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The importance of control strategies in PV–hydrogen systems

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Abstract

The control strategy for a photovoltaic (PV) system with a hydrogen (H_2) subsystem consisting of an electrolyzer, pressurized hydrogen gas storage, and fuel cell has been investigated. Detailed computer simulation models for TRNSYS have been developed, tested, and verified against a reference system, namely the PHOEBUS plant in Jülich, Germany. The basic control strategy and main logical control variables for a PV–H_2 system are described. System performance indicators, parameters, and constraints that can be used to analyze the performance of PV–H_2 systems have been identified. The results from a time series simulation for a typical year are presented. Finally, the importance of selecting smart control strategies is demonstrated.

Keywords: Modeling; PV–hydrogen; Stand-alone power systems

1. Introduction

The seasonal storage of solar energy in the form of hydrogen (H_2) can provide the basis for a completely renewable energy system. One of the most promising applications is that of stationary stand-alone power systems, particularly those located in remote areas where the cost of transporting fuel is high. Photovoltaics (PV) in combination with electrolytically produced hydrogen, H_2-storage, and fuel cells, is a design that has been investigated in various demonstration systems around the world over the last decade (Schucan, 1999). However, due to the relatively new and emerging technologies associated with such systems, little is known about their design and operation. This was the starting point of a larger study undertaken by the author (Ulleberg, 1998). The material presented in this paper focuses on the importance of finding *smart* control strategies for stand-alone PV–H_2 systems.

2. System description

The reference system (Fig. 1) used in the system simulations presented here is the PHOEBUS demonstration plant at the Research Center in Jülich, Germany (Barthels et al., 1998). At the time of the study this system consisted of four differently oriented PV-arrays with maximum power point trackers (MPPTs), a pressurized advanced alkaline electrolyzer, hydrogen and oxygen storage pressure vessels, an alkaline fuel cell, power conditioning equipment (two DC/DC-converters and one DC/AC-inverter), and a lead acid battery bank.

The simulating platform used in this study was TRNSYS, which is a flexible simulation program that allows the user to integrate self-developed models (Klein et al., 1994). All of the simulation models presented here have been tested and verified against measured data from the reference plant (Ulleberg, 1997, 1998). Both operational data and data obtained from separate experiments on individual components were used. The models for the PV, electrolyzer, power conditioning equipment, and battery used in the simulations all reflect the actual components used in the reference plant. However, a model for a proton exchange membrane fuel cell (PEMFC) was used instead of an alkaline fuel cell

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Nomenclature

Symbols

γ	control function (1 = on, 0 = off)
AC, DC	alternating current, direct current
EL_{up}, EL_{low}	electrolyzer set points (related to battery SOC), %
FC_{up}, FC_{low}	fuel cell set points (related to battery SOC), %
H_2	hydrogen
I	electrical current, A
MPPT	maximum power point tracker
p_{H_2}	normalized H_2-storage pressure level, 0 . . . 1
PV	photovoltaics
SAPS	stand-alone power system (s)
SOC	state of charge (battery), 0 . . . 1

Subscripts

bat	battery
EL	electrolyzer
FC	fuel cell
ini	initial
low	lower
set	set point
up	upper

(AFC), because the AFC was not operational at the time of the study and a PEMFC was going to replace it in the near future (Meurer et al., 1999).

The simulation models are based on fundamental theory that covers a wide range of disciplines, such as physics, chemistry, electrochemistry, thermodynamics, and heat transfer. Thus, in order to reduce the complexity of the models (e.g., the transient behavior in batteries), empirical relationships were used to describe the most complex processes. However, great effort was used to derive meaningful empirical relationships (e.g., current–voltage characteristics for PV, electrolyzer, fuel cell, and battery) that require relatively few parameters. The accuracy of the models used to predict the behavior of the components and subsystems was high (∼2–3% error). The simulation models developed are flexible and could be used on different system designs. Incidentally, the basic models (source code) developed for this study has later become part of HYDROGEMS, a hydrogen energy models library now available for TRNSYS 15 users (Ulleberg and Glöckner, 2002).

