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CHAPTER 11

A Salt-Cavern Air Storage Simulator for Inventory Policy Under a Capacity Commitment

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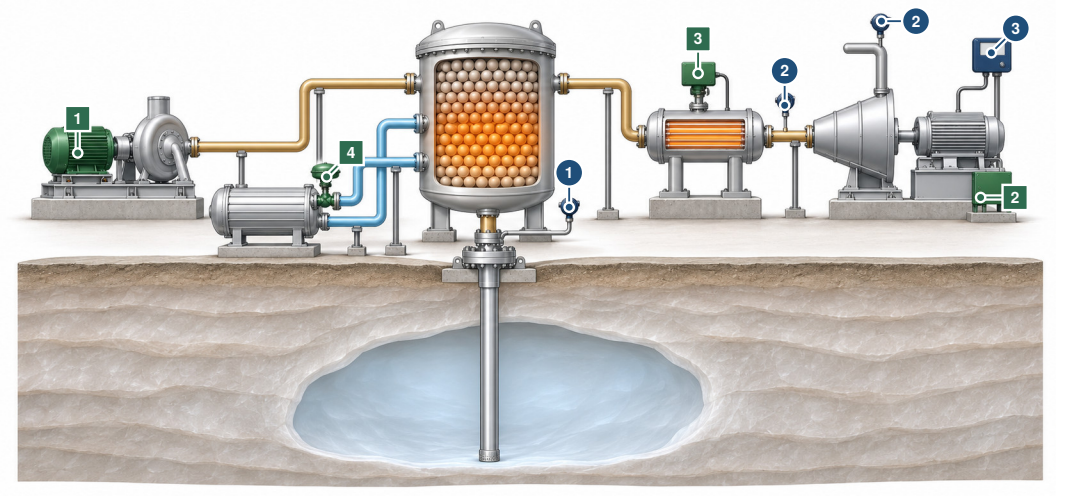
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CHAPTER 11

A Salt-Cavern Air Storage Simulator for Inventory Policy Under a Capacity Commitment



The controller moves 1 compressor and its motor 2 expander load on the generator 3 supplemental heater 4 heat-rejection valve

The controller reads 1 cavern pressure at the wellhead 2 thermometers at the expander inlet and exhaust 3 power meter

Notice that the air passes through the heat store on the way in and on the way out, so the store can run cold while the cavern still holds most of its air. Illustration, not to scale.

IN PLAIN TERMS **Storing Spare Wind as Squeezed Air**

The main idea. When wind power is spare, a compressor squeezes air into a huge hollow in underground salt. Later the air flows back out through a turbine, a machine that the rushing air spins to drive a generator.

The challenge. The air must be warmed before it reaches the turbine. The heat saved from squeezing it runs out in hours, while the air lasts for days. A plant can break its winter promise with most of its air still underground.

Why it matters. The plant is paid to deliver power on the worst winter days, so it must save heat as well as air.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the two history boxes of Section 11.2, the try-it and fact boxes of Section 11.4, the fact and try-it boxes of Section 11.7, and the key points
Study	45 min	The whole chapter with its pause points and the twelve exercises
Practice	15 min	The first page, Section 11.7, Section 11.8, Section 11.9 and the open challenge

The control question A compressed-air plant stores mass in a salt cavern but sells a capacity commitment in megawatts. Which inventory, the gas or the heat, decides whether a winter commitment is kept, and what must a reserve count to protect it?

Learning objectives

- Compute the deliverable power of a fixed-geometry expander from the cavern pressure and the store temperature.
- Compare the gas and heat inventories by capacity, time constant and duration at rating.
- Explain the budget-and-trim split, the capacity floor and the back-calculation limit of an hourly scan.
- Compare three inventory policies and explain why the heater, not the reserve, removes the default.
- Judge a reserve policy against a commitment written in megawatts.

Prerequisites Sections 1.4.4 (storage as an inventory), 1.4.6 (water value), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and data). Chapter 10 is a useful first store with two inventories.

The app https://apmonitor.com/apps/salt-cavern-caes/

See also Volume 9, Chapter 7 (a reservoir held against a forecast), Volume 9, Chapter 6 (a price of heat), Volume 4, Chapter 14 and Volume 4, Chapter 8 (an inventory defended at a floor) and Volume 4, Chapter 2 (the surge override).

11.1 Introduction

The phrase seasonal storage does a great deal of quiet work. A salt cavern of 8×10^6 m^3 cycled between 45 bar and 75 bar holds 253.8 kt of air, which is 24.6 GWh of electricity through the expander train modeled here. That number reads as seasonal and it is 81.9 h at the expander rating, which is three and a half days. The plant is therefore not carrying summer wind into winter. It is being asked to be in the right state on the worst fortnight of the year, while every profitable day between now and then argues for spending the inventory, and nothing in the physics decides that argument.

Underneath the scheduling question is a physical one that is easier to miss and harder to recover from. Stored energy is mass, and deliverable power is a fixed-geometry expander's swallowing capacity multiplied by the specific work available at the cavern pressure. Both fall as the cavern empties, and they fall together. At 75 bar the plant can deliver 282.6 MW. At 50 bar it still holds 3.99 GWh, nearly a day of output at the 175.2 MW it can then deliver. A capacity commitment is sold in megawatts and an inventory policy is written in megawatt-hours, and the constraint that binds first is the one nobody wrote down.

The misconception the application corrects is that a storage plant has a state of charge in the sense a battery does (Section 1.4.4). It has two, the gas in the ground and the heat in the packed bed, they empty on different time scales, and neither of them is the quantity a commitment was made against. The class of problem is inventory management with a state-dependent delivery constraint and a horizon longer than any forecast. Hydropower with a seasonal reservoir, a gas storage field with a contracted withdrawal profile, a refinery tank farm under a shipping schedule and a hospital oxygen system under a surge commitment all share the shape, and the reservoir of Volume 9, Chapter 7 holds empty volume against a storm on the same terms. The classical answer is a marginal water value on the inventory [1], which Section 1.4.6 derives by merit order, and the modern framing is economic model predictive control with the risky part expressed as a constraint [2].

This chapter works with an interactive salt-cavern storage simulator. It gives the model, the control structure and the measured behavior in enough detail that a reader can rebuild them, and it uses them to show that a capacity commitment is defended by the heat in the store as much as by the gas in the ground. The model has ten states for the cavern, the rock and the thermal store, and it computes a capacity floor by bisection on the delivery physics at every scan. The central measurement compares three inventory policies and a seasonal percentage reserve over a simulated hundred and fifty days, and it finds that the heat available to the expander, more than the gas in the ground, decides whether the commitment is kept. With the supplemental heater armed every policy keeps it, at a cost

of 13 GWh to 27 GWh of heat. With the heater off, the threshold rule and the rolling plan default on 0.56 GWh and 0.47 GWh, the operator curve that holds the most gas defaults on 2 MWh, and raising the reserve peak from 25 % to 85 % cuts the plan's default from 1.15 GWh to 0.13 GWh for $1.70 M without meeting the commitment.

Section 11.2 traces the technology from Huntorf. Section 11.3 gives the model, with the deliverability relation at its center. Sections 11.4 and 11.5 give the open-loop character and the regulatory scheme, including the capacity floor and the two overrides. Section 11.6 gives the three inventory policies and the seasonal reserve that bounds them. Section 11.7 reports the scenarios, the policy comparison, the reserve sweep, the drought and the graded challenge. Section 11.8 describes the devices and platforms of a real plant, Section 11.9 states the limitations and Section 11.10 draws the conclusions.

