INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 17 Control of Energy Conversion and Storage

CHAPTER 12

A Solar Hydrogen Simulator for Safety Interlocks and the Question of Keeping the Oxygen

Pages 300–322

Edited by John D. Hedengren

How to cite this chapter. "A Solar Hydrogen Simulator for Safety Interlocks and the Question of Keeping the Oxygen," in *Control of Energy Conversion and Storage*, John D. Hedengren, Ed., vol. 17 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 12, pp. 300–322.

The page numbers in this file are those of the printed volume.

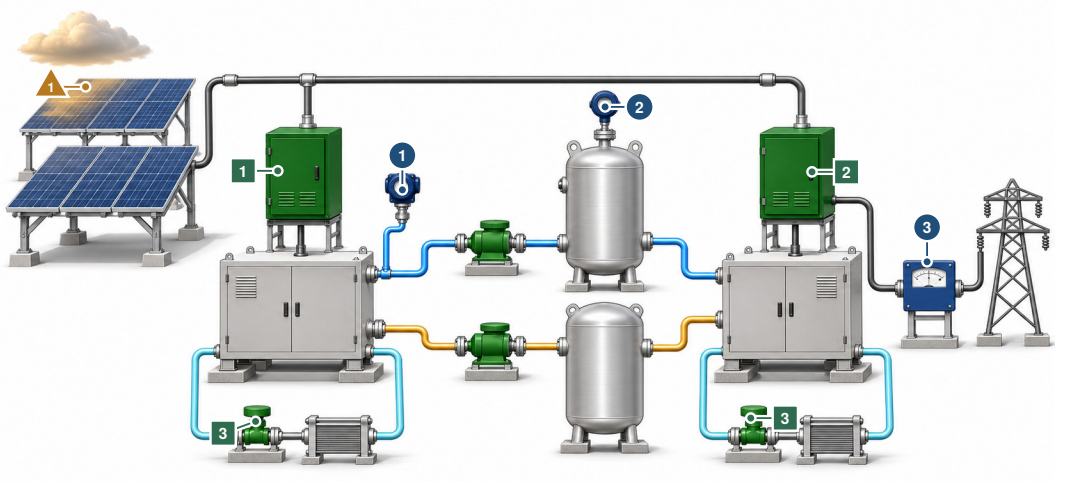
The app for this chapter
https://apmonitor.com/apps/solar-hydrogen/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v17-energy/#solar-hydrogen

Copyright © 2026 Advanced Process Solutions, LLC. All rights reserved. Produced by Advanced Process Solutions, LLC.

CHAPTER 12

A Solar Hydrogen Simulator for Safety Interlocks and the Question of Keeping the Oxygen



The controller moves 1 electrolyzer current (rectifier) 2 fuel cell current (converter) 3 cooling of each stack

The controller reads 1 analyzer for oxygen in the hydrogen 2 hydrogen store pressure 3 power delivered to the grid

What disturbs it 1 clouds over the array

Spare solar power splits water, and the hydrogen and oxygen travel on separate lines to separate tanks and meet again only inside the fuel cell. Illustration, not to scale.

IN PLAIN TERMS Saving Spare Sunshine as Hydrogen

The main idea. At midday a big solar farm makes more power than its line to the grid can carry. The spare power splits water into hydrogen and oxygen, which are stored. In the evening a fuel cell joins the two gases again to make power.

The challenge. The two gases must never mix, so safety checks, not prices, decide when the plant runs. A small leak between them can stay hidden for hours, until the fading sun makes less gas.

Why it matters. Only about a third of the power comes back, so control must waste no spare sunshine and must stop the plant before the gases meet.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the fact box of the Introduction, the two history boxes of Section 12.2, the try-it box of Section 12.5, the fact and try-it boxes of Section 12.7, and the key points
Study	40 min	The whole chapter with its pause points and the twelve exercises
Practice	10 min	The first page, Section 12.7, Section 12.8, Section 12.9 and the open challenge

The control question A solar hydrogen plant returns about a third of the electricity it takes in, and no controller changes that. What does control decide on such a plant, why must interlocks choose the mode while economics only choose setpoints inside it, and is the oxygen worth keeping?

Learning objectives

- Explain why the oxygen in the hydrogen product rises as the electrolyzer is turned down, and why a stack has a minimum load.
- Trace the supervisory machine through a trip, a start and a cloud, and name the role of each interlock, latch, dwell and hysteresis band.
- Decompose the advantage of stored oxygen into cell voltage and blower load, and weigh it against the compression it costs.
- Compare solar following, firm and economic dispatch on a net margin that prices hydrogen inventory and starts.
- Read a membrane fault from an analyzer whose reading depends on the load.

Prerequisites Sections 1.4.4 (inventories), 1.4.6 (water value), 1.4.7 (fast and slow layers), 1.6.2 (velocity form) and 1.6.4 (scenarios and CSV).

The app https://apmonitor.com/apps/solar-hydrogen/

See also Volume 8, Chapter 2 for interlocks as the safety layer beneath the feed, Volume 8, Chapter 13 for a supervisor that diverts and latches, and Volume 8, Chapter 14 for start-stop flapping. Volume 4, Chapter 6 for a limit set by an explosive mixture and Volume 4, Chapter 2 for a protective override.

12.1 Introduction

A water electrolyzer produces two gases in a fixed stoichiometric ratio and almost every commercial installation vents the oxygen. That is not an oversight and it is not obviously right either. Keeping the oxygen costs a second compressor, a second pressure vessel and a second set of safety rules that are not the ones hydrogen needs. It buys about 46 mV per cell at the fuel cell cathode from the Nernst term, the kinetics and the relieved concentration overpotential, and it removes the cathode air blower entirely. Measured on this plant at the rated point the two together are worth 14.3 % of the electricity returned per kilogram of hydrogen, of which 6.0 % is cell voltage and the rest is the blower that disappears. Whether that pays depends on how many hours the fuel cell runs, which makes it a dispatch question rather than a design one.

> **DID YOU KNOW? Ten Million Tonnes a Year**
>
> About 10 million metric tons of hydrogen are produced in the United States each year, mostly from natural gas, for petroleum refining, ammonia and other industrial uses [1]. Electrolyzers that split water with electricity were available in 2020 at the multi-megawatt scale [1].

The misconception this chapter corrects is that a hydrogen plant is an efficiency problem. A round trip of about a third is not going to be improved by control, and a student who spends an afternoon tuning the rectifier loops has learned nothing that matters. What control decides on this plant is narrower and more consequential. It decides whether the conversions that do happen are wasted, which means not curtailing array output the stack could have absorbed, not running the electrolyzer below the current at which crossover takes the product out of specification, not restarting a stack through every passing cloud, and not tripping.

The class of problem is supervisory sequencing under hard safety constraints with an economic layer subordinated to it. Everything dangerous about a hydrogen plant is a mixture, and every interlock in it exists to keep two streams that must never meet on opposite sides of a wall. A batch reactor with a runaway exotherm (Volume 8, Chapter 2), a furnace with a purge sequence, a compressor with an anti-surge lineup (Volume 4, Chapter 2) and an air separation unit all have the same shape.

The formal statement is that the mode is a finite state whose transitions are determined by interlocks alone, and the economics may only choose setpoints inside the mode that is currently legal. Economic model predictive control has a well-developed theory for the setpoint layer [2], and none of it licenses an optimizer to choose a valve lineup.

The chapter answers the oxygen question for one plant and splits the answer into its cell-voltage and balance-of-plant parts. A measurement then shows that the advantage in electricity per kilogram does not by itself decide the case. The simulator behind the answer carries a fifteen-state model of the two gases, a seven-state supervisory machine and a schedule solved by bisection, and it runs at interactive speed in a browser. One of its scenarios is a purity excursion whose fault and whose alarm are four and a half hours apart.

The chapter gives the model, the control structure and the measured behavior in enough detail that a reader can rebuild the simulator, and it uses them to show why the mode must be chosen by interlocks and the setpoint by economics and never the other way round. Section 12.2 traces the domain from the first wind hydrogen demonstrations. Section 12.3 gives the model of the array, the two stacks, the crossover, the stores and the water loop. Section 12.4 describes the open-loop character, and Section 12.5 the four regulatory loops and the minimum current. Section 12.6 gives the supervisory machine and the economic schedule, and Section 12.7 reports the scenarios: the oxygen decision in operation, the membrane fault, three architectures on three cloudy days and the graded challenge. Section 12.8 sets the real instruments, final elements and controllers beside the model, Section 12.9 states the limitations and Section 12.10 the conclusions, and the exercises follow.

12.2 From Utsira to a Firm Evening

Renewable hydrogen systems were demonstrated long before they were economic. The system simulation approach that most later work builds on was developed for advanced alkaline electrolyzers and published as a set of empirical current voltage and Faraday efficiency relations fitted to operating data [3]. That model was then used to design and evaluate the wind hydrogen demonstration on the island of Utsira in Norway, which supplied ten households from a wind turbine, an electrolyzer, a 2400 bar m^3 hydrogen store and a fuel cell, and whose published evaluation is unusually candid about what did not work [4]. The recurring finding from those projects is that availability and part-load behavior, rather than stack efficiency, set the usefulness of the system.

Proton exchange membrane electrolysis changed the operating envelope rather than the efficiency. A PEM stack follows a varying input in seconds where an alkaline stack takes minutes, tolerates differential pressure across the membrane, and delivers hydrogen at tens of bar without a first compression stage. The comprehensive review of the technology collects the cell voltage breakdown, the materials and the cost structure [5], and detailed electrical models of commercial units are available for the alkaline comparison [6].