The on/off-switching of the electrolyzer and fuel cell in a PV–H_2 system that uses a battery as a short-term energy buffer, can be based on the state of charge (SOC) of the battery. The basic control strategy implemented in this study is shown in Fig. 2. The three basic control

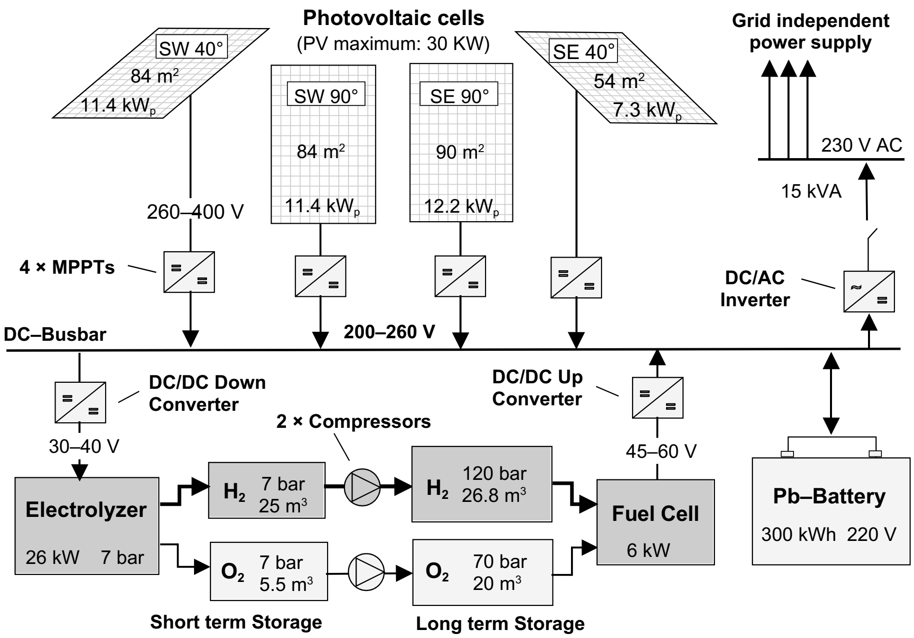

Fig. 1. Reference system.

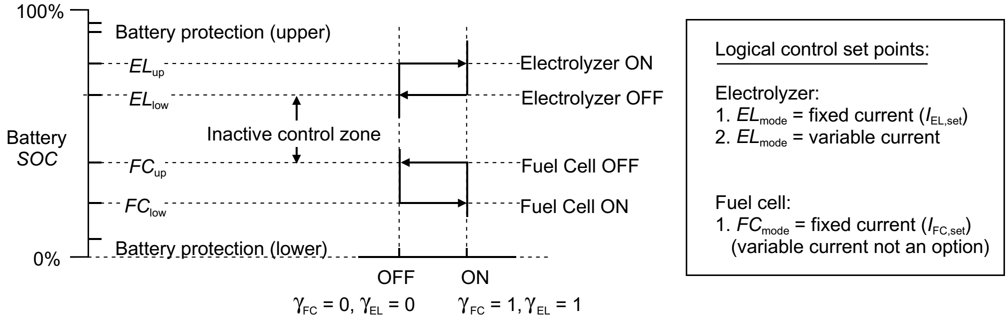

Fig. 2. Basic control scheme and key logical control set points.

parameters for the electrolyzer are EL_{up}, EL_{low} and γ_{EL} respectively, the upper and lower SOC thresholds and the control function for on/off-switching. Analogously, the basic control parameters for the fuel cell are FC_{up}, FC_{low} and γ_{FC} This is similar to the *five-step charge controller* adopted at the reference plant and tested in other stand-alone PV–H_2 systems (Galli et al., 1997).

One of the key system control parameters is the operational mode of the electrolyzer (EL_{mode}), which determines whether the electrolyzer is to operate in a fixed or variable current mode. In the constant current mode (EL_{mode} = fixed) the battery is charged during periods of excess current on the busbar and discharged during periods with deficit current. The battery SOC in this case will mainly depend on two uncontrollable variables, the solar radiation and user load, and one controllable variable, the fixed current (or power) setting of the electrolyzer.

In the variable current scenario (EL_{mode} = variable) only excess current available on the busbar is fed to the electrolyzer, hence the battery SOC remains constant. It is important to note that most alkaline electrolyzers, even advanced ones specifically designed to manage fluctuating input current, can only operate down to about 20% of their rated power, and an idling current needs to be maintained. In addition to the basic control and electrolyzer control parameters described in Fig. 2, there are several other important logical control parameters that need to be implemented into the control system. For instance, the controller must have several clock functions; one for seasonal settings and one for daily settings. The seasonal settings determine what day of the year the electrolyzer should be switched on after the winter, and off in the fall. Conversely, the fuel cell should be switched off and on the same dates. The basic control settings for the on/off-switching of the electrolyzer and fuel cell (Fig. 2) can also be made seasonally dependent. These and other logical control parameters have been investigated in detail (Ulleberg, 1998), but are not included here.