11.2 From Huntorf to a Capacity Market

Compressed-air energy storage has exactly two commercial ancestors and both are still running. The Huntorf plant in Lower Saxony started in 1978 with two solution-mined caverns of about 150 000 m^3 each, operated between 43 bar and 70 bar, and the engineering account of those caverns is the founding document of the subject [3]. Huntorf and the later McIntosh plant in Alabama are diabatic, which means the heat of compression is rejected to atmosphere and natural gas is burned to reheat the air before expansion. That choice is the reason the round-trip efficiency of the first generation is usually quoted at around 42 %, and it is also why the technology is described in the review literature as a hybrid rather than as storage [4].

> ⧖ HISTORY **Huntorf, Built to Restart a Grid (1978)**
>
> The first compressed-air storage plant was completed in 1978 near Bremen in Germany. It was built to provide black-start power, the power that nuclear units near the North Sea need to restart after a complete grid outage, and cheap peak power [5]. Its caverns were first sized for two hours of rated output, later stretched to three, and the plant has been used more and more to balance the growing wind output of northern Germany. Its high-pressure expansion stage came from steam turbine practice, because gas turbines of the time did not suit that pressure range. A recuperator to preheat the air with exhaust heat was left out to keep the start-up short [5].

Adiabatic designs keep the heat. Compressing air to 60 bar in two stages at a polytropic efficiency of 85 % leaves it at 557 K, and a packed bed of rock or ceramic can hold that heat for weeks and give it back before expansion. The concept removes the fuel and adds a second inventory, and the engineering literature on packed-bed stores for this duty is recent and active [6]. A low-temperature variant that accepts a smaller store and a modest fuel burn has been proposed as the practical middle ground [7], which is precisely the trade the simulator's supplemental heater is meant to expose.

> ⧖ HISTORY **McIntosh, a Day of Storage (1991)**
>
> A second plant, of 110 MW, began operating on a salt dome in southwestern Alabama in 1991. It was designed for 26 hours of generation at full power from a single cavern of 560 000 m^3 worked between 45 and 74 bar [5]. Unlike Huntorf it carries a recuperator, which recovers exhaust heat and cuts the fuel burned at full load by about 22 %. Early outages were cured by changes to its combustors, and over ten years of operation its average starting reliability was 91.2 % for generation and 92.1 % for compression [5].

The cavern itself is a thermodynamic object and not a tank. Air entering at aftercooled temperature warms it, withdrawal cools it, and the surrounding salt exchanges heat on a time scale of weeks. Models of that behavior were developed for Huntorf and then generalized, and the review of cavern thermodynamic and hydrodynamic response collects them [8–10]. The mechanical side is a separate literature. Salt creeps, the cavern closes slowly at low pressure, and both the minimum working

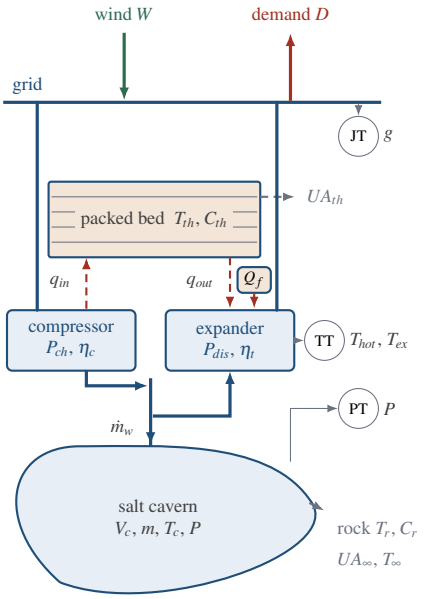


Figure 11.1 Plant arrangement and the symbols used in the equations. Air paths are thick solid arrows and heat paths dashed arrows. A single wellbore carries air in both directions between the compressor train and the cavern, and the rock around the cavern is a thermal capacitance of its own. The packed bed takes the heat of compression on the way in and returns it on the way out, and a supplemental heater Q_f reheats the expander inlet air directly when the bed is too cold. PT measures cavern pressure, TT the expander inlet and exhaust, and JT the grid exchange that the delivery loop controls.

pressure and the permitted rate of pressure change come from a creep analysis rather than from a process requirement [11].

What changed recently is the question being asked. When storage was arbitrage the operating problem was a price forecast. When storage is sold into a capacity market the operating problem is a state constraint, because the plant has undertaken to be able to deliver a stated power when called, and being unable to is a default rather than a trade. The system-level studies of what duration is worth having make the same point from the outside, which is that the value of long-duration storage is concentrated in a small number of hours that cannot be identified in advance [12, 13]. The plant modeled here sits at that junction.

11.3 Process Model

The simulated plant is 850 MW of wind, a 250 MW two-stage intercooled compressor, a 300 MW two-stage reheat expander, a packed-bed thermal store of 6.1×10^{10} J/K, and 8×10^6 m^3 of solution-mined cavern worked between 45 bar and 75 bar. Figure 11.1 shows the arrangement and every symbol used below. The clock is in days, because the horizon is a year. Power is in megawatts, energy in megawatt-hours, mass in kilograms, pressure in bar and temperature in kelvin.

11.3.1 Variables

Table 11.1 classifies what the application exposes. The unusual entry is the inventory reference, which is a state rather than a control, because the supervisory policy writes it through a first-order lag of time constant τ_{ref} rather than stepping it.

Table 11.1 Variable classification

Symbol	Meaning	Unit	Range
Controlled variables			
g	grid exchange, positive short	MW	−900 to 900
S	gas state of charge	—	0 to 1
T_{hot}	expander inlet temperature	K	300 to 590
T_{th}	thermal store temperature (override)	K	320 to 590
Manipulated variables			
P_{ch}	compressor load	MW	0 to 250
P_{dis}	expander load	MW	0 to 300
Q_f	supplemental heat	MW	0 to 120
r	heat rejection	%	0 to 100
Disturbances			
κ_w	wind resource scale	×	0.15 to 1.5
κ_d	demand scale	×	0.7 to 1.4
ΔD	cold snap adder	MW	0 to 200
ε_{fc}	forecast error scale	×	0 to 1.5
States			
m	cavern air mass	kg	to 643 kt
T_c	cavern gas temperature	K	200 to 420
T_r	rock temperature	K	250 to 400
T_{th}	thermal store temperature	K	250 to 620
P^a_{ch}	applied compressor load	MW	0 to 250
P^a_{dis}	applied expander load	MW	0 to 300
Q^a_f	applied heater duty	MW	0 to 120
w	wind variability	—	−1 to 1.6
S_{ref}	inventory reference	—	0 to 1
Φ	cyclic stress accumulator	bar	—

11.3.2 The Cavern

Pressure follows the real gas law with a single linear compressibility correction, solved by three fixed-point passes because the correction depends on the pressure it corrects,

$$Z = 1 + Z_1 P, \qquad P = \frac{m R_s T_c}{V_c}\,\frac{Z}{10^5}\ \text{[bar]}. \tag{11.1}$$

At 70 bar the correction is 2.1 % of the inventory, which over a year is about half a gigawatt-hour and is therefore not negligible. The gas state of charge is defined between the working pressures at the present temperature,

$$S = \frac{m - m(P_{min}, T_c)}{m(P_{max}, T_c) - m(P_{min}, T_c)}. \tag{11.2}$$

The mass balance carries the compressor inflow, the expander outflow and a small cavern loss,

$$\frac{\mathrm{d}m}{\mathrm{d}t} = 86400\,(\dot{m}_{in} - \dot{m}_{out} - \lambda m)\,. \tag{11.3}$$

The cavern energy balance is where pressure and temperature separate. Charging pushes aftercooled air in at 313 K and the cavern warms, withdrawal cools it, and the rock takes weeks to argue,

$$mc_v \frac{\mathrm{d}T_c}{\mathrm{d}t} = 86400\Big[\dot{m}_{in}(c_p T_{after} - c_v T_c) - \dot{m}_{out}(c_p - c_v)T_c + UA_r(T_r - T_c)\Big] \tag{11.4}$$

$$C_r \frac{\mathrm{d}T_r}{\mathrm{d}t} = 86400\left[UA_r(T_c - T_r) + UA_\infty(T_\infty - T_r)\right]. \tag{11.5}$$

The two rock time constants are 40.1 d for the gas to rock exchange and 521 d for the rock to the far field, which is why a cavern that has been cycled hard through a winter is still recovering in the spring.