What PEM does not remove is crossover. Hydrogen and oxygen both permeate the membrane, the flux is set by the partial pressure difference and the membrane rather than by the current, and the consequence is the single most important operating constraint on the technology. As a fraction of the gas being made the crossover climbs as the stack is turned down, so a stack idling at a few percent of rating is the dangerous place on the operating curve rather than the safe one. The pressurized case was measured and modeled directly, and the study that did so is the reason a modern electrolyzer specification quotes a minimum load rather than a turndown ratio [7].

The fuel cell side has its own control literature, developed largely for automotive stacks, whose central problem is oxygen starvation during a load transient and whose standard treatment is a modeling and feedback design text that remains the reference [8, 9]. A plant that stores its own oxygen removes that problem and replaces it with an inventory problem. The unitised regenerative concept, in which one stack does both jobs on a bifunctional electrode, has been pursued for decades and remains a materials problem rather than a control one [10], which is why the plant modeled here has two separate stacks.

HISTORY **Fuel Cells on Pure Oxygen in Space (1960s)**

Fuel cells first went to work on pure hydrogen and pure oxygen. A 1 kW polymer electrolyte fuel cell flew in the Gemini program and a 1.5 kW alkaline unit in the Apollo program, both in the 1960s, and these space units used pure reactant gases [11]. The Gemini stack had 32 cells, typically ran at 50 °C and 2 atmospheres, and gave 0.78 V at 37 mA/cm^2. Decades later a laboratory cell on pressurized hydrogen and air gave the same 0.78 V at about 200 mA/cm^2 and 80 °C [11]. A plant that stores its own oxygen feeds its fuel cell the way the spacecraft did.

The dispatch question arrived with the grid. Electrolyzer operation scheduling is now an active subject with a review of its own [12], and the system studies that size long-duration storage put hydrogen in the hundred-hour role rather than the four-hour one [13]. The plant modeled here sits between those two literatures, with a connection limit that makes curtailment the default and a firm evening commitment that makes the inventory matter.

HISTORY **Electrolyzers Tested as Grid Loads (2009 to 2014)**

A wind-to-hydrogen pilot project in North Dakota, reported in 2009, explored how an electrolyzer could soften the swings of wind output and the limits of the transmission lines, while it made hydrogen for two trucks and a tractor [14]. Its electrolyzer answered load changes in 3 to 7 s, and its maker recommended a minimum load of 43 % of rated power. Laboratory tests reported in 2014 found that electrolyzers of about 40 kW begin to change their demand within milliseconds of a new setpoint and settle within seconds, while a cold start of a PEM unit to full power took 6 minutes and 27 seconds [14]. The plant of this chapter has all three features: a connection limit, a minimum load and a start that costs time.

12.3 Process Model

The simulated plant is a 100 MW photovoltaic array on a 40 MW grid connection, an electrolyzer of 12 700 cells of 1000 cm^2 rated at 2.0 A/cm^2, a fuel cell of 29 000 cells rated at 1.2 A/cm^2, 1540 m^3 of hydrogen storage and 770 m^3 of oxygen storage at 200 bar. At the rated point the electrolyzer draws 49.8 MW and makes 941 kg/h, which is 52.9 kWh/kg. The fuel cell returns 21.5 kWh/kg on stored oxygen. Figure 12.1 shows the arrangement and every symbol used below. The clock is in hours, power in megawatts, mass in kilograms, pressure in bar and temperature in degrees Celsius except inside the Nernst and Arrhenius expressions, where it is in kelvin.

12.3.1 Variables

Table 12.1 classifies what the application exposes. The oxygen mode is an option rather than a continuous manipulated variable, and it is the decision the plant is built around.

12.3.2 The Array

Plane-of-array irradiance is a sine on the solar day raised to a power, and the array output carries the cell temperature derate that makes a clear noon in July worth less than a clear noon in April,

$$G = \sigma G_{max} \sin^{1.25}\left(\pi \frac{h - h_{up}}{h_{dn} - h_{up}}\right) \tag{12.1}$$

$$\begin{aligned} T_{cell} &= T_{amb} + \frac{G}{800}(T_{noct} - 20) \\ P_{pv} &= \frac{P_{pv,0} G}{1000}\left[1 - \beta (T_{cell} - 25)\right] \end{aligned} \tag{12.2}$$

With the defaults the array peaks at 89.3 MW at 12:48 on a 40 MW connection, so almost 50 MW of midday output has nowhere to go except the electrolyzer. Price is a gaussian evening peak on a base with a midday depression, running from −14.0 dollars per megawatt-hour at 12:30 to 227.9 at 19:30. The firm commitment is 18 MW from 17:00 to 23:00, which is 108 MWh.

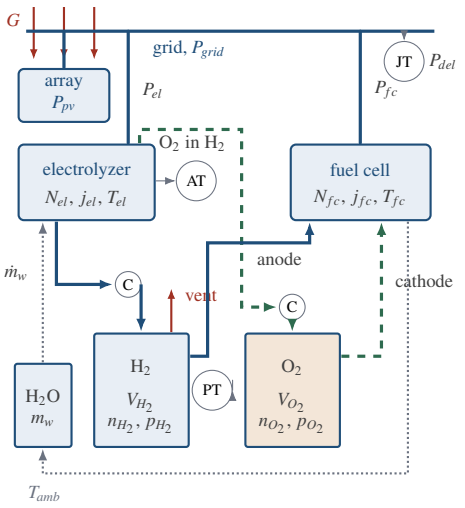


Figure 12.1 Plant arrangement and the symbols used in the equations. The array feeds the grid connection and the electrolyzer, and the part of the array output that exceeds the connection limit is what the electrolyzer is there to absorb. Both product gases pass through their own compressor into their own vessel, and the fuel cell draws hydrogen from one and either stored oxygen or air at the cathode. AT is the analyzer that measures oxygen in the hydrogen product, PT the hydrogen storage pressure, and JT the delivered power that the fuel cell loop controls. The water loop is nearly closed and the difference is purchased and deionized. Hydrogen streams are solid arrows, oxygen streams dashed arrows and water dotted arrows. The thick lines without arrowheads are the electrical connections.

12.3.3 The Electrolyzer

The cell voltage is the reversible potential plus an activation and an ohmic term. No concentration term appears because a PEM electrolyzer fed liquid water does not run out of reactant,

$$E_{rev} = E^0 - 9\times10^{-4}(T_k - 298.15) + \frac{RT_k}{2F}\ln\left(p_{H_2}\sqrt{p_{O_2}}\right) \tag{12.3}$$

$$V_{el} = E_{rev} + \frac{RT_k}{\alpha 2F}\operatorname{asinh}\frac{j}{2j_{0,el}} + R_{\Omega,el}\,j \tag{12.4}$$

$$R_{\Omega,el} = \frac{\mathrm{ASR}_{el}\,\omega_{el}}{\lambda}\exp\left[1600\left(\frac{1}{T_k} - \frac{1}{333.15}\right)\right]. \tag{12.5}$$

The hydration factor λ divides the resistance, so a dry membrane is a resistive one. At the rated 2.0 A/cm^2 and 62 °C the cell sits at 1.9612 V, made up of 1.2694 V reversible, 0.3809 V activation and 0.3110 V ohmic, and the stack draws 49.82 MW for 941 kg/h.

Production and heat follow from Faraday's law and the thermoneutral voltage,

$$\begin{aligned}\dot{n}_{H_2} &= \frac{\eta_F N_{el}\,jA_{el}}{2F}\\ \dot{Q}_{el} &= \frac{N_{el}(V_{el} - V_{tn})\,jA_{el}}{10^6}, \quad V_{tn} = 1.481\,\mathrm{V}\end{aligned} \tag{12.6}$$

Everything above the thermoneutral voltage is heat and everything below it is heat the stack has to be given, which is why a cold stack needs a heater and not a cooler. Temperature matters economically as well as thermally. At 30 °C the same rated current costs 58.0 kWh/kg against 52.9 kWh/kg at 62 °C, a difference of 9.6 % that the control system can do nothing about until the stack has warmed.

Table 12.1 Variable classification

Symbol	Meaning	Unit	Range
Controlled variables			
P_{del}	delivered power	MW	−40 to 40
P_{el}	electrolyzer load	MW	0 to 50
T_{el}	electrolyzer temperature	°C	40 to 80
T_{fc}	fuel cell temperature	°C	40 to 80
Manipulated variables			
j_{el}	electrolyzer current density	A/cm^2	0 to 2.7
j_{fc}	fuel cell current density	A/cm^2	0 to 1.8
u_{el}	electrolyzer cooling duty	%	0 to 100
u_{fc}	fuel cell cooling duty	%	0 to 100
χ_{O_2}	oxygen mode (store, reserve, vent)	—	—
Disturbances			
σ_∞	sky clarity	× clear	0.05 to 1.05
T_{amb}	ambient temperature	°C	−5 to 48
γ	membrane crossover multiplier	×	0.5 to 15
ω_{el}, ω_{fc}	stack wear multipliers	×	0.9 to 2.5
ε_{fc}	forecast error scale	×	0 to 1.5
States			
n_{H_2}	hydrogen in store	mol	to 200 bar
n_{O_2}	oxygen in store	mol	to 200 bar
T_{H_2}, T_{O_2}	vessel temperatures	°C	−40 to 120
T_{el}, T_{fc}	stack temperatures	°C	−10 to 110
λ	membrane hydration	—	0.2 to 1.15
m_w	deionized water inventory	kg	0 to 90 000
j^a_{el}, j^a_{fc}	applied current densities	A/cm^2	—
u^a_{el}, u^a_{fc}	applied cooling duties	—	0 to 1
c	oxygen in hydrogen	ppm	0 to 50 000
σ	filtered sky clarity	—	0 to 1.05
ϕ^a	applied compressor duty	—	0 to 1

12.3.4 Crossover and the Minimum Load

Oxygen permeates the membrane at a rate set by the pressure difference and the membrane rather than by the current, so as a fraction of the hydrogen being made it climbs as the stack is turned down [7],

$$c^* = \begin{cases} c_0\,\gamma\,\dfrac{j_{el,R}}{\max(j^a_{el},\,0.06\,j_{el,R})} & j^a_{el} > 0.01 \\ 0.35\,c_0 & \text{otherwise,} \end{cases} \tag{12.7}$$

with the analyzer and mixing volume as a first-order lag, $\tau_c\,\dot{c} = c^* - c$. The second branch matters as much as the first. With the stack stopped there is no gas being made and nothing to contaminate, so the analyzer reads down toward the header background rather than off the top of its scale, which is the difference between a plant that is idle and a plant that is about to be tripped. The reciprocal in the first branch is the whole reason a modern electrolyzer specification quotes a minimum load rather than a turndown ratio.

