 V), so individual cells are connected in series to form a *stack*. A typical fuel cell stack for micro-cogeneration may consist of a hundred of fuel cells of 15 $\times$ 15 cm^2 ($\sim$2.5 kWe), for example.

Fuel-Cell Operation

Figure 3a illustrates the voltage and power versus current curve for a generic fuel cell. An increase in current density (current per unit area of each cell) results in a decrease in operating voltage due to internal losses in the system. Power output initially increases and reaches a maximum at point 'D', above which, the decreasing voltage and increasing losses in the system results in loss of electrical power output, although the heat generated continues to increase. The nominal operating point is around point 'C', which is typically 2/3 to 3/4 of the open circuit voltage of the cell. The point of operation is a trade-off between electrical efficiency and capital cost[20]; for a micro-cogeneration system, the requirement to service the heat load is also a factor in determining the operating point.

Considering the whole fuel-cell system, Figure 3b shows how the electrical and thermal efficiency varies with the electrical load. In contrast to heat engines which have a maximum efficiency at their nominal operating point, fuel cells are known to have excellent 'turn-down' performance, that is reducing the electrical load results in higher electrical efficiency. However, since there are components that require electrical supply (e.g. sensors, actuators, and control system), and their load is constant regardless of the power delivered by the fuel cell, this parasitic load degrades the system efficiency at low electrical load. There is a point 'B' where the parasitic load equals the power delivered by the fuel cell and the system therefore has 'zero efficiency'. In a similar sense, SOFCs have a lower operational point below which the stack is no longer thermally self-sustaining and begins to cool. There is therefore a practical lower limit below which the system cannot operate, typically of the order of 20% of the nominal operating point.

It can be seen from Figure 3b that as the electrical load on the fuel cell increases, the thermal efficiency increases and the electrical efficiency decreases.

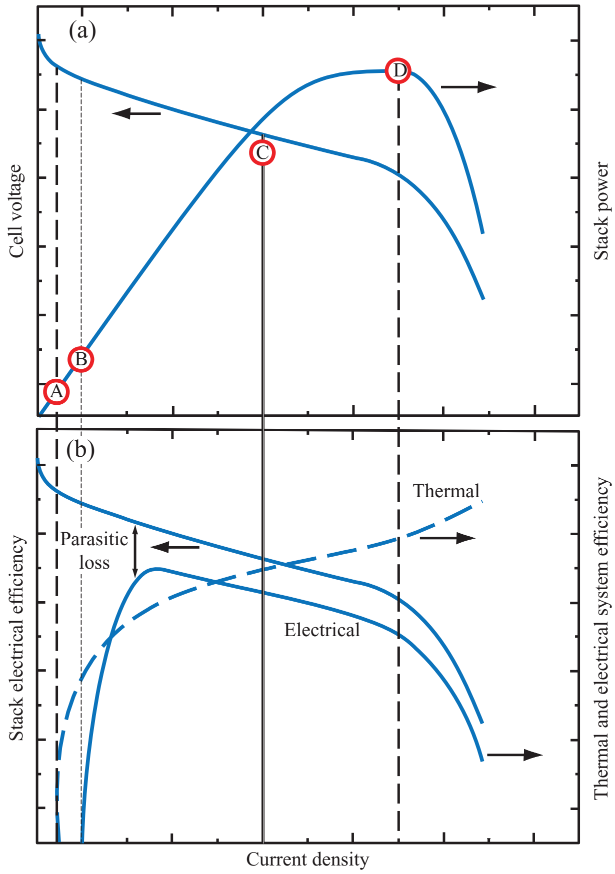

FIGURE 3 | Illustration of the operating range of a fuel cell, showing (a) stack voltage and power and (b) electrical and thermal efficiency. Labeled operating points are described in the text.

The way in which the heat-to-power ratio of the fuel cell varies with electrical load will depend very much on the system design, but will generally tend to increase when subjected to heavy electrical loading. However, it should be remembered that the heat-to-power ratio of the system can also be controlled at any fuel cell operating point by varying the fuel utilization and the amount of heat generated in an auxiliary afterburner.

OVERVIEW OF THE DESIGN PROCESS

Figure 4 illustrates a typical fuel-cell system design procedure in which modeling and optimization play a key role. The first step is to identify a set of design criteria that will be used as objectives or constraints, examples of which include size, efficiency, fuel consumption, heat-to-power ratio, power output, durability, emissions, capital cost, operating cost, and payback period. A few of these are essential for a given application.