11.3.3 The Machines

Compression is staged with intercooling. The specific work and the stage discharge temperature follow the polytropic relations,

$$r = \left(\frac{P}{P_{amb}}\right)^{1/n_c}, \quad w_c = \frac{n_c c_p T_{amb}\left(r^{\kappa} - 1\right)}{\eta_c}, \tag{11.6}$$

$$T_{dis} = T_{amb}\left[1 + \frac{r^{\kappa} - 1}{\eta_c}\right], \qquad \kappa = \frac{\gamma - 1}{\gamma} = 0.2857. \tag{11.7}$$

At 60 bar the work is 541.3 kJ/kg, the stage discharge is 557 K, and the compressor at its 250 MW rating passes 462 kg/s. The heat recovered into the packed bed is taken from the *actual* discharge temperature rather than the isentropic one,

$$q_{st} = \eta_{hx}\left[(n_c - 1)c_p(T_{dis} - T_{amb}) + c_p(T_{dis} - T_{after})\right], \tag{11.8}$$

which is 464.5 kJ/kg at 60 bar. That expression has a consequence worth noticing before anybody optimizes the compressor in isolation. Everything the compressor does to the air becomes enthalpy, and the inefficiency makes the air hotter rather than making it disappear, so a compressor with a poorer polytropic efficiency hands the thermal store more heat, not less.

Expansion is staged with reheat to whatever temperature the store can supply,

$$r_e = \left(\frac{P}{P_{amb}}\right)^{1/n_e}, \quad x = r_e^{-\kappa}, \quad w_t = n_e\,\eta_t\,c_p\,T_{hot}(1 - x) \tag{11.9}$$

$$\begin{aligned} T_{hot} &= T_b + \min\left(\frac{10^6 Q_f^a}{\dot{m}_{out} c_p},\; T_{hot,max} - T_b\right) \\ T_b &= \max(T_{amb},\; T_{th} - \Delta T_p) \\ T_{ex} &= T_{hot}\left[1 - \eta_t(1 - x)\right] \end{aligned} \tag{11.10}$$

The heater fires only into flowing air and only up to the inlet limit $T_{hot,max} = 650$ K, and the duty it actually delivers is what is charged as fuel, together with the additional interstage duty. Specifically, $Q_{reheat} = Q_f(n_e - 1)(1 - x)$ and $Q_{total} = Q_f + Q_{reheat}$, where Q_f is the heat actually delivered to the first-stage inlet. Ideal interstage reheaters hold the same fired temperature, and the fuel ledger and the Fuel tile use Q_{total}. The exhaust temperature is a constraint in its own right, because expanding air that was not reheated enough puts the last stage below freezing and what freezes is the moisture in it. Measured at 60 bar, the exhaust falls from 345 K at a store temperature of 590 K to 259 K at 450 K, crossing the 260 K icing limit while the plant can still deliver 207.7 MW. The icing constraint therefore binds before the power constraint does.

11.3.4 Deliverability

A fixed-geometry turbine swallows in proportion to its inlet pressure, so

$$\begin{aligned} \dot{m}_{max} &= \min\left(\dot{m}_w,\; \frac{\dot{m}_e P}{P_{max}}\right) \\ P_{del} &= \min\left(P_{exp},\; \frac{\dot{m}_{max} w_t}{10^6}\right) \end{aligned} \tag{11.11}$$

Table 11.2 Deliverable power and stored energy across the working band

P (bar)	S (—)	Swallow (kg/s)	w_t (kJ/kg)	P_{del} (MW)	Stored (GWh)
75.0	1.000	780	362.3	282.6	25.54
70.0	0.835	728	358.1	260.7	21.07
65.0	0.669	676	353.5	239.0	16.66
60.0	0.502	624	348.6	217.5	12.34
55.0	0.335	572	343.1	196.2	8.11
50.0	0.168	520	337.0	175.2	3.99
45.2	0.007	470	330.4	155.3	0.16

Equation (11.11) is the center of the application, because both factors fall together as the cavern empties. Table 11.2 evaluates it across the working band at a store temperature of 470 K.

Spending 84 % of the stored energy costs 38 % of the deliverable power. That is the sentence the whole application exists to make measurable, and it is the reason the plant carries a capacity floor rather than a percentage reserve.

🕮 **Pause.** Try Exercise 11.1 before reading on.

11.3.5 The Thermal Store

The packed bed is one lumped capacitance charged by the compressor and discharged by the expander, with a standing loss,

$$C_{th}\frac{\mathrm{d}T_{th}}{\mathrm{d}t} = 86400\,[q_{in} - q_{out} - UA_{th}(T_{th} - T_{amb})] \tag{11.12}$$

$$\begin{aligned} q_{in} &= \dot{m}_{in}\, q_{st}\, \Pi\!\left(\frac{T_{dis} - \Delta T_p - T_{th}}{30}\right)(1 - r) \\ q_{out} &= \dot{m}_{out}\, q_e(T_{th} - \Delta T_p)\; \mathbf{1}[T_{th} - \Delta T_p > T_{amb}] \end{aligned} \tag{11.13}$$

where Π clips to the unit interval, r is the heat rejection override and q_e is the expander train's heat draw per kilogram evaluated at the inlet temperature the store alone can reach. The heater's inlet and additional interstage heat are paid for as fuel and are not taken from the store, and a store too cold to warm the air above ambient gives nothing. Heat only moves into the store while the compressed air is hotter than it, and whatever the rejection override dumps never arrives, which is pure round-trip efficiency thrown at the sky and is what a store at its material temperature limit costs. Between its limits of 320 K and 590 K the bed holds 4.58 GWh of heat. Rated discharge from a full cavern with the bed at 590 K draws 332 MW of it, so the useful heat lasts about fourteen hours at rating against 81.9 h of gas. The standing loss time constant is 101 d. The second inventory therefore empties within a day of the first one starting to be spent, and in the third scenario the bed falls 195 K in 16.5 h while the cavern loses 22 points of charge.

11.3.6 The Year

Wind capacity factor is a sinusoid on the day of the year multiplied by a bounded stochastic shape carried as a state, so that a run reproduces exactly,

$$c_f = \bar{c} + \hat{c}\cos\frac{2\pi(d - d_{peak})}{365} \tag{11.14}$$

$$W = \min\!\left\{P_w,\; P_w\,\Pi_{0.02}^{0.95}(c_f\,\kappa_w)\,\Pi_0^{2.6}(1 + w)\right\} \tag{11.15}$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = -\frac{w}{\tau_w} + \sigma_w\sqrt{\frac{2}{\tau_w \Delta t_c}}\,\xi \tag{11.16}$$

with ξ a seeded standard normal drawn once per controller execution and held across it, so that the derivative function stays pure. Demand carries a winter season and a two-harmonic daily cycle, and the price is affine in the net load between a floor and a cap,

$$\pi = \mathrm{clip}(\pi_0 + \beta(D - W),\ \pi_{min},\ \pi_{cap})\,. \tag{11.17}$$

At day 20 the seasonal wind before the stochastic shape is 468 MW against a daily mean demand of 453 MW, and at day 200 it is 179 MW against 226 MW. The shape itself has a mean of about 1.04, because the clip at zero removes more than the clip at 2.6.