12.3.5 The Fuel Cell and the Oxygen

The fuel cell polarization carries the same reversible, activation and ohmic terms plus a concentration term, the four terms of the solid oxide stack in Chapter 3, and the oxygen mode changes three things

Table 12.2 Fuel cell at rated current and 66 °C on stored oxygen and on air

Quantity	Stored O_2	Air	Difference
Cell voltage (V)	0.8100	0.7639	+0.0461
reversible (V)	1.2182	1.2018	+0.0164
concentration (V)	0.0049	0.0146	+0.0097
flat kinetic term (V)	0.0200	0	+0.0200
Gross power (MW)	28.19	26.58	
Air blower (MW)	0	1.914	
Net power (MW)	28.19	24.67	
Net electricity (kWh/kg)	21.54	18.85	+14.3 %

at once,

$$p_a = \min(p_{H_2}, p_e), \quad p_c = \begin{cases} \min(p_{O_2}, p_e) & \text{stored } O_2 \\ 0.21 \min(1.5, p_e) & \text{air} \end{cases} \tag{12.8}$$

$$V_{fc} = E_{rev} - \eta_{act} - \eta_{ohm} - \eta_{conc} + \Delta V_{O_2} \mathbb{1}[\text{on } O_2] \tag{12.9}$$

$$\eta_{conc} = -\frac{RT_k}{2F} \ln\left(1 - \frac{j}{j_\ell}\right), \quad j_\ell = \begin{cases} 4.2\,\text{A/cm}^2 & \text{on } O_2 \\ j_{\ell,air} & \text{on air} \end{cases} \tag{12.10}$$

The electrode pressure clamp in Equation (12.8) is the detail that keeps the answer honest. A regulator drops both gases to a few bar before they reach the stack, so the Nernst benefit of stored oxygen is a couple of tens of millivolts and not the hundred a reader obtains by putting 200 bar into the logarithm. The cathode air blower is the third effect,

$$P_{blow} = \begin{cases} 0 & \text{on stored oxygen} \\ f_{blow} P_{gross} & \text{on air} \end{cases} \tag{12.11}$$

and it is the largest of the three. Table 12.2 decomposes the comparison at the rated point.

The decomposition is the useful part. Of the 14.3 %, 6.0 % is cell voltage and the remainder is a balance-of-plant load that stops existing. Against that, storing the oxygen costs 0.458 MW of compression at the rated electrolysis flow and a second pressure vessel of 770 m^3, and the compression is paid whenever the electrolyzer runs while the benefit is collected only when the fuel cell runs.

Pause. Try Exercise 12.3 before reading on.

12.3.6 Storage, Water and the Balance of Plant

Both vessels use the same real gas relation with one linear compressibility correction solved by three fixed-point passes, which at 200 bar is worth 12 % of the inventory and is not optional,

$$Z = 1 + Z_1 p, \qquad p = \frac{nR(T + 273.15)}{V} \frac{Z}{10^5} \ \text{[bar]}. \tag{12.12}$$

The hydrogen vessel holds 21 997 kg at 200 bar and 1468 kg at the 12 bar regulator limit, so the usable inventory is 20 529 kg, which is 15.7 h at the fuel cell rating, the duration of Section 1.4.4. Filling a pressure vessel warms it and the vessels are carried as separate temperature states with a 12.3 h loss time constant.

Compression is staged with intercooling from the electrolyzer delivery pressure to the vessel,

$$P_{comp} = \frac{n_s \dot{m} c_p (T_{amb} + 288.15)\,(r^\kappa - 1)}{\eta_{comp}\, 10^6}, \qquad r = \left(\frac{p_{ves}}{p_{stack}}\right)^{1/n_s} \tag{12.13}$$

which is 0.984 MW for hydrogen and 0.458 MW for oxygen at the rated flow into a full vessel.

The water loop is nearly closed and it is the constraint that stops the plant. Electrolysis consumes nine kilograms of water for every kilogram of hydrogen, which at the rated point is 8401 kg/h, and the fuel cell returns it only when it runs,

$$\frac{\mathrm{d}m_w}{\mathrm{d}t} = 3600\big(0.018\,\dot{n}_{H_2,fc} - 0.018\,\dot{n}_{H_2,el} + \dot{m}_{mk} - 0.4\,f_{purge}\big) \quad (12.14)$$

The default makeup rate is 0.12 kg/s, which is 432 kg/h against 8401 kg/h of consumption, so a full tank supports 10.2 h of rated electrolysis and no more.

12.3.7 Thermal and Hydration Dynamics

Both stacks are lumped capacitances with an ambient loss and a cooling term that fades as the stack approaches ambient,

$$C\frac{\mathrm{d}T}{\mathrm{d}t} = 3600\left[10^6\dot{Q} - UA(T - T_{amb}) - u^a Q_{cool}\,10^6\,\Pi\left(\frac{T - T_{amb}}{35}\right)\right] \quad (12.15)$$

The open-loop time constants are 2.78 h for the electrolyzer and 2.43 h for the fuel cell, both far longer than the current loops beneath them.

Membrane hydration is a first-order state driven toward a target that falls with current and with temperature and rises with purge,

$$\lambda^* = \zeta\,\Pi_{0.35}^{1.1}\left[1.05 - 0.22\frac{j_{el}^a}{j_{el,R}} - 0.012(T_{el} - 70)^+ + 0.10 f_{purge}\right] \quad (12.16)$$

with ζ the hydration disturbance and a time constant of 0.25 h. A dry membrane raises both stack resistances through Equation (12.5), so running hard and hot costs voltage twice.

12.3.8 Parameters

Table 12.3 gives the parameters the equations use, with their defaults. The V column marks A for adjustable and shown, H for hidden from the beginner view, and F for a fixed physical constant.

12.3.9 Initialization and Numerics

Each scenario supplies starting hydrogen and oxygen pressures and a starting stack temperature. The vessel temperatures start at ambient plus 8 °C, the hydration at unity, the analyzer at the rated crossover value and the water tank at 55 %.

The engine of Section 1.6.1 integrates by classical fourth-order Runge-Kutta on a fixed step of 0.001 h, which is 3.6 s and about two time constants of the rectifier lag. The regulatory loops execute every 0.002 h, which is 7.2 s, the schedule re-solves every 0.1 h, and the historian logs every 0.017 h, which is seventeen steps or 61.2 s. A post-step clip holds both inventories, the four temperatures, the hydration, the water inventory and the analyzer inside their physical ranges.

12.3.10 Assumptions

1. **Both stacks are one cell scaled by a cell count.** Cell-to-cell voltage distribution, which is what a real stack's monitoring system exists to watch, is absent. The pinhole in scenario ten is therefore a change in a plant-wide crossover multiplier rather than a defect in one cell.

Table 12.3 Model parameters and default values

Symbol	Meaning	Value	Unit	V
$P_{pv,0}$	array rating	100	MW	A
T_{noct}	nominal cell operating temperature	45	°C	H
β	cell power temperature coefficient	0.0038	1/°C	A
G_{max}	peak plane-of-array irradiance	1000	W/m^2	A
h_{up}, h_{dn}	sunrise, sunset	6.4, 19.2	h	A
N_{el}	electrolyzer cells	12 700	—	A
A_{el}	electrolyzer active area	1000	cm^2	A
$j_{el,R}$	rated electrolyzer current density	2.0	A/cm^2	A
ASR_{el}	electrolyzer resistance at 60 °C	0.16	Ω cm^2	A
$j_{0,el}$	anode exchange current density	1.0×10^{-6}	A/cm^2	H
α	anode charge transfer coefficient	0.55	—	H
η_F	Faradaic efficiency	0.985	—	A
C_{el}	electrolyzer thermal mass	2.6×10^8	J/K	A
UA_{el}	electrolyzer ambient loss	2.6×10^4	W/K	A
$Q_{cool,el}$	electrolyzer cooling capacity	14	MW	A
$T_{el,max}$	membrane temperature limit	80	°C	A
$j_{el,min}$	minimum electrolyzer current density	0.12	A/cm^2	A
N_{fc}	fuel cell cells	29 000	—	A
A_{fc}	fuel cell active area	1000	cm^2	A
$j_{fc,R}$	rated fuel cell current density	1.2	A/cm^2	A
ASR_{fc}	fuel cell resistance at 65 °C	0.13	Ω cm^2	A
$j_{0,fc}$	cathode exchange current on air	1.2×10^{-4}	A/cm^2	H
ΔV_{O_2}	flat gain from pure oxygen	0.020	V	A
$j_{\ell,air}$	limiting current density on air	1.9	A/cm^2	A
C_{fc}	fuel cell thermal mass	1.4×10^8	J/K	A
UA_{fc}	fuel cell ambient loss	1.6×10^4	W/K	A
$Q_{cool,fc}$	fuel cell cooling capacity	30	MW	A
$T_{fc,hot}$	nominal fuel cell ready temperature	62	°C	A
$x_{fc,min}$	minimum fuel cell load	0.18	—	A
f_{blow}	cathode blower, fraction of gross	0.072	—	A
V_{H_2}, V_{O_2}	storage volumes	1540, 770	m^3	A
p_{max}	storage design pressure	200	bar	A
p_{min}	regulator limit	12	bar	A
p_e	electrode operating pressure	3.0	bar	H
p_{stack}	electrolyzer delivery pressure	30	bar	A
Z_1	compressibility slope	6.0×10^{-4}	1/bar	H
UA_{ves}	vessel heat loss, each	900	W/K	A
C_{ves}	vessel heat capacity, each	4.0×10^7	J/K	A
n_s	compressor stages	3	—	A
η_{comp}	compressor isentropic efficiency	0.70	—	A
$m_{w,max}$	water tank capacity	90 000	kg	A
$m_{w,min}$	minimum working water	9000	kg	A
c_0	oxygen in hydrogen at rated current	40	ppm	A
c_{max}	purity limit before venting	1800	ppm	A
τ_c	analyzer and mixing response	0.08	h	A
P_{grid}	grid connection limit	40	MW	A
P_{firm}	firm power commitment	18	MW	A
h_{f1}, h_{f2}	firm window	17, 23	h	A
c_{H_2}	value of hydrogen	4.2	$/kg	A
c_{unmet}	penalty for missing the commitment	600	$/MWh	A
τ_j	rectifier current response	4.2×10^{-4}	h	A
τ_{cool}	cooling response	0.014	h	A
τ_λ	hydration response	0.25	h	A
F	Faraday constant	96 485	C/mol	F
R	gas constant	8.314	J/(mol K)	F