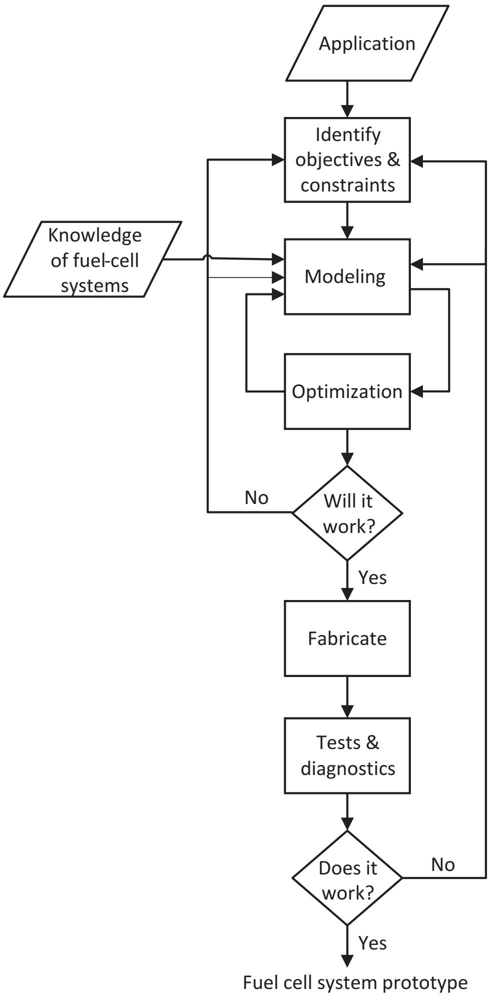

FIGURE 4 | A typical fuel cell system design process. (Reprinted from Ref 4. Copyright 2005, Elsevier.)

It is crucial to identify the criteria that can be overlooked without compromising the object of the design.

Modeling is performed to capture the aspects of the system that are of interest to the designer. Knowledge of fuel-cell phenomena, such as electrochemical, thermodynamic and transport processes, material properties, and various interactions are useful in formulating a model. A mathematical model, which describes certain aspects of the system and predicts its behavior, may be a set of algebraic or differential equations, or a computer-based procedure or subroutine. The model may contain many different design alternatives, which can be obtained by changing the variables, parameters, conditions, or constraints. The criteria defined in the previous step provide the basis for comparison of the different design alternatives.

The model can then be coupled with a numerical optimization algorithm to generate better designs iteratively. This may result in a single or multiple optimal solutions. Modeling and optimization aid the designer in shortlisting candidate designs for further consideration. Optimization, however, does not always generate a good design suitable for fabrication. In this case, iteration of the previous steps is necessary to verify that appropriate fuel-cell phenomena are captured in the model and correct governing equations are used, examine the validity of the assumptions used in modeling, and if necessary, adjust or modify the design requirements and objectives.

The designer then evaluates the design solutions generated from optimization and selects one or more alternatives that can be fabricated, guided by the knowledge of the trade-offs among the objectives, in addition to own experience and other considerations that could not be included in the optimization problem. Tests and diagnostics (e.g. model validation against experiments) are carried out to determine what else can be further improved in the existing design, verify the assumptions, and validate the models. The final design may either result in a final prototype or an iteration of an existing design.

Poor modeling and strict requirements can make the design iteration loop shown in Figure 4 long and recurrent. A good model should be robust, accurate, and able to provide meaningful solutions to fuel-cell problems quickly.[21] A robust model is able to predict fuel-cell performance over a wide range of operating conditions. Accuracy, on the contrary, can be attributed to using reasonable assumptions and correct input parameters such as physical and chemical properties, to the proper identification of the physical phenomena, and to using the correct governing equations. However, improving robustness and accuracy often involves a sacrifice in computational efficiency. A good model should exhibit a balance between robustness, accuracy, and computational efficiency.

CRITERIA FOR DESIGN

A good fuel-cell system design is one that meets the design requirements and represents a trade-off among the different design objectives.[14] Thus, it is imperative to identify the critical criteria and those that can be sacrificed without jeopardizing the design. This section discusses the key issues for some of the most important criteria for the design of a fuel-cell micro-cogeneration plant.

Size

The optimal sizing of a micro-cogeneration unit is a continuing point of discussion among engineers.