11.3.7 Parameters

Table 11.3 gives every parameter the model and controller use, with its default. The V column marks A for adjustable and shown, H for hidden from the beginner view, and F for a fixed physical constant. Four further adjustable entries set only display bands and are omitted.

11.3.8 Initialization and Numerics

Each scenario supplies a starting state of charge, cavern temperature and store temperature. The cavern mass follows from Equation (11.2) inverted at the starting temperature, the rock starts at the undisturbed temperature, and all three actuator states start at zero.

The engine of Section 1.6.1 integrates with classical fourth-order Runge-Kutta on a fixed step of $1/48$ d, which is thirty minutes. The regulatory loops execute every $1/24$ d, which is one hour, the plan re-solves every 0.5 d, and the historian logs the initial state and then one row per simulated hour. A post-step clip holds the cavern mass, the three temperatures, the three actuator states and the inventory reference inside their physical ranges.

The three actuator lags are shorter than the step, with step to time constant ratios of 2.60 for the machines and 5.21 for the heater, and they are not integrated by the Runge-Kutta stages. Each is advanced over the step by its exact first-order solution, and the derivative function evaluates that solution at each stage time, so a commanded load step reaches 92.6 % of its value after one step and a heater step 99.5 %. Carried as ordinary states, the heater lag would lie outside the real-axis stability limit of 2.785 for fourth-order Runge-Kutta and the machine lag would behave as a 1.8 h lag.

11.3.9 Assumptions

1. **The cavern gas is uniform.** A real cavern stratifies during withdrawal and the brine sump at its base exchanges heat and moisture with the air above it [9]. Neither appears here, so the modeled gas temperature swings more than a real one and the wall heat transfer coefficient is a lumped fit rather than a correlation.

2. **The rock is one capacitance and one conductance.** Real cavern wall heat transfer is a diffusion problem whose effective conductance depends on the frequency of the cycling [8], so a single UA_r is right for one cycling rate and wrong for the others.

3. **Salt mechanics appear only as limits.** The minimum working pressure, the maximum pressure and the rated pressure slew come from a creep analysis that is not modeled [11]. The cyclic stress accumulator counts slew beyond the rating and does not feed back into anything.

4. **The packed bed is one temperature.** A real bed has a thermocline whose position matters more than its mean temperature, and the exit temperature during discharge falls in a characteristic way that a lumped capacitance cannot reproduce [6].

5. **The machines are steady-state maps behind first-order lags.** Compressor surge appears only as a minimum load below which the command is zero, and no start cost, minimum run time or thermal stress limit is represented.

Table 11.3 Model parameters and default values

Symbol	Meaning	Value	Unit	V
V_c	total cavern volume	8.0×10^6	m^3	A
P_{min}, P_{max}	working pressure limits	45, 75	bar	A
Z_1	compressibility slope	3.0×10^{-4}	1/bar	H
UA_r	gas to rock conductance	2.6×10^6	W/K	A
C_r	rock heat capacity	9.0×10^{12}	J/K	A
UA_∞	rock to far field	2.0×10^5	W/K	A
T_∞	undisturbed rock temperature	313	K	A
λ	cavern loss rate	2.0×10^{-5}	1/d	A
$\dot{m}_w$	well flow limit	820	kg/s	A
$\dot{\sigma}_{max}$	rated pressure slew	6	bar/d	A
P_{comp}	compressor rating	250	MW	A
P_{exp}	expander rating	300	MW	A
n_c, n_e	compression, expansion stages	2, 2	—	A
η_c	compressor polytropic efficiency	0.85	—	A
η_t	expander isentropic efficiency	0.88	—	A
c_p	air heat capacity	1005	J/(kg K)	H
P_{amb}	ambient pressure	1.0	bar	H
T_{amb}	compressor inlet temperature	288	K	A
T_{after}	aftercooled air into the cavern	313	K	A
f_{surge}	compressor minimum load	0.30	—	A
$\dot{m}_e$	expander swallowing at P_{max}	780	kg/s	A
$x_{e,min}$	expander minimum load	0.15	—	A
P_{aux}	auxiliary load when running	6	MW	A
C_{th}	thermal store heat capacity	6.1×10^{10}	J/K	A
η_{hx}	compression heat recovered	0.90	—	A
ΔT_p	store to air approach	25	K	A
UA_{th}	store standing loss	7.0×10^3	W/K	A
$T_{th,min}$	store useless below	320	K	A
$T_{th,max}$	store material limit	590	K	A
$T_{ex,min}$	lowest allowed exhaust	260	K	A
$Q_{f,max}$	supplemental heater rating	120	MW	A
$T_{hot,max}$	highest fired inlet temperature	650	K	A
d_0	day of the year the run starts	0	d	A
P_w	wind farm rating	850	MW	A
$\bar{c}, \hat{c}$	mean, seasonal swing in c_f	0.38, 0.17	—	A
d_{peak}	day of peak seasonal wind	20	d	A
σ_w, τ_w	wind variability, correlation time	0.85, 0.55	—, d	A
$\bar{D}$	annual mean demand	340	MW	A
D_{win}, D_{diu}	winter adder, daily swing	120, 80	MW	A
π_0, β	price intercept, slope	20, 0.30	$/MWh	A
π_{min}, π_{cap}	price floor, cap	−32, 420	$/MWh	A
c_{unmet}	value of lost load	900	$/MWh	A
c_{fuel}	cost of supplemental heat	46	$/MWh	A
c_{wear}	wear charge on throughput	1.6	$/MWh	A
P_{firm}	firm winter commitment	150	MW	A
d_{from}, d_{to}	firm window	330, 60	d	A
S_{term}	plan's terminal inventory	0.55	—	A
τ_{mach}	machine load response	0.008	d	A
τ_{fuel}	heater response	0.004	d	A
τ_{ref}	inventory reference rate	2.0	d	A
R_s	specific gas constant for air	287	J/(kg K)	F

6. **Air is ideal with one compressibility correction.** At 75 bar and 320 K the single linear term in Equation (11.1) is adequate for inventory accounting and is not a substitute for a real equation of state.

7. **The wind, demand and price are synthetic.** The resource is a sinusoid on an Ornstein-Uhlenbeck process, the demand is two harmonics, and the price is affine in the net load. They are teaching data and are never labeled as measured.

11.4 Open-Loop Character

Manual mode gives the compressor load, the expander load, the heater and the rejection valve directly, and the first experiment shows that the two inventories are not one. The application's third scenario starts a discharge on day 320 with the cavern at 85 % and the store at 560 K and holds an expander command of 280 MW. The expander inlet falls below 500 K after 2.5 h, the exhaust crosses the 260 K icing limit after 7 h (the alarm is raised on the step that ends at 7.5 h), and the store reaches 365 K after 16.5 h, while the cavern pressure goes only from 70.3 bar to 63.8 bar. Delivered power holds the 280 MW command for the first hours and is down to 184 MW at 15 h, and the December reserve floor of 61.4 % ends the discharge at about 18.5 h, before the store reaches its 320 K useful limit. The scorecard at the end of three days reports 3.96 GWh delivered with the cavern still at 62.4 % and the store at 353 K. Deliverable power at that point is 172.0 MW against a nameplate of 300 MW, and nothing about the cavern explains it, because the same 63.7 bar with a 470 K store would deliver 233.2 MW. The scenario's second run gives the expander 60 MW of supplemental heat from the manual station, which keeps the exhaust above its limit for the day and raises the day's delivery from 3.82 GWh to 4.78 GWh for 1.20 GWh of first-stage heat. The Fuel tile, which adds the interstage duty Q_{reheat}, reads more than that.