2. **Crossover is a scalar in the product stream.** The physical process is a permeation flux driven by partial pressure across the membrane [7], and the reciprocal-current form in Equation (12.7) reproduces its operational consequence without its pressure dependence. A pressurized stack would show a stronger effect.

3. **The gases are ideal with one compressibility correction.** At 200 bar and ambient temperature the single linear term in Equation (12.12) is adequate for inventory accounting and is not a real equation of state. Hydrogen's negative Joule-Thomson coefficient at these conditions is not modeled.

4. **The fuel cell has no reactant transport dynamics.** Oxygen starvation during a load transient is the central control problem in the automotive fuel cell literature [8] and it does not appear here, because the plant is fed from pressure vessels rather than from a compressor with its own dynamics.

5. **Membrane hydration is one state for two stacks.** A real plant has separate water management on each, and the shared state overstates the coupling between them.

6. **Degradation is a disturbance slider rather than a mechanism.** The stack wear multipliers are set by hand and do not accumulate with operation, so nothing in the model connects the start count to the stack life it is meant to stand for.

7. **The irradiance and the price are synthetic.** They are teaching data shaped like a clear spring day with an evening peak and are never labeled as measured.

12.4 Open-Loop Character

The round trip is the first thing manual mode makes concrete and the least interesting. Fifty kilowatt-hours of electricity make a kilogram of hydrogen and the kilogram returns about twenty-one, which is a round trip near a third and is a property of the electrochemistry rather than of the control system. No scenario in this application improves it and none of them tries.

The minimum load is the second thing and it is the one worth an hour of a student's time. Turning the electrolyzer down is not free and it is not linear. At the rated 2.0 A/cm^2 the analyzer reads 40 ppm, at 0.4 A/cm^2 it reads 200 ppm, and at 0.12 A/cm^2 it reads 667 ppm, all of it from a crossover flux that did not change. The specification limit is 1800 ppm and the model floors the current ratio at 6 % of rating, so on a stack with nominal membranes the worst reading is 667 ppm and the limit is never reached. A membrane defect changes that completely, and scenario ten is built on it.

🕮 **Pause.** Try Exercise 12.1 before reading on.

The time scales separate cleanly and the separation is what makes the architecture obvious. The rectifiers answer in 1.5 s. The analyzer and the mixing volume answer in 0.08 h, which is about five minutes. The stacks have thermal time constants near 2.5 h. The hydrogen inventory is 15.7 h at the fuel cell rating and the water inventory is 10.2 h at the electrolyzer rating. The day is the outer loop.

Curtailment is the third thing and it is a definition rather than a fault. The array peaks at 89.3 MW on a 40 MW connection, so at solar noon almost 50 MW has nowhere to go except the electrolyzer, and everything the electrolyzer cannot take is thrown away. A plant of this shape is sized so that curtailment is normal operation, which is why the electrolyzer's setpoint in every automatic architecture is the surplus above the connection limit rather than a demand.

12.5 Regulatory Control

12.5.1 The Discrete Algorithm

Four loops share the velocity-form proportional-integral-derivative implementation of Section 1.6.2, Equations (1.10) to (1.13), with the derivative taken on the measurement and back-calculation against

Table 12.4 Regulatory loops as implemented

CV	MV	K_c	τ_I (h)	Action
P_{del}	j_{fc}	0.09	0.004	reverse, +1
P_{el}	j_{el}	0.05	0.004	reverse, +1
T_{el}	u_{el}	9	0.06	direct, −1
T_{fc}	u_{fc}	9	0.05	direct, −1

the applied output. The settings particular to this plant are a tracking time $T_t = \tau_I$, an output bias of zero, no rate limit and $\Delta t_c = 7.2\,\text{s}$. The running sum is never clipped, so anti-windup acts on the integral alone. A loop that is not in service (a cooling loop in Manual, or a current loop whose stack is down or held at its start-up load) solves Equation (1.11) for its integral so that its output equals the value actually applied, which makes the return to service bumpless. The delivered power reaches its loop through a 0.002 h first-order filter and the stack temperatures through 0.01 h filters. All four loops run with $\tau_D = 0$, so there is no derivative action anywhere in this application [15].

12.5.2 Four Loops and Two Parked Setpoints

Table 12.4 gives the pairings and the default tunings, with the action in the convention of Section 1.3 (+1 reverse acting, −1 direct acting), which is also the sign the app's controller carries. The two current loops are reverse acting because more current raises the delivered or the absorbed power. The two cooling loops are direct acting because more cooling makes a colder stack.

Both current loops have output limits that are recomputed every scan rather than fixed, because the current that produces a requested power moves with temperature, hydration and storage pressure. Each limit is found by forty-eight bisections on the corresponding polarization relation.

The two cooling setpoints are parked on their measurements whenever the stack they belong to is down. A temperature setpoint on a stack with no current through it is not a control target but a number, because the stack cools to ambient and the loop can do nothing about it. Parking the setpoint is what a real plant's temperature controller does when its unit is off, and it is the difference between an idle loop and a thirty-degree error that nobody can act on and that contaminates every integrated performance metric in the scorecard. The application logs and scores the parked value for both stacks, so on the fifth scenario the fuel cell loop reports an integrated error of 26.7 °C h by 19:04, of which only 0.3 °C h accumulated in the five hours before the stack was started and the rest while it warmed from 26 °C toward its 66 °C setpoint. Figure 12.4 shows the application at that moment.

12.5.3 The Minimum Current as a Discontinuity

Below the minimum current density the electrolyzer is not merely inefficient, it is on its way out of specification. The loop output is therefore snapped rather than clipped,

$$j_{el} = \begin{cases} j_{el}^{PI} & j_{el}^{PI} \geq j_{el,min} \\ j_{el,min} & j_{el}^{PI} < j_{el,min},\ P_{el}^{SP} > 0.5\,\text{MW} \\ 0 & \text{otherwise} \end{cases} \tag{12.17}$$

which turns a continuous manipulated variable into one with a forbidden band. The snap is applied after the controller, whose own lower limit is zero, so while the floor holds the current above what the loop asks for, the integral winds down to that zero limit. In the second scenario the 2 MW request leaves the controller output at zero and the applied current at the 0.12 A/cm^2 floor, and a later rise in the request has to carry the controller output back up through the floor before the current moves. The same treatment is applied to the fuel cell at 18 % of its rated current. A student who has met this on a real plant recognizes it immediately and a student who has not is usually surprised that it is done deliberately.

Table 12.5 Supervisory state transitions

From	Condition	To
TRIP	interlocks clear	SHUTDOWN
SHUTDOWN	always	OFF
OFF	any demand and clear	STARTUP
STARTUP	not clear	TRIP
STARTUP	fuel cell wanted, warm, H_2 present	FUELCELL
STARTUP	electrolyzer wanted, warm, water	ELECTROLYZE
STARTUP	no demand	SHUTDOWN
ELECTROLYZE	not clear	TRIP
ELECTROLYZE	fuel cell wanted	STANDBY
ELECTROLYZE	no room, no water or no demand	STANDBY
STANDBY	not clear	TRIP
STANDBY	fuel cell wanted and warm	FUELCELL
STANDBY	fuel cell wanted and cold	STARTUP
STANDBY	electrolyzer wanted, room, water	ELECTROLYZE
STANDBY	no demand	SHUTDOWN
FUELCELL	not clear	TRIP
FUELCELL	no H_2 or not wanted	STANDBY

TRY IT IN THE APP **2 · The Minimum Load, and Why It Is Not a Turndown Ratio**

Load scenario 2 and press Run. Watch the electrolyzer current strip. When the scenario asks for 2 MW, the current stops at its floor of 0.12 A/cm^2 and goes no lower, while the controller output beneath it has wound down to zero.