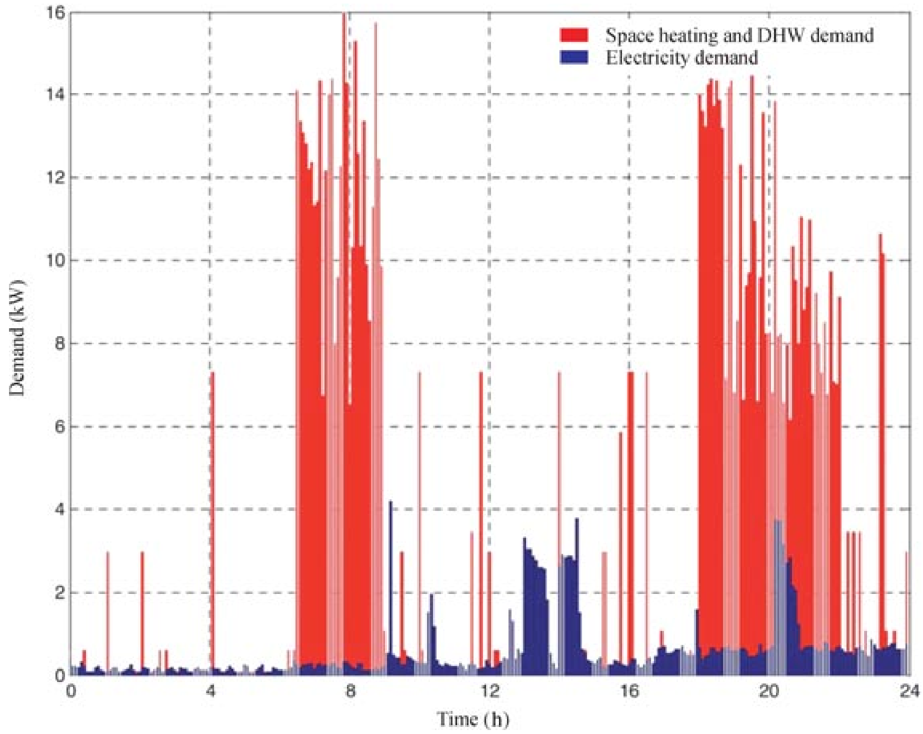

FIGURE 5 | Illustration of a typical electrical and heat load for a UK dwelling. Values are in (average) kW, for each 5 min period of a typical winter day. On the basis of data from IEA Annex 42. (Reprinted from Ref 24. Copyright 2007, IEA.)

A large unit can potentially provide higher electrical outputs, thus higher cost and carbon savings. However, oversizing the unit increases the capital cost, and can lead to excessive heat dumping which erodes the economic and environmental benefits of the system if the power cannot be sufficiently turned down. Also, oversizing often results in cycling operation (repeated short operating cycles), which reduces the efficiency due to the losses incurred during startup and shutdown.[7] Undersizing a micro-cogeneration system, however, will lead to greater reliance on backup heating systems and grid electricity. If such backups are not available, the property will heat up less quickly and may not reach comfortable internal temperatures.[17]

Another key issue in sizing is the electrical output of the system relative to the site's base load electricity demand. If export tariffs are not available, it is beneficial to ensure that all the electricity generated is used on-site. If they are, it may be economically viable to generate large amounts of electricity, provided that the property can utilize the additional heat produced. In some cases, there may be a benefit from using a heat storage which can act as an effective buffer to support the production of hot water at times of peak demand. However, any potential benefits may be undermined by the heat losses associated with currently available heat storage.

The field trials undertaken by the Carbon Trust suggest that matching the capacity of the micro-cogeneration to the heat demand of the property is often advantageous.[17] In this case, the rated heat output of the micro-cogeneration system is sized to adequately meet the comfort requirements of the end user on the coldest winter days. Anything larger than this involves some modulating capability, heat dumping, and/or heat storage.[22]

How a fuel-cell micro-cogeneration unit is sized and operated is a trade-off between system efficiency (fuel cost), unit size (capital cost), and heat-to-power ratio. Ang et al.[20] have quantified the trade-offs between the efficiency and the size of a PEFC stack. In practice, accurate and detailed demand data for heat and electricity are fundamental to accurately sizing a micro-cogeneration unit. Figure 5 shows a representative heat and power load variation over the course of 24 h for a typical family home.

It can be seen that the heat-to-power ratio of the demands varies significantly throughout the day. Moreover, the average ratio, over a day, varies from about 1:1 in summer months to above 8:1 in the winter.[23] Therefore, sizing of the fuel-cell micro-CHP can be a challenge and supplementary generation and storage will typically be required to deal with these dynamics. This problem was investigated by Liso et al.,[23] who found that the most economic solution is to size the micro-CHP for the summer hot-water demands, which in the United Kingdom are about 100 W, and to cover peak hot-water demands using a storage and space-heating demands in the winter with a supplementary burner. The heat-to-power ratio of fuel-cell micro-CHP units, between 0.5:1 and 1.5:1, are an ideal match for the demands in summer which means that they can run continuously throughout the year, which is beneficial for reliability and cost.

Conversion Efficiency

The efficiency of a micro-cogeneration system is the fraction of the chemical energy in the input fuel that can be recovered as electrical power and heat. There are three primary efficiencies associated with micro-cogeneration: the electrical efficiency, the thermal efficiency, and the overall efficiency. In general, maximizing the overall efficiency often results in a high-performance operation.[17] For micro-cogeneration, the electrical efficiency is more important than the thermal efficiency due to the higher value of electricity, relative to heat, in terms of both cost and carbon intensity. Fuel cells offer significantly higher electrical efficiency than engine-based technologies and can rival modern combined cycle gas turbine. However, their overall efficiency is currently lower than engines, which is largely due to their relative immaturity and difficulties in capturing low-grade waste heat.[6]

Heat-to-Power Ratio

The heat-to-power ratio affects the overall energy, cost, and carbon saving benefits of micro-cogeneration. Although the overall efficiency is important, the relative level of electrical output has the biggest impact on carbon saving performance. Relatively small increases in electrical efficiency (i.e. decreases in heat-to-power ratio) can result in significant increases in potential carbon savings.[17] The heat-to-power ratio of a micro-cogeneration system can be varied by operating at different electrical loads and invoking the use of an auxiliary burner.[6]

Fuel cells have relatively low heat-to-power ratio (∼0.5–1.5:1) compared with other micro-cogeneration technologies. They are therefore able to operate well in properties with limited demand for heat.