> **TRY IT IN THE APP** **3 · The Second Inventory, and It Empties First**
>
> Load scenario 3 and press Run. Watch the thermal store temperature beside the cavern pressure. In about 16.5 h the store falls from 560 to 365 K while the cavern goes only from 70.3 to 63.8 bar, and the exhaust alarm comes on after about seven hours.

The second scenario makes the other half of the point. A cavern at 30 % is a cavern at 53.9 bar, and with the scenario's 500 K store that is 204.7 MW of deliverable power (191.8 MW at the 470 K of Table 11.2). It still holds 7.76 GWh. Asked for 300 MW, the expander peaks at 199 MW in the first hour and falls below 150 MW after 11 h, by which time the pressure is 50.5 bar and the store 399 K, and the summer reserve floor of 13.9 % ends the discharge at about 16.5 h, at 49.5 bar and 15.0 %. A fixed-geometry expander swallows in proportion to its inlet pressure, and the specific work falls with the pressure ratio and with the store temperature at the same time.

The time scales are widely separated and that separation is the reason the control problem decomposes. The machine lag is 11.5 min, solved exactly across the half-hour step. The grid exchange the delivery loop controls moves on the hour. The cavern holds 81.9 h at rating, so the inventory moves over days. The rock responds over 40 d and the far field over 521 d. The reserve policy is written for a year. Four decades of time scale between the hourly loop and the yearly decision is more than any single controller should be asked to span, and the architecture in Section 11.5 follows that split exactly.

> **DID YOU KNOW?** **A Storage Plant That Ramps Fast**
>
> The Alabama plant can change its output by about 18 MW per minute, about 60 % faster than a typical gas turbine, and its heat rate rises only from 4330 to 4750 kJ h/kW between full load and 20 % load [5]. Hours of storage, not minutes of response, are the scarce quantity.

Table 11.4 Regulatory loops as implemented

CV	MV	K_c	τ_I (d)	Character
g	P_{dis}	1.1	0.20	direct, trim only
S	P_{ch}	10	2.50	reverse, Any only
T_{hot}	Q_f	0.2	0.15	reverse, costs fuel
T_{th}	r	6	0.40	direct, override

11.5 Regulatory Control

11.5.1 The Discrete Algorithm

Four loops share one proportional-integral-derivative implementation in velocity form, with the derivative taken on the measurement,

$$e_k = \gamma(\mathrm{SP}_k - \mathrm{PV}_k), \quad P_k = K_c e_k, \quad D_k = -K_c \tau_D \gamma \dot{\mathrm{PV}}_k \tag{11.18}$$

$$\begin{aligned} \Sigma_k &= \Sigma_{k-1} + (P_k - P_{k-1}) + (D_k - D_{k-1}) \\ c_k &= u_{bias} + \Sigma_k + I_{k-1}, \qquad u_k = \mathrm{clip}(c_k, u_{min}, u_{max}) \end{aligned} \tag{11.19}$$

$$I_k = I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - c_k}{T_t} \right] \Delta t_c \tag{11.20}$$

These are Equations (1.10) to (1.13) of Section 1.6.2 in this chapter's symbols, with $\Sigma_k = S_k$, $c_k = v_k$ and the action $\gamma = a$, and that section explains the back-calculation and the bumpless transfer from Manual. Here u_k is the demand c_k clipped to the loop limits with no slew limit, the tracking time T_t is τ_I on all four loops, $\Delta t_c = 1/24$ d, and all four loops run with $\tau_D = 0$.

One tuning consequence of the one-hour scan is worth recording. While an output is clipped, Equation (11.20) is a first-order recursion in I with pole $1 - \Delta t_c / T_t$, so the back-calculation is stable only for τ_I above $\Delta t_c / 2$, which is half an hour, and it oscillates for τ_I below an hour. The integral-time sliders stop at 0.08 d for the grid and inlet loops, 0.3 d for the inventory loop and 0.04 d for the rejection override, all above the limit, the last with a pole of -0.04. A value of 0.02 d, below the slider's range, shows what the limit means. In a counterfactual run of the fifth scenario at that value the override's integral, which sits exactly at zero while the store is below its margin, picks up rounding noise and grows by 8 % per scan, the override starts dumping compression heat on alternate scans on day 19.6 of the run, and $|I|$ passes 10^6 by day 24.2. The tuned values are 0.15 d or more.

11.5.2 Four Loops on Four Time Scales

Table 11.4 gives the pairings and default tunings. Two loops are direct acting ($\gamma = -1$ in the convention of Section 1.6.2), because more expander power reduces the grid shortfall and more rejection cools the store. The other two are reverse acting ($\gamma = +1$). The grid loop measures g through a first-order filter of 0.01 d, and the inventory loop measures S through one of 0.02 d against the lagged reference S_{ref}. The inventory loop's output reaches the compressor only when the charging source is set to Any. Every Auto scenario ships with Surplus only, which gives the compressor the wind surplus $W - D - P_{aux}$ up to its rating before the overrides and discards the loop's output, so $K_{c,S}$ and $\tau_{I,S}$ change nothing in those runs and a run with $K_{c,S} = 0$ is bit-identical. The inlet-temperature loop runs only in Auto with the heater armed and the expander running.

The hourly sampled inlet loop uses $K_{c,H} = 0.2\,\mathrm{MW/K}$. A gain of 1.6 MW/K exceeds the sampled-loop stability limit, and its command alternates between zero and the heater rating. The exact actuator lag does not cure a controller scanned too slowly. The gain of the table settles at both the minimum reference flow and the design flow, and all heater-armed results below use it.

Table 11.5 Capacity floor for a 150 MW commitment

Store temperature (K)	S_{cap}, no heat	S_{cap}, heater armed
590	0.000	0.000
500	0.000	0.000
450	0.021	0.000
400	0.190	0.000
350	0.407	0.000

11.5.3 Budget and Trim

The expander is commanded by two numbers that are deliberately kept apart. The budget says how much energy today is worth and comes from the inventory policy. The trim says how much of that budget this hour actually needs, and it is the grid loop. The trim is allowed to reduce the budget and never to exceed it,

$$P_{dis} = \mathrm{clip}(B + u_g,\ 0,\ P_{lim}), \qquad u_g \in [-B, 0]. \tag{11.21}$$

A command below the 15 % expander minimum load is then set to zero, and a scan that asks for charge and discharge together keeps only the larger. The grid loop's own limits see neither cut. Giving the grid loop authority to exceed the budget is the instructive failure, and the application does not offer it as a control. In a counterfactual run with the trim's upper limit raised to the expander rating, the taper of Equation (11.22) still holds the challenge year's minimum inventory at 24.9 %, and the failure arrives as money instead. The loop discharges into deficit hours whose price the plan had refused, and over the hundred and fifty days the margin falls by $2.87 M and curtailment rises by 24.9 GWh.

The discharge limit P_{lim} is not the expander rating. It is the deliverable power of Equation (11.11) multiplied by a taper that closes as the state of charge approaches the binding floor,

$$P_{lim} = \min(P_{del}, P_{exp})\,\Pi\!\left(\frac{S - S_{floor}}{0.04}\right). \tag{11.22}$$

A tapered limit of this kind is the cascade anti-windup of Section 1.4.4, and Chapter 10 tapers the charge and discharge limits of a flow battery in the same way.