12.6 The Supervisory Machine

The mode is a finite state with seven values and explicit transitions. The transition function depends only on an interlock vector and a demand vector, and the economics contribute to the demand vector alone,

$$m_{k+1} = \Phi(m_k,\ \mathbf{ok},\ \mathbf{want}). \tag{12.18}$$

The interlock vector is evaluated from measurements alone. It carries whether the plant is clear, which requires the analyzer inside specification whenever the stack is running, both stack temperatures below 82 °C (two degrees above their limits), the hydrogen vessel below 212 bar (6 % over its design pressure) and the water above a hard floor of 2700 kg. It also carries whether there is water, which is latched off at the 9000 kg working minimum until the makeup has refilled the tank to 10 800 kg, whether there is room for more hydrogen, latched off at 199 bar until the store falls below 194 bar, whether there is hydrogen above the regulator limit, and whether each stack is warm enough to be loaded, which for the electrolyzer means above 8 °C and for the fuel cell above $T_{fc,hot} - 14\,°\mathrm{C}$, or 48 °C. On the fifth scenario the fuel cell is started at 17:04 and loaded at the scan at 17:46, at 48.0 °C, and it reaches the 62 °C of $T_{fc,hot}$ only at 18:17. Table 12.5 gives the transitions.

Three properties of that table are worth stating because they are design decisions rather than consequences. Every path into TRIP depends on interlocks alone, so no economic setting can prevent a trip and no economic setting can cause one. Every path out of TRIP goes through SHUTDOWN and OFF, so recovery is a sequence and not a toggle. And STARTUP is not an idle state. A cold fuel cell cannot be loaded and the only heat available to it is its own inefficiency, so STARTUP holds the stack at its minimum load until it is warm enough to be useful. That is what a start costs and it is why the scorecard counts them.

Pause. Try Exercise 12.2 before reading on.

Table 12.6 Scenarios

#	Start	Architecture	Subject
1	10:00	manual	two stacks and the round trip
2	09:00	manual	the minimum load
3	08:00	follow	the connection limit and curtailment
4	06:00	follow	solar following to a full store
5	12:00	firm	the firm evening commitment
6	12:00	firm	should the oxygen be kept
7	09:00	follow	a cloud front and the state machine
8	05:00	economic	what a stored kilogram is worth
9	05:00	economic	three days of low solar
10	10:00	follow	a purity excursion and a trip
11	05:00	open	the graded challenge

A minimum dwell of 0.08 h applies to every transition except one into TRIP. Real supervisory machines all have one, for the same reason, which is that the physical act of starting a stack is not instantaneous and a machine that can leave a state faster than the plant can enter it is a machine that will.

The demand vector carries hysteresis for the same reason. The electrolyzer start threshold is a fraction of the array rating, and once the stack is running the threshold drops to 55 % of that value. Without it a surplus wandering across the threshold starts and stops the stack every few seconds, and the start counter fills with chatter instead of with the effect it was built to show. A server fleet scaled without such a band flaps in the same way in Volume 8, Chapter 14.

Three architectures write the demand vector. Solar following runs the electrolyzer on surplus and the fuel cell only when the array cannot meet the commitment. Firm runs the fuel cell through the whole commitment window. Economic adds a schedule that computes what a kilogram in the bottle is worth, by simulating thirty-two half-hour blocks forward at a trial threshold price and bisecting sixteen times for the lowest threshold that still ends on the terminal inventory,

$$\text{run the fuel cell in block } k \iff \pi_k \, \varepsilon_{kg} > \theta \tag{12.19}$$

where ε_{kg} is the megawatt-hours a kilogram returns, measured at the rated point rather than assumed and therefore different on oxygen and on air. The threshold θ is the value of a stored kilogram, the water value of Section 1.4.6, found here by forward simulation and bisection rather than by a merit order.

12.7 Scenarios and Measured Results

Table 12.6 lists the eleven scenarios and Table 12.7 gives the scorecard at the end of each window with every setting as loaded. In the two manual cases the cooling is left at zero, so the electrolyzer reaches its 110 °C model limit in the first. In the third and eighth the water tank reaches its working minimum at 15:37 and 15:38, and in the fourth the store fills at 15:32, so the electrolyzer stops for the rest of the afternoon and most of their curtailment comes after it.

> **DID YOU KNOW? Cloudy Days Throw Away Almost Nothing**
>
> From the simulator: seventy-two hours at 30 % of clear-sky sunshine in scenario 9 curtail only 1.3 MWh, while the ten-hour run of scenario 3 on a clear day curtails 20.9 MWh, most of it after the water tank has reached its working minimum (Table 12.7).

12.7.1 The Oxygen Decision in Operation

The sixth scenario switches the fuel cell from stored oxygen to an air cathode at 18:00, an hour into the evening commitment, and its briefing asks for the twelve-hour run of the fifth scenario to

Table 12.7 Scorecard at the end of each scenario window

#	Hours	Unserved (MWh)	Curtailed (MWh)	H_2 made (kg)	Starts	Margin ($)
1	3	0.00	12.4	2196	1	6 399
2	3	0.00	78.6	483	1	483
3	10	0.00	20.9	4867	1	25 504
4	14	2.44	23.1	4820	2	25 241
5	12	0.00	9.0	3240	2	13 287
6	12	0.00	9.0	3240	2	11 066
7	8	0.00	4.2	3864	2	15 187
8	20	0.01	22.2	4867	2	22 533
9	72	2.83	1.3	4820	4	15 656
10	6	0.00	4.6	4536	1	17 202
11	20	57.60	56.4	571	9	−44 664

be repeated once on each policy. The rated-point comparison in Table 12.2 says stored oxygen is worth 14.3 % more electricity per kilogram, and the twelve-hour pair says something more useful. On stored oxygen the run consumes 3684 kg of hydrogen and 3.41 MWh of compression to deliver its commitment. On air it consumes 4200 kg and 2.46 MWh of compression, and the cathode blower draws 6.83 MWh and raises the auxiliary load from 7.87 MWh to 13.75 MWh. Storing the oxygen therefore costs 0.95 MWh of extra compression, saves 5.88 MWh of auxiliary load net of it over the same window, and saves 516 kg of hydrogen.

The net margin includes delivered electricity and oxygen sales, missed-commitment penalties, the value of hydrogen inventory changes and stack-start costs. At $4.20 per kilogram, the extra hydrogen consumed by the air cathode reverses its cash advantage. Stored oxygen nets $13 287 against $12 830 on air, an advantage of $457. The inventory ledger includes vents and storage losses, and each movement is valued at the configured price when it occurs. Start costs are incurred at each counted start, so changing a price mid-run does not reprice earlier activity.

12.7.2 The Fault and the Alarm

The tenth scenario opens a pinhole at 11:30 that raises the crossover rate twenty-fold, and the plant does not trip for four and a half hours. At noon the stack is at 1.87 A/cm^2, 94 % of rated current, and the analyzer reads 858 ppm, close to the 800 ppm that Equation (12.7) gives for a twenty-fold crossover at rated current and comfortably inside the 1800 ppm limit. The reading climbs only when the surplus falls in the afternoon, to 1664 ppm at 16:00 with the current at 0.91 A/cm^2, and the plant trips at the scan at 16:06, when the same leak has become a much larger fraction of a much smaller hydrogen flow. The machine restarts the stack and trips twice more, at 16:30 and 16:51, before the surplus is gone.

> **TRY IT IN THE APP** **10 · A Purity Excursion, and a Trip**
>
> Load scenario 10 and press Run. Watch the purity trace beside the electrolyzer current. The pinhole opens at 11:30, yet the reading is 858 ppm at noon. It climbs only as the current falls in the afternoon, and the plant trips at 16:06.

Nothing about the plant changed between the fault and the alarm except its load. A monitoring calculation that normalized the analyzer reading by the current would have seen the step immediately, and the reason plants do not usually have one is that nobody asked the analyzer what it was for. That observation transfers directly to any composition measurement on a stream whose flow rate is a manipulated variable. Figure 12.2 draws Equation (12.7) for the healthy and the leaking membrane with the readings of this section.

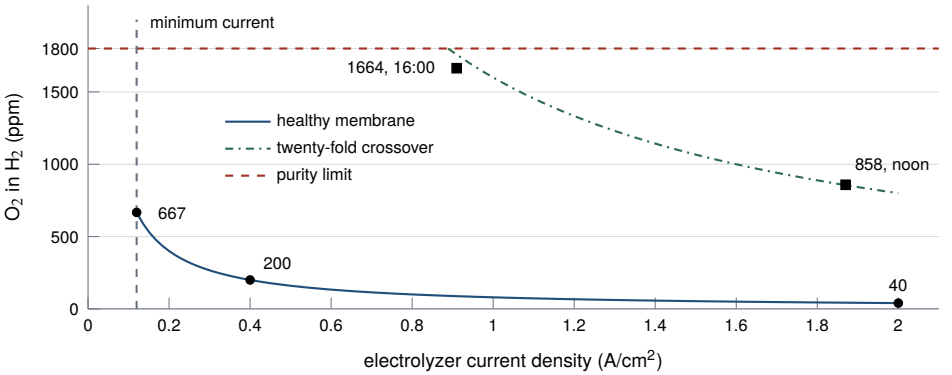


Figure 12.2 Oxygen in the hydrogen product against current density at steady state, from Equation (12.7), for a healthy membrane (solid) and for the twenty-fold crossover of scenario 10 (dash-dot), with the purity limit (dashed). Dots are the readings of Section 12.4 and squares the readings of scenario 10 at noon and at 16:00, which trail the curve by the analyzer's lag. Notice that the same leak sits far inside the limit at full current and reaches it only when the current falls.

Table 12.8 Three architectures over seventy-two hours of low solar

Architecture	Unserved (MWh)	Fuel cell (MWh)	Final H_2 (bar)	Margin ($)
solar following	5.08	273.05	92.2	15 468
firm	2.83	281.62	89.1	16 508
economic	2.83	321.85	70.3	15 656

12.7.3 Three Architectures on Three Cloudy Days

The ninth scenario runs seventy-two hours at 30 % of clear-sky irradiance with a firm evening commitment on each day and the bottle starting at 150 bar. Table 12.8 compares the three architectures on it.