Transient Response

Low-temperature fuel cells are expected to operate intermittently in people's homes, starting up and shutting down on most days.[7,25,26] The energy required to start and stop the fuel-cell system over the course of a year can be significant, as electronic systems must run before and after operation to provide adequate stack conditions, and a long period of preheating is required to raise the generator's mass up to the operating temperature. Although the fuel-cell stack may be able to operate from ambient temperature (in the case of PEFC), the fuel processor must be heated to several hundred degrees before hydrogen can be produced. The annual seasonal efficiency of a fuel cell micro-cogeneration system will be lower than when measured at steady state, as the additional gas and electricity consumed during startup and shutdown need to be accounted for.[7]

Reliability/Availability/Lifetime

Fuel-cell micro-cogeneration systems are expected to operate for 40,000–80,000 h, equivalent to 10–20 years of intermittent usage. The effect of real-life conditions such as impurities in fuel and oxidant can make the system's operating life shorter.

The latest PEFC systems are expected to exceed the 40,000 target[27]; however, as none of these units have been operating for more than a year in the field, this is impossible to verify at present. The longest reported lifetimes so far from the Japanese field trials have been around 20,000 hours.[7] Because of challenging material requirements, SOFC lifetimes are currently around half of those for PEFC, with up to 15,000 h reported in field trials, and 20,000 h expected to be attainable by micro-cogeneration systems by 2015.[7]

Currently, both PEFC and SOFC stacks lose power at a rate between 0 and 5% per thousand hours, depending on the design and materials used. Reduced catalytic activity in the cells and reformer, combined with increasing cell resistance, causes a gradual drop in output voltage, and thus power output. This can shorten stack lifetime, but mechanical deterioration of the cells is usually the limiting factor.

Emissions

Hydrogen-powered fuel cells produce no emissions at the point of use, the only by-product being pure water. However, CO2 is emitted when a reforming process is used to produce the hydrogen from another fuel, for example methanol, but this is typically much lower than that of an internal combustion engine or from using grid electricity due to the fuel cell's high efficiency.

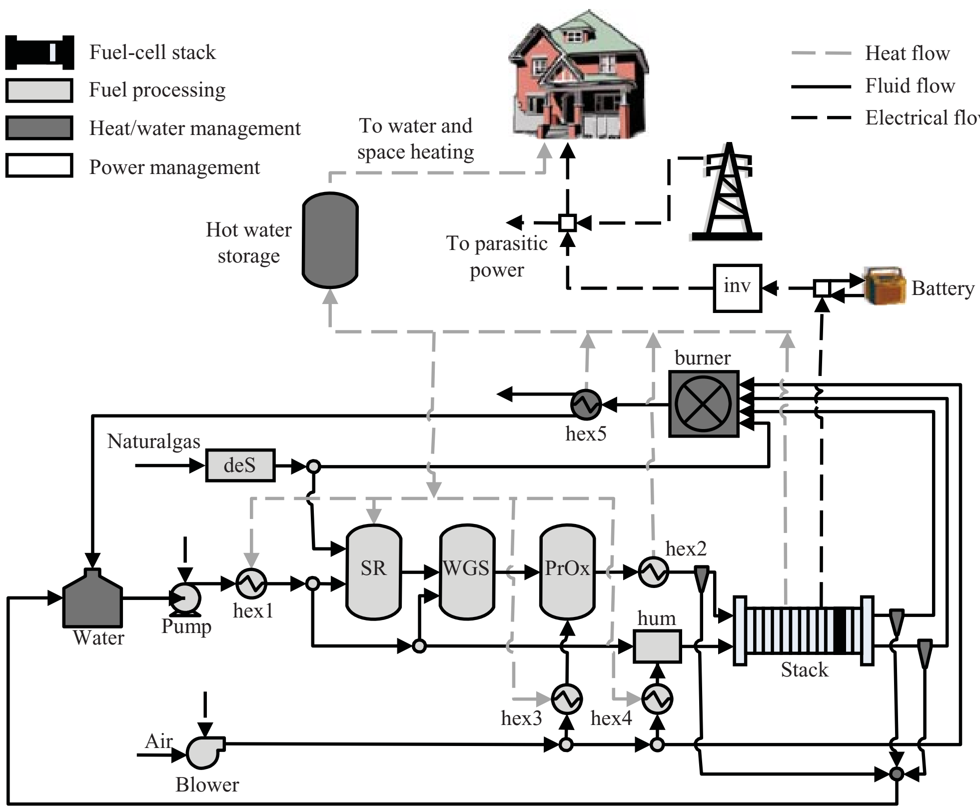

FIGURE 6 | Schematic of a fuel cell micro-cogeneration system. The symbols in the diagram refer to as follows: deS, desulfuriser; hex, heat exchanger; hum, humidifier; inv, DC/AC converter; PrOx, preferential oxidation reactor; SR, steam reformer; WGS, water gas shift reactor. (Reprinted with permission from Ref 14. Copyright 2011 Elsevier.)

When analyzing the emissions of a fuel-cell system, the entire life cycle should be considered. If hydrogen is produced from other fuel, the emissions resulting from the reforming process should be taken into account regardless of whether the hydrogen generation takes place in a central refinery or at the micro-cogeneration site. Producing hydrogen from water via electrolysis is an alternative option, which can result in zero life cycle emissions if powered by renewable electricity.

Cost

Perhaps the overriding design criterion is cost. However, cost is not always a practical choice as a design criterion because it can be very difficult to quantify. In addition, although the design with the lowest cost is usually the preferred choice, a narrow focus on low cost will not necessarily lead to a well-balanced and successful design. Careful consideration of the other criteria such as lifetime, emissions, size, etc. is important.