3. Results and discussion

The purpose of the simulations presented below is to illustrate that for a system with a fixed design, such as the reference system in Fig. 1, there exists a set of optimal control settings. In this case an optimal control strategy is defined as one that over the year best utilizes the existing hydrogen storage without violating any system component operating constraints. To find a true optimum it is necessary to perform a techno-economic optimization where the sizing of the individual system components depends on the control strategy, and vice versa. However, this requires accurate and meaningful cost functions, which are still hard to obtain. The coupling of cost functions to technical models was therefore not part of this particular study, but left as a recommendation for future work.

The focus of this study was instead to study *smart* (near optimal) operating schemes and to identify key system performance indicators that can be used in subsequent optimization studies. It turns out that it makes sense to use the final hydrogen energy storage pressure (i.e., the H_2-storage "state of charge") at the end of the year as a key performance indicator. That is, if this pressure is greater than the initial pressure the energy balance over the year is positive, indicating that a good control strategy was selected. Numerous simulations were run to find a set of optimal control settings. Table 1 summarizes the results discussed below.

The two main simulation inputs, hourly data for the solar radiation and user load, were produced from measurements at one-minute intervals taken at the reference plant in 1996. The user load was similar to that of an office building: maximum peak power was 15 kW; the daily average (working hours) was 4.5 kW in the winter and 3.6 kW in the summer; and the base load (non-working hours) was 1.8 kW. The auxiliary power for the electrolyzer, compressor, converters, inverter, and data acquisition and control system (~0.5 kW) was taken from the grid in order to ensure uninterrupted and stable operation of the demonstration plant. In the final

Table 1
Influence of alternative control strategies on system performance

Component/system		Units	Simulation					
			Electrolyzer variations			Fuel cell variations		
			A	B	C	D	E	F
Control set points:								
Electrolyzer	$I_{EL,set}$	A	Variable	***550***	Variable	Variable	Variable	Variable
	EL_{up}	%	90	90	***80***	90	90	90
	EL_{low}	%	80	80	***70***	80	80	80
Fuel cell	$I_{FC,set}$	A	250	250	250	***125***	***65***	***125***
	FC_{up}	%	55	55	55	55	55	***45***
	FC_{low}	%	45	45	45	45	45	***35***
Key performance indicators:								
H_2-storage	$p_{H_2,ini}$	0...1	0.45	0.45	0.45	**0.30**	0.30	0.30
	$p_{H_2,final}$	0...1	0.24	**0.11**	0.20	0.45	**0.57**	0.48
Performance parameters/constraints:								
Electrolyzer	Energy consumption	MW h	10.56	9.94	10.83	10.55	10.55	10.43
	Average power	kW	7.48	**21.01**	7.37	7.54	7.51	7.45
	Number of starts	–	156	**273**	162	152	152	160
	Average run time	h	9.0	**1.7**	9.1	9.2	9.2	8.8
	H_2 production	Nm^3	2719	2473	2788	2719	2716	2687
Fuel cell	Energy production	MW h	3.39	3.40	3.58	3.37	3.29	3.16
	Average power	kW	6.04	6.04	6.04	4.45	**2.59**	4.45
	Number of starts	–	61	61	64	50	**27**	44
	Average run time	h	9.2	9.2	9.3	15.2	**47.0**	16.1
	H_2 consumption	Nm^3	3366	3378	3558	2274	**1904**	2127
Battery	Energy, discharging	MW h	9.74	**15.09**	9.54	9.65	9.29	9.71
	Energy, charging	MW h	8.90	**13.68**	8.85	8.82	8.47	8.90
	SOC dist. = 0...40	%	0	0	0	0	3	**9**
	40...60	%	24	25	28	25	21	21
	60...80	%	21	25	**66**	21	22	19
	80...100	%	55	50	**6**	54	54	51

Italics = change in set point.
Bold = major effect due to change in set point.

design of a stand-alone power system the auxiliary power demand will have to be significantly reduced. This can potentially be achieved by coupling the PV-panels directly to the busbar, increasing the electrolyzer operating pressure (reduces the compressor work), and/or by using more efficient power conditioning equipment.