11.5.4 The Capacity Floor

Inside the firm window the binding floor is the larger of two quantities. One is the seasonal reserve the year has to end on. The other is the state of charge at which the deliverable power would fall to the commitment, which is computed by twelve bisections on Equation (11.11) at every scan inside the window and is zero outside it,

$$S_{cap} = \min\left\{S : P_{del}\left(P(S, T_c),\, T_{th},\, Q_f\right) \geq P_{firm}\right\}. \tag{11.23}$$

The distinction between S_{cap} and a percentage reserve is the point of the application, because the commitment was sold in megawatts and a percentage is only a proxy for them. Table 11.5 shows how far the proxy drifts.

The same commitment is defended at a state of charge of zero with a hot store and at 40.7 % with a cold one, and a fixed percentage reserve cannot express that. The application draws S_{cap} on the inventory trend alongside the seasonal curve so that the reader can watch the two cross. With the heater armed, which means plant and heater both in Auto, the calculation and the Deliverable tile count the heater up to the inlet setpoint its loop would hold, 500 K by default. At that inlet even the bottom of the band makes 174.5 MW, so the floor is zero at every store temperature in the table, and the heater does deliver that heat when it is called. The floor also uses the store temperature of the present scan, so it rises behind a discharge that cools the store rather than ahead of it.

11.5.5 Two Overrides

The compressor carries a pressure override. Its command is multiplied by a headroom factor that closes over the last 1.5 bar below the maximum working pressure, and below the anti-surge minimum load the command is zero rather than small, because a machine on recycle is pure loss. The surge line that sets such a minimum load is the subject of Volume 4, Chapter 2. Salt does not negotiate about the upper pressure and the override is not a controller with a setpoint, it is a multiplier.

The thermal store carries a rejection override that sits against zero until the bed approaches its material temperature limit. What it rejects never reaches the store, which is round-trip efficiency thrown at the sky, and it is the correct action because a bed above its material limit is a capital loss rather than an efficiency loss.

11.6 Three Inventory Policies

Every architecture in this application is a different way of writing the inventory reference trajectory, and all three are bounded below by the same seasonal reserve, which is a squared raised cosine on the day of the year,

$$S_{res}(d) = \frac{R_{min}}{100} + \frac{R_{peak} - R_{min}}{100} \left[\frac{1 + \cos \frac{2\pi (d - d_{res})}{365}}{2} \right]^2 . \tag{11.24}$$

With the defaults it runs from 12.0 % at day 147.5 in late May to 62.0 % at day 330, and it is 12.2 % in late April. The squared raised cosine is chosen so that the floor is expensive only where it is needed, relaxing quickly through the spring and tightening through the autumn. It is enforced by projection rather than as a penalty term, because a winter reserve that can be bought off with a weight is not a reserve.

The first policy is a pair of price thresholds and nothing else. Empty at rating whenever the price is above the discharge threshold, fill whenever it is below the charge threshold, and never go below the seasonal floor. There is no forecast anywhere in it. With the shipped Surplus only charging source, which every policy uses, the compressor takes the wind surplus whatever the price, and the charge threshold acts only when grid charging is allowed.

The second policy is the operator's own reference curve. The expander budget rises from zero to rating as the measured state of charge climbs from the curve to five points above it, and the compressor follows the error to the curve only when grid charging is allowed.

The third policy is a water value. The marginal value of a megawatt-hour in the ground is the classical answer to this problem [1] and it is far cheaper than an optimizer. Section 1.4.6 reads it from a merit order of forecast prices. The plan here finds it by bisection on a forward simulation instead, as Chapter 6 does for its own store. The plan simulates the next thirty daily blocks forward under a trial threshold price, charging from whatever surplus the wind forecast offers and discharging the forecast deficit plus a quarter of the expander rating, up to the rating, in every block whose price clears the threshold divided by the one-way efficiency $\eta_{plan} = 0.72$, while the seasonal floor stops it selling,

$$\begin{aligned} S_{k+1} &= \mathrm{clip}\left(S_k + \frac{\Delta E_k}{E_{cap}}, 0, 1 \right) \\ \Delta E_k &\geq -\left(S_k - S_{res,k} \right) E_{cap} \end{aligned} \tag{11.25}$$

Raising the threshold sells into fewer days and ends with more in the ground, so the end-of-horizon inventory is monotone in the threshold, and sixteen bisections find the lowest threshold that still meets the terminal target, which moves from the floor at the horizon's end toward S_{term} as the terminal weight rises to 10. That threshold is the marginal value of the inventory. It is computed rather than chosen, it moves by itself when the month turns windy, and dividing it by η_{plan} gives the sell price the expander budget is dispatched against. Nobody has to pick a threshold.

One detail of Equation (11.25) was found by the model failing and is worth stating. The floor stops the plant selling, and it does not manufacture gas. Written instead as a clamp that raises the state up onto the floor, the forward simulation invents energy out of the constraint, the end-of-horizon inventory stops depending on the threshold at all, and the bisection then reports the price floor as the value of everything in the ground.

🕮 **Pause.** Try Exercise 11.3 before reading on.

11.7 Scenarios and Measured Results

Table 11.6 lists the eleven scenarios in selector order with the day of the year each one starts on, the dispatch policy it loads and what a learner must do to complete it. Credit, the challenge and its voiding rule work as Section 1.6.4 describes. Table 11.7 gives the scorecard at the end of each scenario's trend window with the settings as shipped. Every result in this section is for the shipped random seed. Reset keeps the learner's settings and reloading restores the case's own (Section 1.6.1), and a case loaded from the menu or rerun after Reset reproduces the case loaded first exactly. Figure 11.3 shows the eighth scenario sixty-three days into its run.

11.7.1 Three Policies on the Same Hundred and Fifty Days

The comparison the application is built around runs the challenge scenario's year, a hundred and fifty days from day 245 including a sixteen-day December wind drought from day 337 and a 70 MW cold snap that overlaps its end, under each of the three inventory policies with everything else at the challenge's suggested configuration. That configuration arms the supplemental heater, so each policy is also run with the heater left in Manual at zero, which is the purely adiabatic plant. Table 11.8 gives the result.

With the heater armed, all three policies keep the commitment with zero default and no day below it, burning 21.0 GWh, 13.0 GWh and 23.1 GWh of heat for the rule, the curve and the plan, and a pair of price thresholds books \$0.77 M more than the rolling plan, which delivers the most energy. The explanation is in the price model. Price here is affine in the net load, so a price threshold is a net-load threshold, and the net load is exactly the quantity the water value is trying to forecast. A policy that reacts to the present value of a variable it can measure perfectly is hard to beat with a forecast of the same variable. The plan earns its place on the days when price and net load come apart, and this price model never lets them.

The reliability in the upper half of the table is the heater's. Its applied duty stays below the 120 MW limit and is small in the drought itself, but the armed heater counts in the capability whether it fires or not, and measured against the unfired capability the plan would be below the commitment on 28.4 d of the firm window, the rule on 25.5 d and the operator curve on 0.3 d. With the heater off, the rule and the plan default on 0.56 GWh and 0.47 GWh and spend 17.0 and 15.3 days short, while the operator curve, which never lets the inventory below 33.9 %, defaults on 2 MWh and is short for 7 h. Once the stored heat is gone the commitment is protected either by gas held back or by heat bought, and the operator curve, which holds the gas, books the least. Figure 11.2 draws the table as bars.