The total cost of a fuel cell system is the aggregate of capital cost, fuel production cost, operating cost, maintenance and repair cost, emissions cost, and disposal cost. The cost must compete with that of the technologies that the fuel cell systems replace, that is grid electricity and condensing boilers for stationary fuel cell systems.

In some cases, *return on investment* is used as a criterion instead of the total cost. An example is the payback time, which is the ratio between the capital cost and annual savings in operating cost (relative to the system that is replaced), and measures the number of years it takes for an investment to pay back. Alternative criteria of return are the net present value and the internal rate of return.

DESIGN OF A FUEL-CELL MICRO-COGENERATION PLANT

Figure 6 shows a schematic of a typical PEFC-based fuel-cell system for residential micro-cogeneration running on reformed hydrogen from natural gas (the description of the subsystems are given in Ref 14). This system has been used as the basis for modeling studies to investigate optimization of fuel-cell micro-cogeneration. The design of such system naturally involves simultaneous optimization of two or more conflicting objectives including many decision variables and constraints. This section considers two cases that illustrate such conflict between design criteria.

Efficiency Versus Size of a Fuel-Cell Stack

The trade-off between efficiency and size is inherent in the design of a fuel-cell stack.[20] These two criteria are both related to economics. Fuel consumption, hence operating cost, is directly determined by the efficiency. On the contrary, the bulk of the capital cost is contributed by the size of the membrane electrode assembly (MEA).[a,28] The compromise between the capital investment and operating cost is not the only motivation for the trade-off investigation between size and efficiency. In the current consumer demographic, the size of the fuel-cell system relative to a conventional boiler may be a deciding factor for households that lack substantial spare floor space. On the contrary, other users may value operating costs more than convenience when locating the system.

Fuel Consumption Versus Power Output of a Micro-Cogeneration System

There is a trade-off between the net electrical power output and the fuel consumption of a fuel-cell micro-cogeneration system. Ideally, the system is operated at high-power output and low-fuel consumption; thus, the optimization problem will involve maximization of power output and minimization of fuel consumption. These are conflicting because more fuel is needed to produce additional power. Also, in some cases, electricity in excess of the site requirements is generated which can be sold to the grid. The value of the exported electricity depends on the situation; sometimes, the electricity used on-site is more valuable; in others, such as with some feed-in tariffs, excess electricity is sold to the grid at higher than market rates. Deciding which of the two objectives—power output or fuel consumption—is more important depends on the cost of the fuel and electricity and the buyback rate of electricity exported to the grid. The inherent variability in the cost introduces difficulty in deciding which operating point is most beneficial economically. Thus, information that shows the compromise between the power output and the fuel consumption is an important tool in identifying the most suitable operating design for a given thermal and electrical demands.

Multi-Objective Optimization

For both the design problems, the aim is to determine a set of trade-off optimal solutions, called a nondominated set or a Pareto set[10–13] that simultaneously optimizes the design criteria. The determination of a Pareto set is a multi-objective optimization problem. Mathematical models that describe and predict the behavior of the process are required for this purpose. The detailed description and formulation of one such fuel-cell stack model can be found in Ref 20.[20] This model was extended to a micro-cogeneration plant by integrating the stack with the necessary subsystems for it to operate as a residential heat and power generator as described in Refs 14 and 29.

Since multi-objective optimization requires evaluation of a large number of design alternatives with correspondingly high computational requirements, simple and fast models are preferable. The models have acceptable accuracy and are complex enough to differentiate between alternative designs, while being simple enough to allow for repeated calculations during optimization.[20]

There are a variety of techniques for solving multi-objective optimization problems.[10–13] In this work, the weighting method is used to approximate the Pareto set. This method transforms the multi-objective optimization problem into a single-objective optimization problem by associating each objective function with a weighting coefficient and then minimizing the weighted sum of the objectives:

$$\min z = \sum_{i=1}^{N} \omega_i z_i(x)$$

where z is the weighted sum of the objectives, z_i is a single objective, and $\omega_i \in (0, 1)$ is a weighting factor with $\sum_{i=1}^{N} \omega_i = 1$. The extreme points $\omega = 0$ and $\omega = 1$ represent the single-objective optimization problems. Solving the optimization problem for any $\omega \in (0, 1)$ will generate solutions between these two extremes where the two objectives are considered simultaneously; the value of ω determines the relative importance of each objective. A Pareto set can be generated by evaluating a series of single-objective optimization problems with different values of the weighting factor to avoid having to, *a priori*, select a particular weighting between objectives.

The optimization problem is subject to the constraints imposed by the mass and energy balances, the electrochemical model, the equilibrium relations, the transport equations, physical constraints, and bounds on the design variables. The model was written in the GAMS[30] modeling language and was solved using LINDOGlobal. LINDOGlobal employs the branch-and-cut method to break a nonlinear programming model down into a list of subproblems.[31] A discussion of the branch-and-cut method is given in Ref 32.