In order to resemble the performance of the reference system as closely as possible, several assumptions and simplifications were made in the system simulations. The oxygen gas system, for instance, was not simulated, nor were all of the hydrogen losses (e.g. losses during start-up/shutdown of electrolyzer/fuel cell) and parasitic loads (e.g. compressors and pumps). It should be noted that the simulation models developed are designed so that these factors could quite easily have been included.

3.1. Typical simulation

In order to better understand how to interpret the simulations, a few illustrative plots for a typical week (Fig. 3) and year (Fig. 4) are presented first. A summary of the results from the example simulation discussed here is given in Table 1, *Sim A*. Fig. 3(a) shows the solar radiation (given by the MPPT power) and user profiles for a typical week. In general, the load for the reference system was lower during nighttime than daytime, while it remained constant during the weekend. Furthermore, the load profile had a small peak in the morning, before it settled at a more constant level later in the day. The solar radiation during the sample week varied from medium high (Monday), to low (Tuesday–Thursday), and back to high (Friday–Sunday). Fig. 3(b) shows the

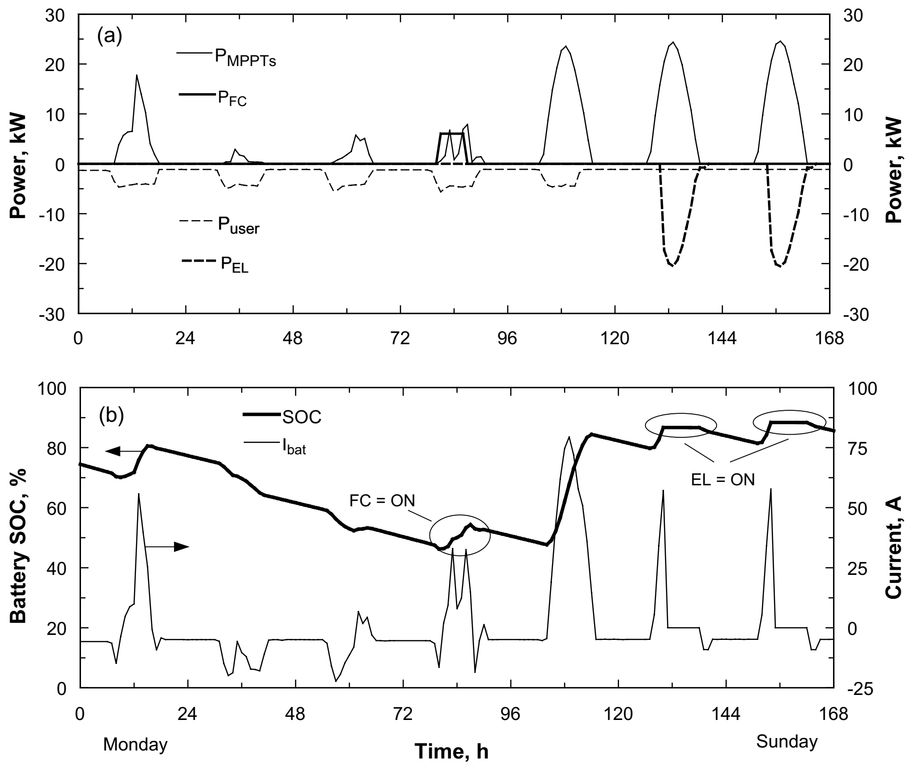

Fig. 3. Typical week. (a) Power from MPPTs and fuel cell (positive values) and power to user load (inverter) and electrolyzer. (b) Battery state of charge and net current (positive values = charging).

resulting battery charging/discharging current and SOC. The corresponding on/off-switching of the fuel cell and electrolyzer is shown in Fig. 3(a). During the period with low solar radiation the battery SOC dropped below 45% (FC_{low}), and the fuel cell was switched on. About 8 h later (Thursday afternoon) the SOC was greater than 55% (FC_{up}), and the fuel cell was switched off. When the SOC reached 90% (EL_{up}) (Saturday morning), the electrolyzer was switched on in the variable current mode, and the SOC remained constant until it was switched off.

