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Application of an improved operational strategy on a PBI fuel cell-based residential system for Danish single-family households

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HIGHLIGHTS

► We formulate an improved operational strategy for a Danish single-family household.
► We analyze a HT-PEMFC-based micro-CHP system in terms of operational performance.
► The results indicate the potential of the system if an improved strategy is applied.
► The average total efficiency of the system is 85.9%.

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ABSTRACT

A proposed residential energy system based on the PBI (Polybenzimidazole) fuel cell technology is analyzed in terms of operational performance. Conventional operational strategies, such as heat-led and electricity-led, are applied to the simulated system to investigate their performance characteristics. Based on these findings, an improved operational strategy is formulated and applied in an attempt to minimize the shortcomings of conventional strategies. System parameters, such as electrical and thermal efficiencies, heat dumping, and import/export of electricity, are analyzed. The applied load profile is based on average data for a single-family household in Denmark and includes consumption data for electricity and heat demands. The study analyzes the potential of the proposed system on market penetration in the area of residential heat-and-power generation and whether this deployment can be justified as compared to other micro-CHP system technologies. The most important findings of this research study indicate that in comparison to non-fuel cell-based micro-CHP systems, such as Stirling Engine-based systems, the proposed system has significantly higher efficiencies. Moreover, the lower heat-to-power ratios allow the system to avoid high thermal surpluses throughout the whole annual operational profile.

1. Introduction

The application of fuel cell technology in residential micro-CHP (Combined Heat and Power) systems has been gaining an increased amount of interest during the recent years, which is mainly due to their promising efficiency performance. Many advantages can be listed for these systems, as well for the fuel cell itself and the system in general. The main advantages of fuel cells include, among others, high electrical efficiencies and low greenhouse gas emissions [1–4]. In addition to these advantages, the micro-CHP technology can provide increased cogeneration efficiencies, due to the thermal efficiency utilization. Also on-site power-and-heat production eliminates transmission and distribution losses, which are inevitable for centralized systems [5–7]. Another important aspect of fuel cell-based micro-CHP technology is the fact that fuel cell systems can operate efficiently at part-load operation, which provides greater flexibility in adopting an operational strategy. Further on, fuel cells possess the capability of responding rapidly to load changes. As a consequence of high efficiency, fuel cell systems can offer the potential of reduced operational costs, which has been becoming extremely influential in the recent years due to the rapidly increasing cost of fossil fuels.

In the current research study, different operational strategies are examined to investigate the response of the system to changing loads, primarily with respect to efficiency. The overall goal of this research work is to investigate the application of conventional operational strategies such as heat-led and electricity-led operation [6], and then formulate an improved operational strategy, which

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provides a higher average net electrical (and total) efficiency for the system. In this manner a comparison can be made with the conventional operational strategies, drawing assumptions for discussion and analysis. Also a thermal storage tank is modeled and coupled to the system to increase its operational flexibility. Finally, an investigation of the heat losses exhibited by the thermal storage tank is carried out throughout the whole annual operational load profile. This is done to monitor the periods exhibiting the highest losses. The applied load profile is based on averaged consumption data for a typical single-family household in Denmark [5,6].

2. Literature review

Residential micro-CHP systems can be categorized in four main types, based on their respective prime mover technology: Stirling engines (SE), internal combustion engines (ICE), proton exchange membrane fuel cells (PEMFC), and solid oxide fuel cells (SOFC). SE- and ICE-based micro-CHP systems are considered to be the most mature technologies, since they are commercially available from a number of manufacturers [8–11]. The operating principle of the SE is based on an external combustion engine with an internal piston being driven via a temperature difference between the ends of a cylinder. SE residential systems typically have low electrical efficiencies ranging from 0.07 to 0.15 (based on LHV) [9,12], while their respective overall efficiencies are comparable to that of a condensing boiler. In terms of operational behavior, they have rapid startup times and quick load changing responses [12]. The operating principle of an ICE micro-CHP system is based on combustion occurring inside a cylinder driving a piston to create mechanical work, which is converted to electrical energy in a generator. Electrical efficiencies are typically at around 0.25 (based on LHV), with similar operational behavior as SE-based systems [12,13].