The year is one seeded realization, so the comparison was repeated on seven other seeds. The margins move by about \$6 M between seeds, the rule books more than the plan with the heater armed in six of eight, the operator curve books the least in all eight, and with the heater off the operator curve has the fewest days short in all eight. The ordering is robust and the size of each gap is not.

> ✦ DID YOU KNOW? **No Forecast, More Money**
>
> From the simulator: with the heater armed, a pair of price thresholds that uses no forecast at all books \$16.04 M over the 150 days, and the rolling plan that looks thirty days ahead books \$15.28 M while delivering the most energy, 128.46 GWh (Table 11.8).

Table 11.6 Scenarios and Completion Requirements

#	Scenario	Day	Policy	Kind	Required to complete
1	Two machines	100	manual	Experiment	In Manual, charge at 250 MW until the cavern pressure exceeds 74 bar, then discharge at 300 MW for one day.
2	Full cavern short of rating	200	manual	Demonstration	At a 300 MW expander command, deliver more than 50 MW for 6 h, then continue until the reserve floor stops the expander (delivery below 5 MW within 2 points of the floor).
3	Second inventory	320	manual	Demonstration	Discharge at 280 MW for one day with no supplemental heat, then Reset, set 60 MW of supplemental heat and discharge for another day.
4	Spring surplus	105	schedule	Experiment	Two 30-day runs, with the inventory reference at 80% and, after Reset, held at 30% from the start (logged reference never above 40%).
5	Price thresholds	200	rule	Experiment	Three 60-day runs with the thresholds at $18 and $62 as shipped, at least $60 apart, and at most $28 apart, each set before the run.
6	Reserve floor in April	95	rule	Experiment	Three 60-day runs with the reserve peak held from the start at 62%, at 90% or more, and at 20% or less.
7	Winter drought	340	rule	Experiment	With the heater armed, run until the inventory has stayed within 3 points of the binding floor for one day of the drought, then on to run day 30.
8	Rolling plan	250	plan	Experiment	Two 90-day runs with the terminal weight held at 8 and, after Reset, at 0.
9	Compressor trip	110	plan	Experiment	Forty days through the scripted loss of half the compressor on run day 4 and its return on run day 18.
10	Forecast bias	300	plan	Experiment	Two 60-day runs with forecast bias scale 1.1 and wind 0.72, with the reserve peak held at 62% and at 77% or more.
11	Challenge	245	rule	Challenge	Over 150 days, default below 0.5 GWh, deliverable power below 150 MW on less than 4 days of the firm window, inventory above 20% and margin above $14.8 M, with the model parameters and disturbances as given.[a]

[a] As shipped (threshold rule at $40 and $45, reserve peak 25%, heater off, weak tuning) the case fails all four clauses, with 1.11 GWh of default, 25.08 days short and a lowest inventory of 19.5%, and its $14.36 M misses the margin. With the suggested settings (rolling plan, reserve peak 50%, heater armed, tuned loops) it passes with 0.00 GWh, 0.0 days, 24.9% and $15.28 M, the same whether entered before Run or carried through Reset, $0.48 M and 4.9 points inside the margin and inventory limits, burning 23.1 GWh of heat. The same settings with the heater off fail with 0.47 GWh and 15.33 days short.

11.7.2 What the Seasonal Reserve Costs

The seasonal reserve peak was swept across its useful range with everything else at the suggested rolling-plan configuration, once with the heater armed and once with it off. Table 11.9 gives the result.

With the heater armed, raising the seasonal reserve from 25 % to 85 % costs $3.11 M of margin, buys 15.5 points of minimum inventory, and leaves the unserved counter at zero at every setting. That zero is not the capacity floor at work, because with the heater armed the capacity floor is zero at every store temperature. It is the heater, which keeps the capability above the commitment through the drought. With the heater off, the same sweep cuts the default from 1.15 GWh to 0.13 GWh and the shortfall from 575 h to 227 h for $1.70 M of margin, and no setting meets the commitment. Across the eight seeds the armed sweep always costs between $3.0 M and $5.0 M, while the reduction in default with the heater off ranges from −0.01 to 1.03 GWh, the shipped seed giving the largest.

🕮 **Pause.** Try Exercise 11.2 before reading on.

The practical lesson survives in a sharper form. A floor in megawatts is in the right units, and

Table 11.7 Scorecard at the end of each scenario window, as shipped

#	Days	Delivered (GWh)	Charged (GWh)	Curtailed (GWh)	Min S (—)	Margin ($M)
1	4	0.00	0.00	32.70	0.472	0.00
2	6	2.65	0.00	21.47	0.150	-0.03
3	3	3.96	0.00	23.56	0.621	-0.11
4	30	20.81	55.92	81.44	0.349	2.59
5	60	34.89	61.70	19.64	0.236	3.93
6	60	57.17	90.61	109.43	0.130	6.60
7	40	40.77	47.03	18.15	0.237	5.22
8	90	81.87	133.14	78.02	0.239	8.98
9	40	52.77	79.71	75.25	0.132	4.70
10	60	39.24	60.26	30.50	0.239	3.86
11	150	115.06	229.62	111.99	0.195	14.36

Table 11.8 Three inventory policies over the same 150 days

Policy	Heater	Delivered (GWh)	Unserved (GWh)	Min S (—)	Hours short	Margin ($M)
threshold rule	armed	118.16	0.00	0.249	0	16.04
operator curve	armed	118.21	0.00	0.339	0	12.34
rolling plan	armed	128.46	0.00	0.249	0	15.28
threshold rule	off	105.87	0.56	0.296	408	15.05
operator curve	off	111.23	0.00	0.339	7	12.19
rolling plan	off	115.52	0.47	0.250	368	14.55

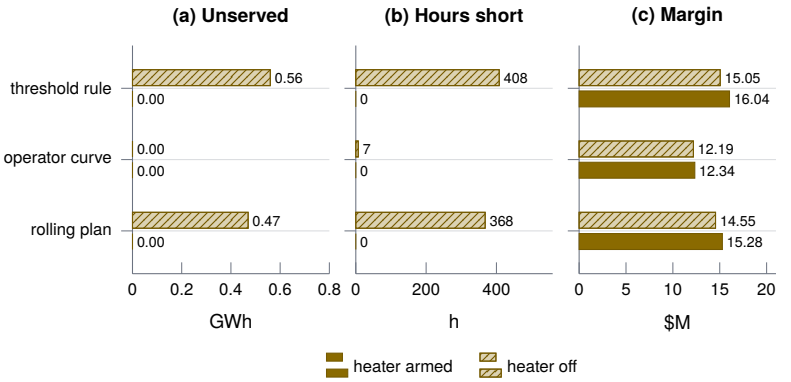


Figure 11.2 The three inventory policies over the same 150 days, from Table 11.8: (a) unserved energy, (b) hours below the commitment and (c) margin. Solid: supplemental heater armed. Hatched: heater off. Notice that with the heater armed every policy keeps the commitment, and that with it off the operator curve, which books the least margin, comes closest to keeping it.

Table 11.5 shows how far a percentage drifts from it. It is computed from the store temperature of the present scan, though, and a discharge into a drought cools the store faster than it empties the cavern, so the floor rises behind the discharge rather than ahead of it. In the challenge year with the heater off, the plan spends from 51 % on day 330 to 31.5 % by day 336, leaves the store near 365 K, and then holds between 147 and 151 MW of capability through the drought while the capacity floor climbs past an inventory the plant can no longer refill. A reserve that protects this commitment has to count

Table 11.9 Seasonal reserve peak swept over 150 days, rolling plan

	Heater armed		Heater off		
R_{peak} (%)	Min S (—)	Margin ($M)	Unserved (GWh)	Hours short	Margin ($M)
25	0.184	16.25	1.15	575	14.65
50	0.249	15.28	0.47	368	14.55
68	0.296	14.02	0.38	333	13.59
85	0.339	13.14	0.13	227	12.95

the heat as well as the gas, and the configurations here that do so are the one that holds more gas and the one that buys heat.