An annual view of the MPPT power and the on/off-switching of the fuel cell and electrolyzer is shown in Fig. 4(a), while the resulting H_2-storage pressure level and battery SOC is shown in Fig. 4(b). The electrolyzer had 156 startups versus 61 for the fuel cell. Another interesting point is that the fuel cell only needed to be switched on four times during the summer. The fuel cell operating power was fixed at 6 kW, while the electrolyzer operated in the range 0.8–21.7 kW, at an average of 7.5 kW. The average electrolyzer run time per startup was 9 h. In other words, once switched on, it remained switched on for several hours. This was a direct result of the fact that the electrolyzer was operated in the variable current mode. Fig. 4(b) also shows that the battery SOC was at a higher level during the summer than during the winter. On a few occasions the SOC rose above 100%, and energy needed to be dumped. This situation occurred only when the electrolyzer was switched off for the season. The SOC operating range was 44–100%, but most of the time (55%) the SOC was high (80–100%).

The fluctuations in the H_2-storage pressure (Fig. 4(b)) reflect the hydrogen production by the electrolyzer and the hydrogen consumption by the fuel cell. The hydrogen produced is first fed to the short-term H_2-storage (buffer) before it is compressed and fed into the long-term H_2-storage (Fig. 1). The pressure in the H_2-buffer varied from 3 to 5 bar. The purpose of the H_2-storage is to use it as a seasonal energy storage, where hydrogen is produced during summer and consumed during winter. The pressure in the H_2-storage in the simulation presented here (Fig. 4(b)) varied from 7 to 114 bar, thus the utilization of the capacity (120 bar) was quite good.

3.2. Alternative control strategies

In a system with a fixed design, user load, and solar radiation input, the only way to affect the hydrogen energy balance over the year is by adjusting the control strategy. A key system performance indicator is the final

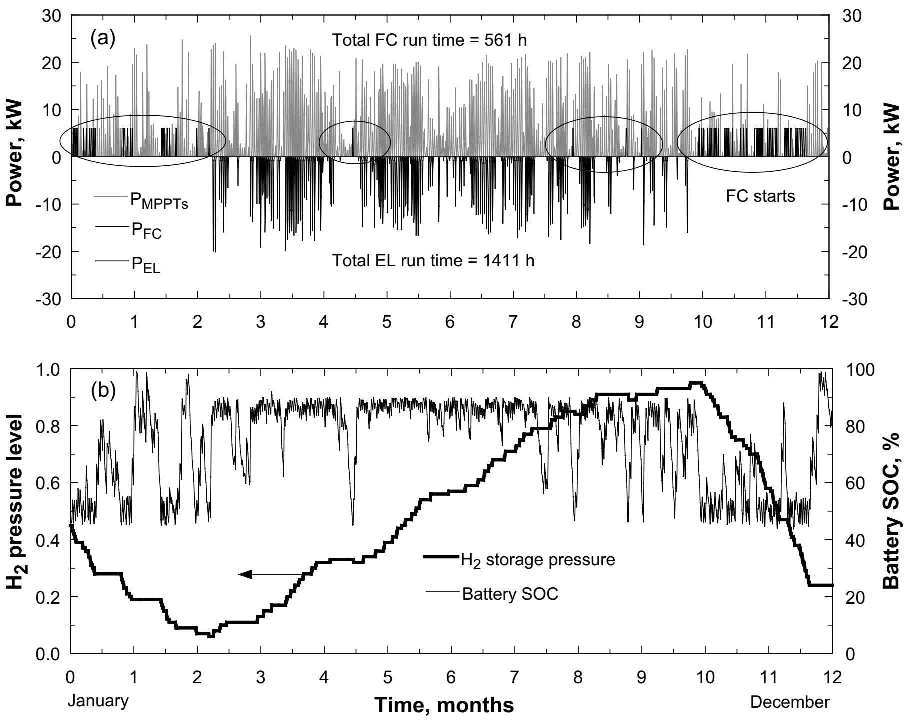

Fig. 4. Typical year. (a) Power from MPPTs (grey plot), fuel cell (positive values), and electrolyzer. (b) H_2-storage pressure level (normalized with respect to maximum pressure) and battery SOC.

pressure in the H_2-storage at the end of the year $p_{H_2,final}$ which needs to be compared to the initial pressure $p_{H_2,ini}$. If $p_{H_2,final} > p_{H_2,ini}$ and no system constraints have been violated, a good control strategy has been selected. The importance of selecting *smart* control strategies can be illustrated by showing the results from simulations where a few of the system control parameters and set points are altered. The interpretation of the simulation results can get quite involved, especially when a large number of alternative control strategies are to be evaluated. Thus, to simplify, only a few system controls variations are discussed here. The results are given in Table 1.