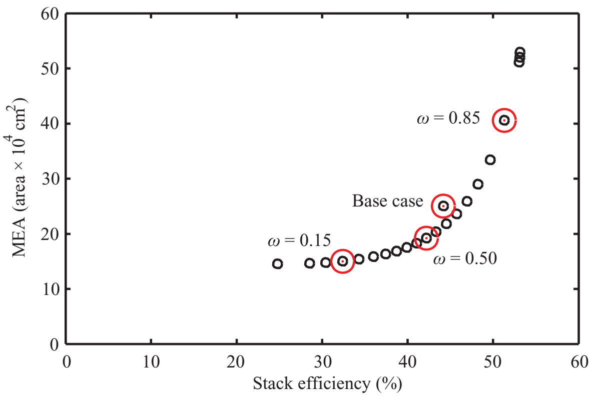

FIGURE 7 | A Pareto set showing the trade-off between efficiency and size of the stack. (Reprinted with permission from Ref 20. Copyright 2010 Elsevier.)

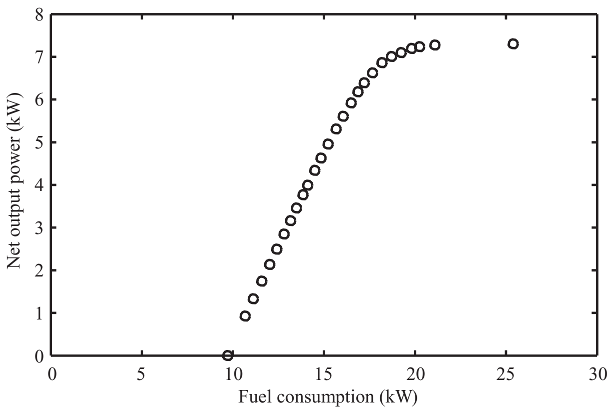

FIGURE 8 | Pareto set showing the trade-offs between the net electrical power output (W_{del}) and fuel consumption (W_{fuel}). (Reprinted with permission from Ref 14. Copyright 2011 Elsevier.)

Trade-Offs in the Design

Figure 7 shows the trade-off, or Pareto, curve for system efficiency versus fuel-cell size. The efficiency and the total MEA area (cell area multiplied by number of cells) are plotted on the two axes and the curve consists of a set of designs that are all optimal in a Pareto sense. The highest point at the top right of Figure 7 represents the optimal solution for the single-objective optimization problem of maximizing the efficiency of the system without taking the size into account. Conversely, the lowest point (bottom left) in the curve corresponds to the optimal solution for the minimization of the size regardless of the efficiency. From the results, it can be concluded that the efficiency and size of the system must be considered simultaneously. If only the efficiency is maximized, the outcome may be an impractically large system. On the contrary, optimizing for size results in a system almost four times smaller but with an efficiency that is lower than other competing technologies.

A base case from Ref 20 is shown in Figure 7 to be a dominated solution as it lies 'inside' of the Pareto set. The points that correspond to $\omega = 0.60$ up to $\omega = 0.65$ have both a higher efficiency and a smaller size compared with the base case so they improve on both objectives.

The points at the far right of Figure 7 represent solutions in which the size of the system is compromised in favor of the efficiency. Moving down the curve, to the left, the size of the system is improved but the efficiency reduces. None of the points is essentially superior and the final choice of design will depend on the factors specific to the application. For stationary applications, the size of the system can be traded off for the efficiency with relatively minor consequences. This is not the case, however, for mobile and transportation applications, which require highly efficient and small systems. Furthermore, at efficiency of approximately 47% and above, the slope of the curve is very steep. In this region, large increases in the size of the system result in small gains in efficiency. Conversely, at efficiency of about 40% and below, the curve appears to be flat. This suggests that in this region, a small change in the size of the system leads to a large impact on the efficiency. Overall, to make the most of the trade-off behavior in Figure 7, the stack should be operated at an efficiency of between 40 and 47%.

Figure 8 gives the trade-off solutions for fuel consumption versus power output of a fuel-cell micro-cogeneration plant at a thermal power rating of 9 kWth. The highest point is the optimal solution for the single-objective maximization of the net electrical power output without taking the fuel consumption into account. Conversely, the lowest point is the optimal solution for the single-objective minimization of the fuel consumption regardless of the power output. The results indicate that the lowest fuel consumption occurs when the system is operating in 'boiler only' mode, that is the net electrical power output is zero. In this case, the system is still generating some electrical power but all of this is used to service the parasitic loads such as the blower and the water pump.

It can also be observed from Figure 8 that at power output below 7 kWe, the power output trades almost linearly with the fuel consumption. In this region, roughly 0.85 We additional power is produced for every W of extra fuel. At power output above 7 kWe, it is not economically practical to operate the system because there are no significant gains in power output with increase in fuel consumption. The limit on the maximum attainable net power output can be

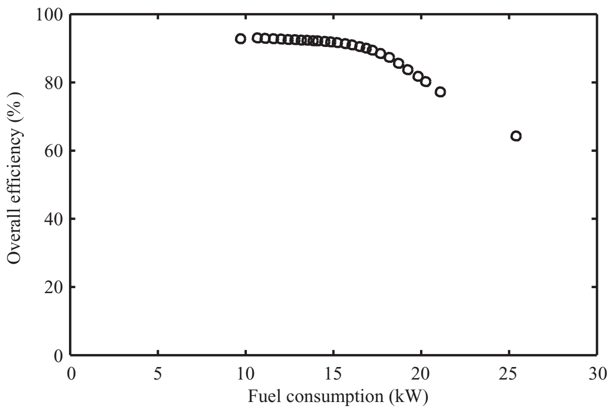

FIGURE 9 | Values of the overall efficiency corresponding to the Pareto set in Figure 8. (Reprinted with permission from Ref 14. Copyright 2011 Elsevier.)

attributed to the fixed size of the fuel cell. In this study, the total active area of the MEA is considered to be 1.6 m^2 (e.g. 40 cells, each with active area of 20×20 cm^2).