The economic schedule delivers 321.85 MWh from the fuel cell against 273.05 MWh on solar following and leaves 2.25 MWh less unserved. Its cash advantage is \$10 101, but pricing the depleted store reduces its net-margin advantage to \$188. Firm dispatch earns \$16 508, compared with \$15 656 for the economic schedule and \$15 468 for solar following. The schedule forecasts energy and inventory, but does not optimize the complete plant ledger including starts. More electricity sold is therefore not necessarily more profit. Figure 12.3 draws the table as bars.

12.7.4 The Graded Challenge

The eleventh scenario opens twenty hours from five in the morning with weak tuning, vented oxygen, an 18 % start threshold and stack setpoints of 74 °C and 76 °C against 33 °C ambient. It trips eight times on stack temperature, with a logged electrolyzer peak of 81.8 °C, leaves 57.6 MWh unserved, curtails 56.4 MWh and nets −\$44 664. Retuning the four loops removes the trips and gives 0.04 MWh unserved, a 78.6 °C peak and \$5 467 net margin, below the \$6 000 target.

The suggested configuration uses solar following, stored oxygen, a 15 % start threshold, temperature setpoints of 62 °C and 66 °C and the default tunings. It leaves 0.068 MWh unserved, trips not at all, peaks at 67.6 °C, curtails 10.42 MWh, starts twice and nets \$6 959. Its electricity and oxygen cash margin is \$20 012, reduced by \$8 653 of hydrogen inventory depletion and \$4 400 of starts. Five additional forecast seeds give the same result because solar following does not use that forecast.

With the remaining settings as suggested, firm dispatch nets \$6 601 and the economic schedule \$6 277. The latter sells more electricity but also burns more stored hydrogen. Lowering the start

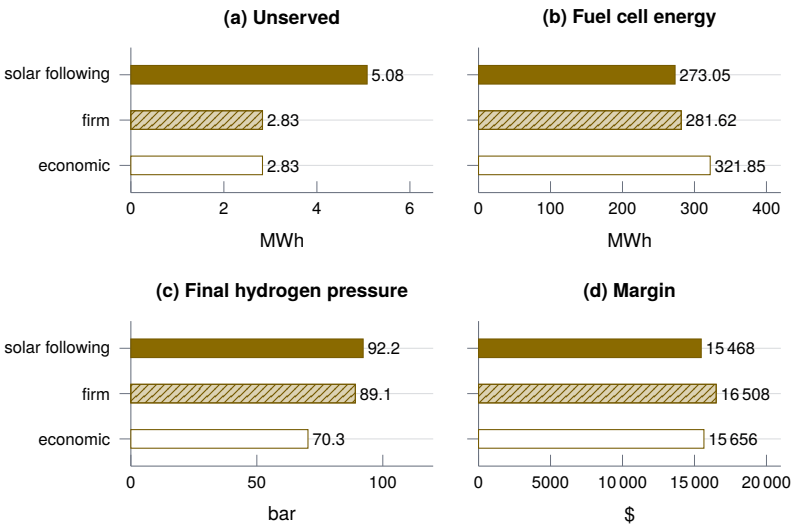


Figure 12.3 The three architectures over seventy-two hours of low solar, from Table 12.8: (a) unserved energy, (b) energy from the fuel cell, (c) hydrogen pressure at the end and (d) net margin. Solid: solar following. Hatched: firm. White: economic. Notice that the economic schedule sells the most energy and leaves the emptiest store, and that firm dispatch, not the economic schedule, earns the most margin.

threshold to 4 % on solar following reduces curtailment to 2.81 MWh, adds a third start and lowers net margin to $5 436. Venting oxygen lowers net margin to $5 546. Applying the suggested structure to weak loops still fails: 5.64 MWh unserved, an 81.2 °C peak and $1 480 margin. Neither tuning alone nor structure alone passes the revised challenge.

12.8 Technology in Practice

The symbols of Figure 12.1 are, in a plant, an analyzer on the hydrogen product, a pressure transmitter on the store, thermometers in both stacks, power measurements on the electrolyzer feed and at the grid connection, two power converters, two cooling systems and a valve that stores or vents the oxygen. Figure 12.5 draws the chapter's loops with that hardware in place of the schematic's symbols.

What Measures It

The measurement that decides whether the plant runs is the oxygen in the hydrogen product, a composition read by an analyzer with a sample system. The chapter lumps the analyzer and the mixing volume into one 0.08 h lag and gives no sample system that can fail. The stack temperatures and the two power measurements serve the regulatory loops, and the store pressure is the inventory of Equation (12.12).

> **TECHNOLOGY** **Sensor: The Oxygen-in-Hydrogen Analyzer**
>
> Most industrial analyzers sit away from the process and receive a sample through tubes, filters, regulators and heaters, and many analyzer problems start in that sample system [16]. A gas sample is held at steady pressure and temperature, kept clean and dry, and carried in metal tubing when the species of interest is at parts per million, because some plastic tubes let gases through. One oxygen sensing principle is the micro fuel cell, which makes a current from oxygen by oxidizing a lead fuel inside it and must be replaced as that fuel is used up [16]. A plugged sample line leaves an analyzer reading old gas with no way of knowing, which on a trend is a purity reading that stops following the current. The chapter's AT is exact behind a 0.08 h lag.

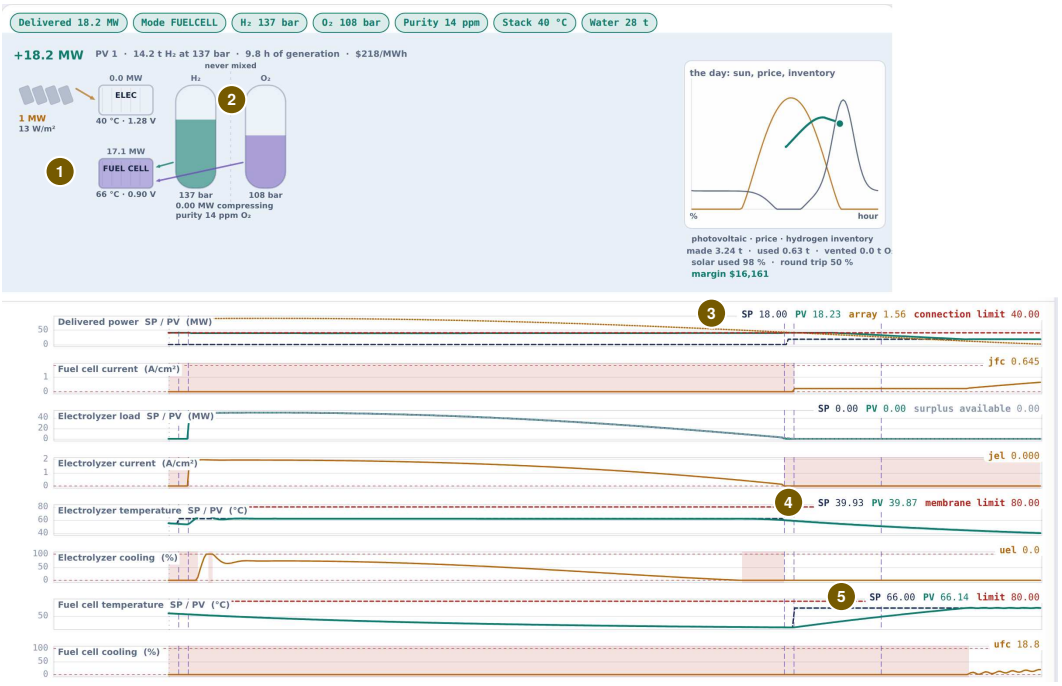


Figure 12.4 The application at 19:04 on the fifth scenario, seven hours into the run and two hours into the firm evening commitment, with the fuel cell running on stored oxygen. The delivered power strip reads 18.23 MW against a setpoint of 18 MW while the array contributes 1.56 MW, and the two current strips show the electrolyzer at zero and the fuel cell at 0.645 A/cm^2. The electrolyzer temperature strip shows its setpoint parked on the measurement (39.93 °C against 39.87 °C) since the stack stopped at 16:59. The fuel cell setpoint follows its measurement down until STARTUP at 17:04, then steps to 66 °C, and the loaded stack now reads 66.14 °C. The mode badge reads FUELCELL, which is the only state in which the economics are permitted to choose anything, and the scene labels the wall between the two vessels *never mixed*. The plant view and the trend panel are cut from the full window. Callouts: (1) the running fuel cell, (2) the wall marked *never mixed*, (3) the delivered power strip, (4) the parked electrolyzer setpoint, (5) the fuel cell setpoint after its step.

What Moves It

Five final elements act on the plant. The rectifier and the fuel cell converter set the two stack currents within limits recomputed every scan. The two cooling duties hold the stack temperatures. The oxygen valve chooses between the store and the vent. The power electronics between the grid and an electrolyzer can also offer the grid services of power quality and power factor correction, which the laboratory tests of 2014 could not assess [14].

> **TECHNOLOGY** **Final Element: The Rectifier Under the Current Loop**
>
> An electrolyzer takes its direct current from rectifiers and other power electronics that convert the alternating current of the grid [14]. In a controlled rectifier, thyristors take the place of plain diodes, and a phase-control circuit sets the output by timing the trigger pulse of each thyristor against the alternating waveform. A drive with a feedback loop of its own acts as the slave of a cascade and takes its setpoint from the process controller [16]. Tested units began to change their demand within milliseconds and settled within seconds [14]. The chapter's rectifier lag of 1.5 s stands for that response, and its current loops are the masters that write the setpoint.