Electrolyzer mode of operation (*fixed or variable*): The benefit of operating the electrolyzer in a variable current mode rather than at a fixed current is illustrated by comparing *Sim A* to *Sim B*. In *Sim B*, where $I_{EL,set} = 550$ A (~21 kW), the electrolyzer on/off-switching is much more frequent than in *Sim A*. This is also reflected in the low average run time. The net result is less hydrogen production, yielding a lower final pressure level in the H_2-storage at the end of the year. In *Sim A*, on the other hand, a large fraction of the energy from the PV-arrays was used directly to run the electrolyzer. As a consequence the use of the battery was minimized. A comparison between *Sim A* and *Sim B* shows that the battery discharging energy increased by about 50%. Other fixed current set points have been investigated (Ulleberg, 1998) and the trend is the same: variable electrolyzer operation mode gives a better system performance than fixed current mode.

Basic control strategy for electrolyzer: The influence of reducing the upper and lower thresholds for the on/off-switching of the electrolyzer can be seen by comparing *Sim A* to *Sim C*. In *Sim C*, where both EL_{up} and EL_{low} have been lowered by 10% compared to *Sim A*, the main effect was that the battery operated much more frequently at medium high SOC (60–80%), and less at high SOC levels. Hence, the higher threshold settings used in *Sim A* gives a better utilization of the installed battery capacity. In general, there is a trade off between battery capacity utilization on one hand, and the need to dump energy (at SOC > 100%) on the other. This needs to be incorporated into the control strategy.

Fuel cell fixed current set point: The effect of reducing fixed current set points for the fuel cell can be seen by comparing *Sim D* or *Sim E* to *Sim A*. In *Sim D*, where $I_{FC,set} = 125$ A (~4.5 kW), the system performance increased dramatically. In fact, the hydrogen energy balance over the year went from a deficit to a surplus. However, *Sim E* demonstrates what happens if a too low fuel cell current set point $I_{FC,set} = 65$ A (~2.6 kW) is chosen. Even though the final pressure $p_{H_2,final} = 0.57$, indicating a significant increase in system performance, the average fuel cell run time increased to about 2 days. Depending on the basic control strategy selected, this may cause battery damage. In *Sim E* the battery was operating at very low SOC (0–40%) about 3% of the time.

Basic control strategy for fuel cell: The influence of reducing the upper and lower thresholds for the on/off-switching of the fuel cell can be seen by comparing *Sim F* to *Sim D*. In *Sim F* both FC_{up} and FC_{low} were lowered by 10% compared to *Sim D*. The result was operation at very low SOC levels (0–40%) about 9% of the time. Depending on the type of battery, this may cause excessive battery wear and should probably be avoided.

4. Conclusions and recommendations

This study demonstrates that the performance of a PV–H_2 system can be significantly affected by relatively small changes made in the control strategy. The study also shows how pressure in the hydrogen storage can be used as a key system performance indicator, provided no operating constraints are violated. Based on the results from numerous simulations of the PV–H_2 reference system (only the most illustrative simulations were presented in this paper), the following general recommendations can be made:

- The electrolyzer should operate in a variable power mode, rather than in a fixed power mode.
- The set point for switching on the electrolyzer should be as high as possible (depending on constraints).
- The fuel cell should operate at the lowest power possible power level (depending on constraints).
- The set point for switching off the fuel cell should be as low as possible (depending on constraints).

In order to get a complete view of the overall system performance, and to differentiate between alternative control strategies, it is necessary to avoid operating schemes that are likely to reduce the lifetime (due to degradation) of the various electrochemical components (electrolyzer, fuel cell, and battery). Hence, other system performance parameters, such as the number of starts and stops for the electrolyzer and fuel cell and battery state of charge levels, must also be considered. Degradation effects could be built into the technical models, but this would require more detailed models than the ones developed. In any case, this study does indicate the importance of introducing logical operational constraints, such as minimum allowable run times, or maximum number of start-ups.

To find a true optimal solution it is necessary to perform a combined techno-economic optimization that takes into account both system design (sizing of components) and the control strategy, even though this requires accurate and meaningful cost functions. Hence, future work will be to develop a simulation program that automatically finds the optimal control set points for a fixed system. The next goal is to develop a simulation program that simultaneously optimizes the control strategy and system design based on a cost function that includes both investment and operational costs.

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