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Constant Power Generation by Scheduling Installation of SOFC Modules Operating in Varying Power Mode

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ABSTRACT

In this paper, producing constant power load of 550 MW from systems of Solid Oxide Fuel Cells (SOFCs) operating in varying power output mode was investigated. This is useful because previous research has shown that individual cells can have significant lifetime extensions when operated according to certain dynamic trajectories in which power production decreases over time. In this study, we determined that a constant net power output of a system comprised of many individual SOFC modules can be achieved by scheduling the installation and operation of each SOFC module in a particular manner. All the modules were operated under the optimal operating conditions obtained in our previous optimization study where power output of each module declined over time. The dynamic degradation of SOFCs was taken into account by using a detailed mathematical model of long-term performance degradation as a function of operating conditions. The result is a system in which every 5 days, one new SOFC module is brought online, replacing one module near the end of its useable life at the same time. With this staggered approach, the overall power output of the system can be maintained at an almost constant level at all times (550 MW for our example). The new module then gradually reduces its power output over time according to an optimal trajectory. With this approach, the overall system can produce an essentially constant supply of power at lower costs than a traditional approach where all SOFC modules within a large system are each operated at constant power.

Keywords: SOFCs, performance degradation, optimal operating conditions, optimal operating mode, constant power output.

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INTRODUCTION

Solid Oxide Fuel Cells (SOFCs) are known for their high electrical efficiency and low environmental burdens, but they are yet to be commercialized in large-scale [1]. The degradation of these fuel cells is one main barrier for adoption [1]. SOFCs degrade due to a confluence of multiple phenomena which occur under normal operating conditions [2]. Several research studies focused on overcoming this issue by developing novel materials for different components of SOFC or by changing the structure [3–5]. But none of these new technologies had the required technical or economical feasibility for widespread commercialization. The focus of our research however is to overcome this barrier by understanding the degradation mechanisms through mathematical models and using them to determine operating strategies which reduce the rate of degradation.

In our prior study, we constructed a dynamic mathematical model of degradation by integrating six different models which each represent a different degradation reaction into thermodynamic models of overpotentials [6]. The developed model is capable of accurate prediction of long-term performance decline in SOFCs as a function of operating conditions, most importantly current density. This model allows investigators to extend the lifetime of SOFCs and operate them more economically by avoiding detrimental conditions that accelerate SOFC breakage. This can be easily achieved by adjusting the operating conditions and running SOFCs with an appropriate operating trajectory that involves slow and gradual changes over the course of its lifetime.

The findings of a techno-economic analysis (TEA) performed in our previous study using this model showed that conventional SOFCs can operate as long as 14 years economically if run at optimal operating conditions and with optimal dynamic trajectories [7]. The results also indicated that the optimal strategy for long-term operation of SOFCs is to gradually decrease the current density drawn from the fuel cells and let the power output drop over time. According to those findings, operating an SOFC in constant power mode (i.e. baseload power generation mode) is undesirable, because to achieve constant power one must continually increase the current density to compensate for degradation over time. This increasing current density in turn further accelerates the degradation of the fuel cells and thus should be avoided. Thus, even though constant power mode is often used in practice, the prior work shows that it is significantly more expensive than operating in a mode in which power gradually drops over time.

However, constant power output is nonetheless required for some applications and so gradually decaying power production is not useful or desirable. However, we can overcome this challenge by recognizing that some SOFC systems consist of many individual cells bundled into stacks, which are in turn bundled into modules, and the system itself can contain many modules. Thus, depending on the size of the system, modules, stacks, or even individual cells can be independently operated in varying power mode under optimal conditions, but the modules, stacks, or cells are installed gradually at different points of time such that the overall SOFC system delivers a constant amount of power.

DEMOSTRATION OF THIS WORK

For this study, we used the optimal sizes and operating trajectories obtained for SOFCs in varying power mode in our previous TEA study [7]. In other words, we assume that once an SOFC is started, its current density and power should follow a particular declining trajectory that has been predetermined by economic optimization as presented in the previous work (see Figure 1). One key parameter is the desired replacement schedule of the cell modules. The designer can choose the scheduled replacement time of a cell module (between 1 and 10 years in our study), and as long as the cell does not experience unexpected catastrophic failure, there will be some optimal way of operating that cell module within the desired lifetime.