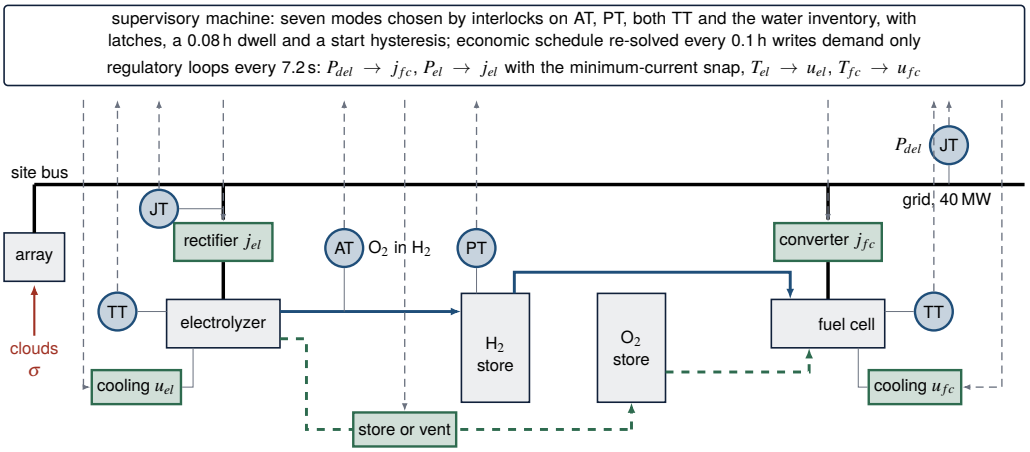


Figure 12.5 The chapter's loops with their hardware. Sensors are the round tags: the analyzer AT on the hydrogen product, the pressure transmitter PT on the hydrogen store, thermometers TT on both stacks, and power measurements JT on the electrolyzer feed and at the grid connection. Final elements are the square tags: the electrolyzer rectifier, the fuel cell converter, two cooling duties and the valve that stores or vents the oxygen. Solid arrows carry hydrogen and dashed arrows oxygen. Notice that the analyzer and the pressure transmitter feed only the supervisory machine, which chooses the mode, while the four regulatory loops act inside it.

Where the Controller Runs

A programmable logic controller holds instructions for logic, timing, counting and proportional-integral-derivative control, and in a distributed system it acts as a local controller under a supervisory scheme [17]. Such loops run with cycle times from milliseconds to minutes. The chapter's regulatory loops run every 7.2 s on a 3.6 s physics step, and the schedule re-solves every 0.1 h. The interlocks belong in a safety instrumented system, made of sensors, logic solvers and final elements that bring the plant to a safe state when a threshold is crossed. It is designed to IEC 61511 and is often independent of the basic control system, so that a failure of the control system does not weaken it [17]. The chapter's machine, whose transitions to TRIP depend on interlocks alone, is that separation written as a table.

> ⚠ **IN PRACTICE** **Two Gases, Two Sets of Rules**
>
> United States workplace rules treat the two products of this plant in separate sections, 29 CFR 1910.103 for hydrogen systems and 1910.104 for bulk oxygen systems on a user's premises [18, 19]. Hydrogen containers carry relief devices arranged to discharge upward and unobstructed to the open air [18]. Bulk oxygen equipment is cleaned of oil, grease and other readily oxidizable materials before it enters service, its gaskets, valves, gauges and regulators must be suitable for oxygen service, and its storage must not be exposed by flammable gas lines [19]. Keeping the oxygen brings a second vessel under a second rule.

What Is Modernizing It

Three developments touch this plant. The first is the grid role of the electrolyzer. Its subsecond dynamic response, validated in national laboratory projects that simulate grid fluctuations, enables services such as voltage and frequency stabilization [1]. In one test on an isolated grid of a diesel generator, a load bank and an electrolyzer, the frequency after a load step was restored faster with the electrolyzer's help than without it [14]. The second is the stack itself. Reversible fuel cells, still under development, would split water and make electricity in one unit [1], the role that the chapter's two separate stacks share. The third is the network. Operational systems increasingly resemble

information systems as they adopt standard computers and protocols, which leaves them less isolated and in greater need of security, and some modern safety systems are designed to communicate with the control system [17].

12.9 Limitations

The scorecard is an operating-margin ledger rather than a project valuation. It counts electricity and oxygen cash flows, missed-commitment penalties, actual hydrogen inventory changes and starts. It omits capital, financing and maintenance beyond the synthetic per-start charge. Hydrogen is valued at the parameter's configured price when its inventory moves, including leaks and vents. The economic dispatcher remains a forecast-based energy schedule, rather than a complete optimization of this ledger. The round-trip tile compares electricity per kilogram in each direction and is independent of the initial inventory.

The crossover model has no pressure dependence, where the measured process is driven by the partial pressure difference across the membrane [7]. The reciprocal-current form reproduces the operational consequence at one delivery pressure, and a student who changes the delivery pressure slider will see nothing happen to the analyzer, which is wrong.

Both stacks are single cells scaled by a count, so the pinhole in scenario ten is a change in a plant-wide multiplier rather than a defect in one cell of twelve thousand. Real plants detect that fault through cell voltage monitoring long before the product analyzer moves, and nothing in this model can pose that detection problem.

The irradiance and price are synthetic and the results should be read as the shape of an answer rather than as its magnitude. In particular, the economic schedule delivers the most fuel cell energy in Section 12.7 partly because the price here is a fixed daily shape independent of the array output, which is a favorable case for a forecast.

> **OPEN CHALLENGE** **Cheap Hydrogen From Cheap Electricity**
>
> In 2020 hydrogen from low-temperature electrolysis cost $5 to $6 per kilogram at electricity prices of 5 to 7 cents per kilowatt-hour. Electricity at 2 to 3 cents from new wind and solar plants, with better electrolyzers, offers a path below $2 per kilogram, but consistent, widely available low-cost electricity still needs work, and research is still needed to cut the cost and raise the efficiency and durability of electrolyzers [1]. The cheap midday power of this chapter's plant comes in bursts, and its stack wear does not grow with its starts. Progress would be a stack life known as a function of starts and load, so that a start could be priced from wear.

12.10 Conclusion

A solar hydrogen plant returns about a third of what it takes in, and no control system is going to change that. What the control system decides is whether the conversions that do happen are wasted, and the decisions that matter are discrete rather than continuous. The mode is chosen by interlocks, the setpoint is chosen by economics inside that mode, and the ordering is the architecture rather than a detail of it. An optimizer that can select a valve lineup can select an unsafe one.

Two measured results carry beyond this plant. Keeping the oxygen is worth 14.3 % of the electricity returned per kilogram of hydrogen, of which only 6.0 % is cell voltage and the rest is a cathode blower that stops existing, so the case for it is an operating case decided by a duty cycle and not a thermodynamic one. And a crossover flux that is constant in absolute terms is a rising fraction of a falling product flow, so a membrane defect that appears at half past eleven in the morning raises its first alarm just after four in the afternoon, with nothing having changed in between except the load. A specification written as a concentration and a plant operated on a flow are two different statements about the same stream, and the gap between them is where the alarm was.

KEY POINTS

- A solar hydrogen plant returns about a third of the electricity it takes in, and control decides only whether the conversions that do happen are wasted.
- The mode is chosen by interlocks and the setpoint by economics inside that mode. An optimizer that can select a valve lineup can select an unsafe one.
- Keeping the oxygen is worth 14.3 % of the electricity returned per kilogram, and only 6.0 % of it is cell voltage.
- A constant crossover is a rising fraction of a falling hydrogen flow, so the membrane fault raised its alarm hours after it appeared.

Where else this applies. A limit set by an explosive mixture also governs Volume 4, Chapter 6, and a band against start-stop flapping serves Volume 8, Chapter 14.

References

[1] U.S. Department of Energy, "Department of energy hydrogen program plan," U.S. Department of Energy, Washington, DC, Report, 2020.

[2] J. B. Rawlings, D. Angeli, and C. N. Bates, "Fundamentals of economic model predictive control," in *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*, 2012, pp. 3851–3861.

[3] Ø. Ulleberg, "Modeling of advanced alkaline electrolyzers: a system simulation approach," *International Journal of Hydrogen Energy*, vol. 28, no. 1, pp. 21–33, 2003.

[4] Ø. Ulleberg, T. Nakken, and A. Eté, "The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools," *International Journal of Hydrogen Energy*, vol. 35, no. 5, pp. 1841–1852, 2010.

[5] M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, "A comprehensive review on PEM water electrolysis," *International Journal of Hydrogen Energy*, vol. 38, no. 12, pp. 4901–4934, 2013.

[6] A. Ursúa and P. Sanchis, "Static-dynamic modelling of the electrical behaviour of a commercial advanced alkaline water electrolyser," *International Journal of Hydrogen Energy*, vol. 37, no. 24, pp. 18 598–18 614, 2012.

[7] M. Schalenbach, M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, "Pressurized PEM water electrolysis: Efficiency and gas crossover," *International Journal of Hydrogen Energy*, vol. 38, no. 35, pp. 14 921–14 933, 2013.

[8] J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, *Control of Fuel Cell Power Systems*, ser. Advances in Industrial Control. London: Springer London, 2004.

[9] ——, "Modeling and control for PEM fuel cell stack system," in *Proceedings of the 2002 American Control Conference*, 2002, pp. 3117–3122.

[10] S. Altmann, T. Kaz, and K. A. Friedrich, "Bifunctional electrodes for unitised regenerative fuel cells," *Electrochimica Acta*, vol. 56, no. 11, pp. 4287–4293, 2011.