Figure 9 shows the overall efficiency plotted against the fuel consumption. The figure indicates that placing more importance on the net power output as an objective leads to a decrease in the overall efficiency. Furthermore, the micro-cogeneration system can achieve an overall efficiency as high as 93%. The lowest overall efficiency is about 65% which is still higher than the 50–60% overall efficiency of a modern combined cycle power plant.[33]

Figure 10 shows the values of the electrical and thermal efficiencies corresponding to the Pareto set in Figure 8. It can be observed that a maximum value of the electrical efficiency occurs for a particular value of the weighting factor. Interestingly, the solution of the single-objective maximization of the power output does not necessarily result in a maximum electrical efficiency. Finally, there is a trade-off between the thermal efficiency and the electrical efficiency. At high thermal efficiency, the electrical efficiency is low and *vice versa*. This clearly demonstrates the ability of the fuel cell to operate with a variable heat-to-power ratio.

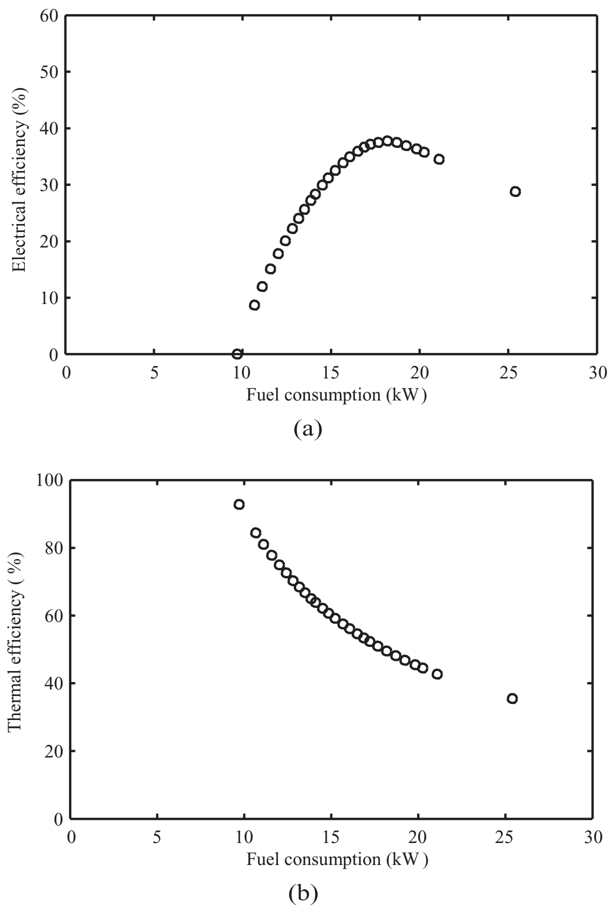

FIGURE 10 | Values of the individual efficiencies, (a) electrical efficiency and (b) thermal efficiency, corresponding to the Pareto set in Figure 8. (Reprinted with permission from Ref 14. Copyright 2011 Elsevier.)

CONCLUSIONS

Fuel cells offer many benefits for residential micro-cogeneration because of their high electrical efficiency, low emissions, and low heat-to-power ratio. There is a great opportunity for modeling and optimization to be used to inform system design, which often results in savings in design cycle time and cost, and better design and operation.

The design of fuel-cell micro-generation systems naturally involves conflicting objectives such as size, efficiency, fuel consumption, and power output, among others; an improvement in one of the objectives often involves sacrifice in the value of another one. This paper provides an overview of an effective approach to designing fuel-cell micro-cogeneration systems so as to achieve a balance among the conflicting objectives. Illustrations are presented to show how a multi-objective optimization framework can be used to quantify the trade-offs between competing objectives. This approach offers flexibility to design engineers by providing them with a set of design alternatives that contain such trade-offs.

Finally, it is worth noting that as with any models used in decision making, it is necessary to make certain that the model correctly represents the behavior of the actual system. The design solutions are only useful within the limitations of the model assumptions, and their quality depends on how well the model has been formulated. When properly formulated and validated, modeling and optimization are useful tools in the design of fuel-cell micro-cogeneration systems as they provide ways to generate different design alternatives and identify good designs.

NOTES

[a]The costs of the other components such as the bipolar plates and auxiliaries (humidifiers, air compressor, and water coolant) which add up to the capital cost are strongly correlated with the variation in the area of the MEA.