As noted in the previous work, targeting shorter replacement times means it is optimal to use the cell more aggressively, drawing more power out of it but causing significant degradation such that the cell erodes quickly. Longer target replacement times (up to 14 years) are possible but it is optimal to operate much less aggressively and in a fashion which avoids decay. The previous work shows that longer lifetimes are more economical but the target replacement time in practice will depend on factors such as the risk of catastrophic failure, which the model cannot predict and may be unique to each specific manufacturer. Therefore, the target replacement time is taken as a parameter in this work, with two extremes considered for brevity (1 year and 10 year).

In the prior work, the SOFC systems were constrained to produce an average of 550 MW electrical power output during their lifetime, and the optimal size of SOFC active membrane area (A_m) for production of this power was found. The optimal cumulative power profile which minimizes levelized cost of electricity (LCOE) for a given target cell lifetime and has this average of 550 MW power produced is shown in Figure 1b. It is assumed that the fuel cells are identical, and each SOFC module contains multiple stacks of identical fuel cells. At the end of lifetime of the SOFCs (which all occur simultaneously), they are all replaced with identical fuel cells of the same size. This procedure is repeated during the 20 years life of the plant.

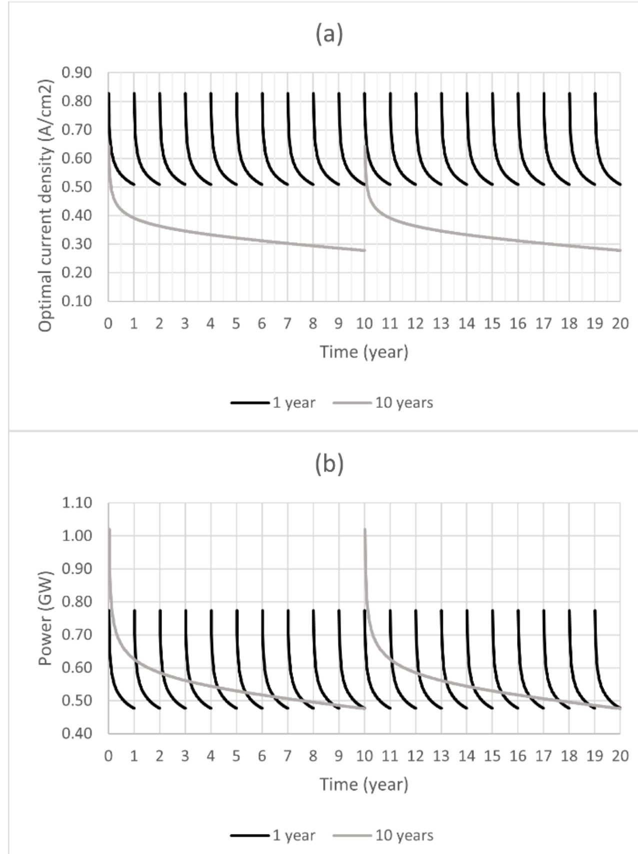

Figure 1. a) Optimal current density and b) power output of SOFCs with 1- and 10-year lifetimes during 20 years life of the plant [7].

In this study, instead of installing all the fuel cells at once, we install one module every 5-days. A module consists of a group of 1 or more stacks. It should be noted that all the modules have the same size and all individual SOFCs follow the same optimal trajectories found in our prior work (Figure 1) [7]. With this approach every 5 days a new module is brought online and at the same time a module that has reached end of its life is replaced. In this scheduled system, even though the SOFC modules in operation degrade and provide less power over time, the brand-new modules, brought online later, provide higher power, and compensate for the performance decline of the older modules. As a result, the system reaches steady state after a while and can provide constant power regardless of the performance drop of individual modules.

Figure 2 shows the net power output of staggered systems with individual SOFCs in varying power mode with 1- and 10-year lifetimes.