[11] U.S. Department of Energy, National Energy Technology Laboratory, "Fuel cell handbook," U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Morgantown, WV, Report, Seventh Edition, Contract DE-AM26-99FT40575, Nov. 2004. [Online]. Available: https://netl.doe.gov/sites/default/files/netl-file/FCHandbook7.pdf

[12] J. Wang, J. Wen, J. Wang, B. Yang, and L. Jiang, "Water electrolyzer operation scheduling for green hydrogen production: A review," *Renewable and Sustainable Energy Reviews*, vol. 203, p. 114779, 2024.

[13] N. A. Sepulveda, J. D. Jenkins, A. Edington, D. S. Mallapragada, and R. K. Lester, "The design space for long-duration energy storage in decarbonized power systems," *Nature Energy*, vol. 6, no. 5, pp. 506–516, 2021.

[14] J. Eichman, K. Harrison, and M. Peters, "Novel electrolyzer applications: Providing more than just hydrogen," National Renewable Energy Laboratory, Golden, CO, Technical Report NREL/TP-5400-61758, 2014.

[15] K. J. Åström and T. Hägglund, *Advanced PID Control*. Research Triangle Park, NC: ISA – The Instrumentation, Systems, and Automation Society, 2006.

[16] T. R. Kuphaldt, *Lessons in Industrial Instrumentation*, version 2.33 ed. Open textbook, Creative Commons Attribution 4.0 license, ibiblio.org/kuphaldt/socratic/sinst, 2024.

[17] K. Stouffer, M. Pease, C. Tang, T. Zimmerman, V. Pillitteri, S. Lightman, A. Hahn, S. Saravia, A. Sherule, and M. Thompson, "Guide to operational technology (OT) security," National Institute of Standards and Technology, Gaithersburg, MD, Special Publication 800-82r3, 2023.

[18] Occupational Safety and Health Administration, "29 CFR 1910.103, hydrogen," Code of Federal Regulations, Title 29, Part 1910, edition of July 1, 2024, govinfo.gov, 2024.

[19] ——, "29 CFR 1910.104, oxygen," Code of Federal Regulations, Title 29, Part 1910, edition of July 1, 2024, govinfo.gov, 2024.

12.11 Exercises

12.1 Concept check · 2 min

In scenario 2 the electrolyzer is turned down from 30 MW to 6 MW on a healthy membrane, and the oxygen-in-hydrogen analyzer settles at a reading more than four times higher. Which explanation is right?

(a) The membrane grows more permeable at low current, so the crossover flux rises
(b) The crossover flux stays the same while the hydrogen flow falls with the current
(c) The analyzer lag overshoots after a load reduction and has not yet settled back
(d) A cooler stack at low load dissolves more oxygen into the hydrogen product

12.2 Concept check · 1 min

Which statement about the supervisory machine of Table 12.5 is right?

(a) The economic schedule may send the plant to TRIP when the price is negative
(b) Recovery from TRIP returns the plant directly to the state it was in before
(c) Every path into TRIP depends on interlocks, and every path out passes SHUTDOWN and OFF
(d) STARTUP holds a cold stack at zero current until it has warmed to its ready point

12.3 Concept check · 2 min

A reader puts the 200 bar storage pressure into the Nernst term and predicts about a hundred millivolts per cell from running the fuel cell on stored oxygen. Table 12.2 shows 16.4 mV of reversible gain. Which statement explains the difference and names the largest part of the 14.3 % advantage?

(a) The vessels are cooler than the stack, and most of it is the concentration term
(b) The compressibility removes most of the gain, and most of it is the kinetic term
(c) The analyzer limits the oxygen purity, and most of it is the reversible potential
(d) A regulator drops both gases to a few bar, and most of it is the blower that is removed

12.4 Theory and calculation · 6 min

Use Equation (12.7) in steady state ($c = c^*$) with $c_0 = 40\,\text{ppm}$, $j_{el,R} = 2.0\,\text{A/cm}^2$ and the purity limit $c_{max} = 1800\,\text{ppm}$.

(a) With nominal membranes ($\gamma = 1$), find the reading at 0.4 A/cm^2 and at the 0.12 A/cm^2 minimum current. *Checkpoint:* 200 ppm and 667 ppm.

(b) Without the 6 % floor in the equation, at what current density would a nominal stack reach the limit? Say why the model can never show it. *Checkpoint:* 0.044 A/cm^2, below the 0.12 A/cm^2 floor.

(c) After the pinhole of scenario 10 ($\gamma = 20$), find the reading at the rated current and the current density below which the steady reading exceeds the limit. *Checkpoint:* 800 ppm and 0.889 A/cm^2.

12.5 Theory and calculation · 6 min

The electrolyzer makes 941 kg/h of hydrogen at its rated point, and Equation (12.14) charges 0.018 kg of water for each mole of hydrogen made (molar mass 2.016 g/mol). The makeup is 0.12 kg/s, the tank holds 90 000 kg, the working minimum is 9000 kg and the water interlock releases at 10 800 kg. The fuel cell is off and the purge is zero.

(a) Find the water consumption at the rated point and the net drain rate. *Checkpoint:* 8402 kg/h and 7970 kg/h.

(b) Find how long a full tank supports rated electrolysis, and how long the 55 % starting inventory does. *Checkpoint:* 10.2 h and 5.08 h.

(c) Once the interlock has stopped the stack, how long does the makeup alone take to release it? *Checkpoint:* 4.17 h.

12.6 Theory and calculation · 7 min

Use the rated-point values of Table 12.2 and the oxygen compression of 0.458 MW at the rated electrolysis flow of 941 kg/h.

(a) From the table, find the gain in cell voltage, the gain in net electricity per kilogram, both as percentages of the air values, and the blower load as a fraction of gross power on air. *Checkpoint:* 6.0 %, 14.3 % and 0.072.

(b) Find the oxygen compression energy per kilogram of hydrogen made and the extra electricity per kilogram burned on stored oxygen. *Checkpoint:* 0.487 kW h and 2.69 kW h.

(c) Storing the oxygen costs compression on every kilogram made and pays only on the kilograms burned. Find the fraction of the hydrogen made that must later be burned on stored oxygen for the energy to break even. *Checkpoint:* 0.181.

12.7 App challenge · 8 min

Load scenario 2, The minimum load, and change no setting. The schedule asks for 6 MW at 0.5 h and for 2 MW at 1.6 h. Run at 1x with the default seed past 2.6 h, pause and export the CSV file. Use the last rows at or before 0.45 h, 1.5 h and 2.5 h.

(a) Read `jel_A_cm2` and `purity_ppm` in the three rows. *Checkpoint:* 1.296, 0.288 and 0.120 A/cm^2; 61.4, 278.2 and 666.7 ppm, within 1 ppm.

(b) Multiply each reading by its current density and compare the products with $c_0 j_{el,R}$. *Checkpoint:* About 80 in every row.

(c) Read `Pel_MW` in the last row against the 2 MW request, and explain the difference. *Checkpoint:* 2.43 MW.

12.8 App challenge · 8 min

Load scenario 5, The firm evening commitment, and run at 5x with the default seed to about 12 h, then pause and export the CSV file. Pause, Reset, set Oxygen policy to Vent before Run, and repeat. In each file use the last row at or before 12 h.

(a) Read the Margin tile at the pause in each run. *Checkpoint:* $13,287 on Store and $12,830 on Vent, within $5.

(b) Read `metric_h2_used_kg` in each file, and compare the ratio of the two with the 14.3 % rated-point advantage. *Checkpoint:* 3684 kg and 4200 kg, within 2 kg, a ratio of 1.140.

(c) Read `metric_cash_margin` and `metric_hydrogen_value` in each file, and explain which policy the cash alone would favor and why the Margin tile ranks them the other way. *Checkpoint:* $19,610 and −$1,924 on Store; $21,320 and −$4,090 on Vent, within $5.

12.9 App challenge · 10 min

Load scenario 11, the graded challenge, and run all 20 h at 5x with the default seed. Export the CSV file at the end of each run.

(a) Run the case as given. Read the Unserved and Margin tiles, the last value of `metric_trips`, and the clock time of the first trip from that column. *Checkpoint:* 57.60 MWh, −$44,664, 8 trips, the first near 13:50.

(b) Pause, Reset, and set the eight tunings to the defaults of Table 12.4 before Run. Read Unserved, Curtailed and Margin, and the largest `Tel_C` in the file. *Checkpoint:* 0.04 MWh, 10.7 MWh, $5,467 and 78.6 °C.

(c) Reset again and keep the tunings. Set Oxygen policy to Store, the start threshold to 15 % and the two stack temperature setpoints to 62 °C and 66 °C. Read the same values, then check that the last-row `metric_cash_margin` less the hydrogen value loss and `metric_start_cost` gives the margin. *Checkpoint:* 0.07 MWh, 10.4 MWh, $6,959 and 67.6 °C.

Give money within $5 and temperatures within 0.1 °C.

12.10 Application area · 4 min

A plant engineer is asked whether a new electrolyzer, whose fuel cell will run only as backup for a few hours a month, should keep its oxygen. Using the chapter, list what keeping the oxygen costs and what it buys, and give a recommendation with its reason.

12.11 Application area · 3 min

A vendor quotes a PEM electrolyzer with a turndown of ten to one. Explain why a specification should quote a minimum load instead, and what a supervisor should do with a surplus below that load.

12.12 Review the agent · 5 min

An AI assistant reviews the trend of scenario 10 and writes: “After the pinhole at 11:30 the analyzer read 858 ppm at noon, under half of the 1800 ppm limit. The membrane is therefore within specification, and the plant can run until the analyzer says otherwise. Dividing the reading by the current would add nothing, since the analyzer already measures the concentration directly.” Find the flaw and say how you would check it with the app.