REFERENCES

1. Hawkes AD, Brett DJL, Brandon NP. Role of fuel cell based micro-cogeneration in low carbon heating. *J Power Energy* 2011, 225:198–207.
2. Staffell I, Barton J, Blanchard R, Hill F, Jardine C, Brett D. UK microgeneration. Part II: technology overviews. *Energy* 2010, 163:143–165.
3. Obara S. *Distributed Energy Systems*. New York; Nova Science Publishers, Inc.; 2009.
4. Barbir F. *PEM Fuel Cells: Theory and Practice*. San Diego, CA: Academic Press; 2005.
5. Larminie J. *Fuel Cell Systems Explained*. 2nd ed. Chichester, UK: John Wiley & Sons; 2003.
6. Hawkes A, Staffell I, Brett D, Brandon N. Fuel cells for micro-combined heat and power generation. *Energy Environ Sci* 2009, 2:729–744.
7. Staffell I. *Fuel cells for domestic heat and power: are they worth it?* Ph.D. Thesis. Birmingham, United Kingdom: University of Birmingham; 2010.
8. Japan Fuel Cell Association. About the subsidy programme (2012). Available at: http://www.fca-enefarm.org/subsidy/subsidy.html (in Japanese) (Accessed February 29, 2012).
9. Ang SMC, Brett DJL, Fraga ES. Optimal design of fuel cell systems. In: Columbus E, ed. *Fuel Cell Efficiency*. New York: Nova Science Publishers, Inc; 2010.
10. Diwekar U. *Introduction to Applied Optimization*. New York: Springer; 2008.
11. Miettinen K. *Nonlinear Multiobjective Optimization*. Norwell, MA: Kluwer Academic Publishers; 1999.
12. Ngatchou P, Anahita Z., El-Sharkawi MA. *Pareto multi objective optimization*. In: Proceedings of the 13th International Conference on Intelligent Systems Application to Power Systems, 2005; 2005, 84–91.
13. Rangaiah GP, ed. *Multi-objective Optimization: Techniques and Applications in Chemical Engineering*. Vol. 1. Singapore: World Scientific Publishing Co. Pte. Ltd.; 2009.
14. Ang SMC, Fraga ES, Brandon NP, Samsatli NJ, Brett DJL. Fuel cell systems optimisation—methods and strategies. *Int J Hydrogen Energy* 2011, 36:14678–14703.
15. Parker D. *Microgeneration: Low Energy Strategies for Larger Buildings*. Oxford, UK: Elsevier Ltd.; 2009.
16. Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on useful heat demand in the internal energy market and amending Directive 92/42/EE. Technical report, European Union, Bruxelles; 2004.
17. Carbon Trust. Micro-CHP Accelerator: Interim Report. Technical report, Carbon Trust, London; 2007.
18. Harrison J. Micro Combined Heat & Power. In: *Micro Energy Systems: Review of Technology, Issues of Scale and Integration.* Suffolk, UK: Wiley–Blackwell; 2004, 77–98.
19. EG&G Technical Services, Inc. *Fuel Cell Handbook*. 7th ed. Morgantown, West Virginia: U.S. Department of Energy; 2004.
20. Ang SMC, Brett DJL, Fraga ES. A multi-objective optimisation model for a general polymer electrolyte membrane fuel cell system. *J Power Sources* 2010, 195:2754–2763.
21. Spiegel C. *PEM Fuel Cell Modeling and Simulation Using Matlab*. Burlington, MA: Academic Press; 2008.
22. The Energy Institute. *Combined heat and power: selecting, installing and operating CHP;* 2003.
23. Liso V, Zhao Y, Brandon NP, Nielsen MP, Kaer SK. Analysis of the impact of heat-to-power ratio for a SOFC-based mCHP system for residential appli-cation under different climate regions in europe. *Int J Hydrogen Energy* 2011, 36:13715–13726.
24. International Energy Agency (IEA). Annex 42 - detail load profiles.
25. Osaka N, Nishizaki K, Kawamura M, Ito K, Fujiwara N, Nishizaka Y. Development of residential PEFC cogeneration systems. In: *Fuel Cell Seminar and Exposition*. California: Palm Springs; 2005.
26. Hamada Y, Goto R, Nakamura M, Kubota H, Ochifuji K. Operating results and simulations on a fuel cell for residential energy systems. *Energy Conv Manage* 2006, 47:3562–3571.
27. Panasonic Corporation. Tokyo Gas and Panasonic to launch new improved "Ene-Farm" home fuel cell with

world-highest power generation efficiency at more affordable price. Available at: http://www.panasonic.co.jp/corp/news/official.data/data.dir/en-0.5-0.50209-2/en110209-2.html (Accessed July 1, 2011).

28. Hung AJ, Chen YH, Sung LY, Yu CC. Cost analysis of proton exchange membrane fuel cell systems. *AICHE J* 2008, 54:1798–1810.
29. Ang SMC. *Model-based design and operation of fuel cell systems*. Ph.D. Thesis. London: University College London; 2012.
30. Rosenthal RE. *GAMS—A User's Guide*. Washington, District of Columbia: GAMS Development Corporation; 2008.
31. Lindo Systems, Inc. *LINDOGlobal*.
32. Lucena A, Beasley JE. Branch and cut algorithms. In: Beasley JE, ed. *Advances in Linear and Integer Programming*. New York: Oxford University Press, Inc.; 1996, 187–221.
33. The Institution of Engineering and Technology. Combined heat and power (CHP). Technical report; 2008.