Fuel cell-based micro-CHP systems is the least mature technology, since a number of technical and economic issues must be resolved before its potential can be realized. Nevertheless, it is the most promising technology because it has the potential of achieving high electrical and overall efficiencies [2,5,12,14]. Startup times are rather slow for the SOFC type [15,16], while for PEMFCs are significantly faster. On the other hand, low-temperature PEMFCs (Nafion) have a very low heat-to-power ratio. They are also very sensitive when operated with reformate fuel, requiring extensive carbon monoxide reduction. A relatively new technology is HT-PEMFCs, which operate at temperatures at around 160 °C and they are relatively tolerant to carbon monoxide poisoning [5,17,18]. Fuel cell systems are able to respond to load changes rapidly, although a regular load changing operational pattern will deteriorate the fuel cell membrane, and therefore reduce its lifetime. Electrical efficiencies can reach 0.40 (based on LHV), while the overall efficiency is as high as the ICE and SE types at nominal load. In addition, the fuel cell electrical efficiency is significantly higher at part-load, because of the higher cell voltage at lower loads [17].

2.1. Market penetration projections

Micro-CHP technology has the potential to reduce transmission and distribution losses that typically occur when a large remotely located power station transmits electricity to a household [5]. This suggests that onsite produced and consumed electricity will have negligible losses, while imported/exported electricity will still have the usual losses. Therefore an effort should be made to choose an operational pattern which will minimize grid interaction. According to the Danish Energy Association [19], the fleet of central power plants in Denmark is relatively old, and the newest power plant was built in 2002. This fact in connection to the new initiative to promote the fuel cell-based micro-CHP technology in Denmark, where gas-fired boilers will be replaced with fuel cell-based micro-CHP systems, may change the residential heat-and-power consumption in the near future. The Danish micro-CHP project is explained in detail in [14].

One significant uncertainty in fuel cell-based micro-CHP technology is the type of system configuration and operating modes of micro-CHP systems, which must be efficient and also practical [20]. Although the capital cost of a micro-CHP system is greater than the one for a conventional domestic boiler, a micro-CHP system provides the opportunity to recover expenditure. This is because the import of electricity from the network grid is minimized, while surplus electricity can be exported [6]. In addition, residential micro-CHP systems can satisfy the heat-and-power demand more efficiently than conventional configurations and therefore decrease fuel consumption.

2.2. Operational strategies in the literature

A common practice is to operate the micro-CHP system during times of increased load demand, while the system is switched off during low demand. This practice is more common for heat engines (i.e. ICE, SE), because part-load efficiencies are very low, as explained above. On the other hand, daily on/off operation results in slower responses from the system (with associated losses), and also decreases the lifetime of the system [10,21]. Since a low heat-to-power ratio is available for fuel cell-based systems, the system can be operated continuously without any efficiency reduction, or the need to dump heat, provided a thermal energy system is coupled to the system. However, it should be noted that if the stack is continuously operated at a part-load below 25%, the higher selected nominal cell voltage does not necessarily mean higher operating efficiency. This is due to operation at very low current densities, where parasitic losses, including gas permeation through the polymer membrane, may not be negligible [22].

A number of operational strategies applied to micro-CHP systems are available in the literature. These are primarily simple strategies such as heat-led operation, where the system operates in accordance to the heating load demand. Similarly, an electricity-led operation operates in accordance to the electrical load demand. In 1991, an extensive investigation of energy consumption in single-family households in Denmark was performed. In this study the consumption data were measured as 15 min averages. The study included 25 different households. The consumption data included electricity, space heating and hot water consumptions for a whole year, yielding a total dataset of $3 \times 35{,}000$ points [6]. According to the Danish Energy Association [19], the average electricity consumption for a single-family household is 3960 kWh, while the consumption in 1991 was 4849 kWh. Although a safe and accurate comparison (based on the circumstances) cannot be made based on those two values, a decrease in electricity consumption is explained by the use of more efficient equipment and changes in household structures during recent years. Korsgaard et al. [6] applied the aforementioned load profile in a dynamic HT-PEMFC-based micro-CHP system using the average consumption of the 25 houses. The investigated operational scenarios were heat-led operation and combined heat-and-power operation with different thermal storage tank sizes.

The heat and power demand can be significantly different throughout the fluctuations of the consumption data. This is due to a number of reasons, such as the weather season (e.g., summer vs. winter vs. mid-season) or the time period (e.g., day vs. night, or weekday vs. weekend day). An averaged representation of the consumption data for an averaged single-family household in Denmark, including the electricity load and the total heating load, is shown in Figs. 1 and 2. By observation, the electrical demand is