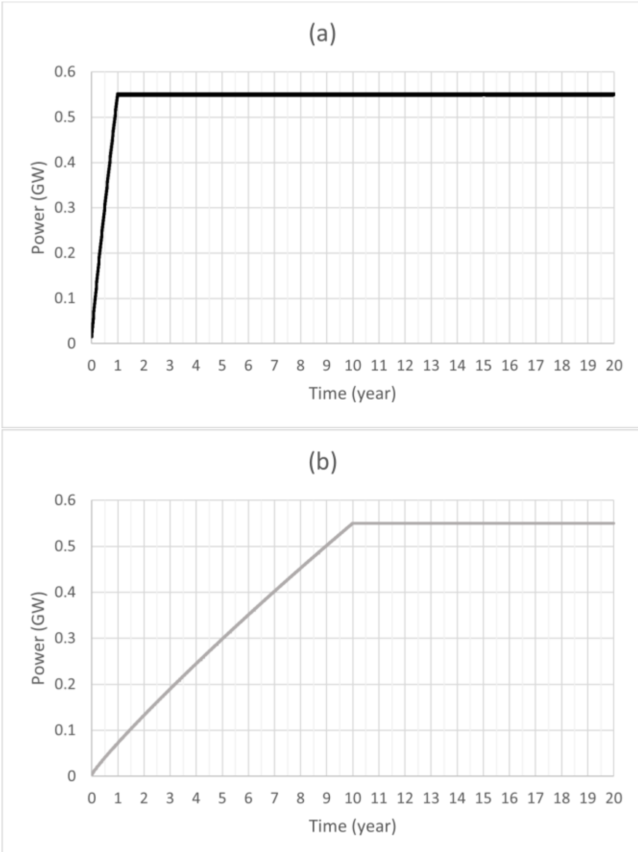

Figure 2. Net power output of systems in which modules are installed every 5 days and individual SOFCs are allowed to have variable power with a) 1- and b) 10-year lifetimes.

With this methodology, the system does not reach steady state instantaneously. Depending on the size of the modules and the optimal trajectories, different systems reach constant net power output at different times. For instance, with the given scheduling plan and optimal trajectories, the system of SOFCs with a 1-year replacement plan reaches almost constant power of 550 MW after 1 year of operation, while the system of SOFCs with a 10-year replacement plan provides nearly constant power of 550 MW after 10 years of operation.

This is a critical finding as it indicates that to get a constant net power from SOFC systems, individual SOFCs in the system should not necessarily be operated in baseload power generation mode. Instead, they can have variable power and constant net system power can be achieved by installing SOFC modules on a scheduled basis. The importance of the current methodology is in enabling constant net power generation with lower costs comparing to traditional baseload power generation mode. The characteristics and economics of systems in current methodology and traditional baseload power generation mode are shown in Table 1.

Table 1: Characteristics and economics of SOFC systems with constant power output. Project lifetime is 20 years.

	Individual SOFCs operated in varying power mode. (Modules are staggered every 5 days.)		**Individual SOFCs operated in baseload power mode. (All stacks are installed at once.)**	
Replacement Schedule:	**1 yr**	**10 yr**	**1 yr**	**10 yr**
Area of individual SOFC (cm²)	414	414	414	414
Average lifetime power produced by one SOFC (W)	123	85	106	79
SOFCs per stack	259	259	259	259
Average lifetime power produced by one stack (kW)	32	22	27	20
Total size needed (m²)	184,555	267,690	215,637	289,657
Total stacks needed	17,212	24,965	220,111	120,275
Stacks per module	236	34	N/A	N/A
Total lifetime average power (MW)	537.9	424.3	550	550
Steady state power (MW)	550	550	550	550
System power at beginning of replacement cycle (MW)	789	1014	550	550
System power at end of replacement cycle (MW)	477	476	550	550
Time to reach steady state	1 yr	10 yr	immediate	immediate
LCOE ($/kWh)	0.357	0.131	0.409	0.143

FUTURE STUDY

The major drawback of the current approach is that the net system power does not reach a constant load instantaneously. Future work can focus on generation of constant power throughout the entire life of the plant from an SOFC system in which individual SOFCs are allowed to have variable power. This can be achieved using either of the following methods: a) solving a separate problem to find optimal size, installation scheduling, and operation of stacks that should be used before systems shown in Figure 2 reach steady state, such that combination of the system and these additional stacks generate nearly constant load of 550 MW throughout 20 years life of the plant, b) solving a general optimization over 20 years of every individual stack/module to find optimal schedule and operation for each stack/module such that the system produces 550 MW at all times during plant's life. The latter problem may be intractable.

CONCLUSION

This research showed that by using stacking capability of SOFCs a net constant power load can be generated from a system of SOFC modules in which individual fuel cells follow an optimal declining trajectory. By bringing a new module online and replacing a module near end of its life every 5 days, the system can reach steady state and produce a constant power output. This is significant because it enables a steady power output while avoiding using fuel cells in traditional baseload power mode in which fuel cells degrade at high rates. As a result, this approach was shown to be more economical than constant load production by running all fuel cells in baseload power mode.

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