11.7.3 The Drought

The seventh scenario opens on day 340 with the caverns at 80 %, 22.40 GWh on the stored-energy trace, and drops the wind to 30 % of normal for fifteen days with 60 MW of cold-snap demand on top, under the threshold rule with the heater armed. The fortnight needs several times what is stored, so it is not covered and was never going to be. The thermal store goes first. It falls from 520 K to 380 K in twelve hours and to 313 K in a day and a half, near the temperature below which it can no longer warm the air above ambient. The heater rises to about 113 MW by a day and a half, then stops when discharge is no longer scheduled. By day 3 the inventory is near 24.6 % at 52.3 bar. The armed heater is counted in the capability even when it is idle. Over forty days the plant delivers 40.8 GWh, imports 178.2 GWh, burns 12.2 GWh of heat and ends near 24.1 %.

> **TRY IT IN THE APP** **7 · A Two-Week Winter Wind Drought**
>
> Load scenario 7 and press Run. Watch the thermal store temperature for the first two days. It falls from 520 to 380 K in twelve hours and to 313 K in a day and a half, while the supplemental heat rises to about 113 MW to hold the expander inlet.

The instructive trace is the deliverable capacity. The Deliverable tile reads 207.3 MW on the floor, counting the armed heater up to the 500 K inlet setpoint, while the unfired deliverable power of the same cavern and store is 119.5 MW, below the 150 MW commitment. The unserved counter stays at zero because the heater is there to be fired. With the heater left in Manual the capacity floor climbs to 54 % within a day as the store cools to 325 K, and the plant holds 56.5 % of its gas at 61.9 bar while it can deliver only about 149 MW, booking 0.11 GWh of default by day 15 and 0.12 GWh by day 40. The gas is there and the heat is not.

11.7.4 The Graded Challenge

The eleventh scenario opens on day 245 for a hundred and fifty days with weak tuning, the threshold rule at $40 and $45, a reserve peak of 25 %, the heater in Manual and a forecast error scale of 0.6. As shipped it books $14.36 M, defaults on 1.11 GWh of its firm commitment, falls below the commitment on 25.08 d of the firm window and takes the cavern to 19.5 %. The suggested configuration, which is the rolling plan with a reserve peak of 50 % and a spring minimum of 15 % peaking at day 335, the heater armed with a 505 K inlet setpoint, a terminal weight of 10 and the tuned gains, books $15.28 M with no default and a minimum inventory of 24.9 %, burning 23.1 GWh of heat, and the app gives the same run whether these settings are entered before Run or carried through Reset. The difference is $0.92 M and the whole of the reliability gap, and the reliability part of it is the heater. Arming the heater alone on the shipped configuration removes the default and the shortfall for 10.0 GWh of heat and raises the margin to $15.71 M, failing only on its 15.7 % minimum inventory, while the suggested configuration with the heater left in Manual fails with 0.47 GWh and 15.33 d short. Across

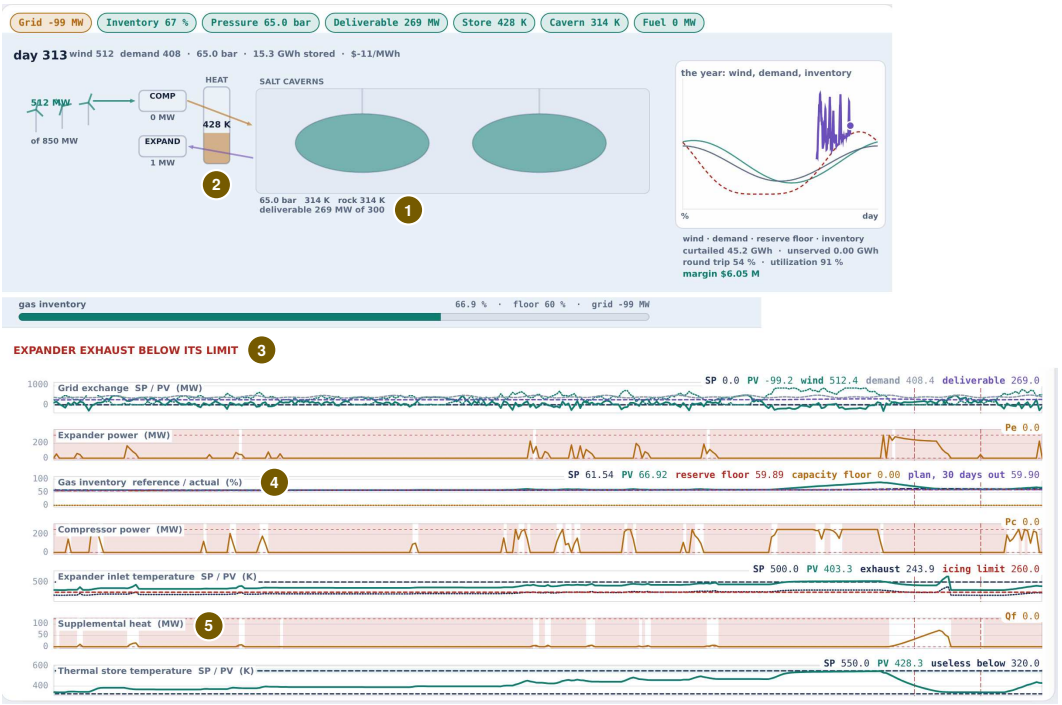


Figure 11.3 The application on day 313 of the eighth scenario, sixty-three days into a rolling-plan run that began on day 250, cut to the plant view and the trends. The callouts mark (1) the deliverable power under the caverns, (2) the thermal store, (3) the exhaust alarm, (4) the inventory trend and (5) the supplemental heat trend. The inventory trend carries the three curves the reader is asked to distinguish, which are the measured state of charge at 66.9 %, the seasonal reserve floor at 59.9 % on its way to its 62 % peak at day 330, and the capacity floor at 0.0 %, because it is computed only inside the firm window that opens on day 330 (and with the heater armed it would read zero there too). The plant has curtailed 45.2 GWh, left 0.00 GWh unserved and booked $6.05 M. The store is at 428 K and the expander, idling at 1 MW, sees 403 K at its inlet against the 500 K setpoint, so the exhaust alarm is active at 243.9 K against the 260 K icing limit, an alarm the dispatch does not act on. The supplemental heat trend shows the heater firing in bursts whenever the expander runs and idle now, and the 269 MW Deliverable badge counts the armed heater up to the inlet setpoint against an unfired 217 MW.

the shipped seed and seven others, the suggested configuration passes six of eight times. Seeds 2 and 3 meet every physical clause but miss the margin target at $14.14 M and $13.46 M. The shipped configuration fails at the default seed. The absolute margin target is a benchmark for that scenario, rather than a guarantee across different synthetic winters.

11.8 Technology in Practice

The instruments and machines of Figure 11.1 are, in a plant, a pressure transmitter on the wellhead, thermometers on the store and the expander, a power measurement at the grid tie, a motor-driven compressor, a heat-rejection valve, a fired heater and an expander train. Figure 11.4 draws the chapter's loops with that hardware in place of the schematic's symbols.

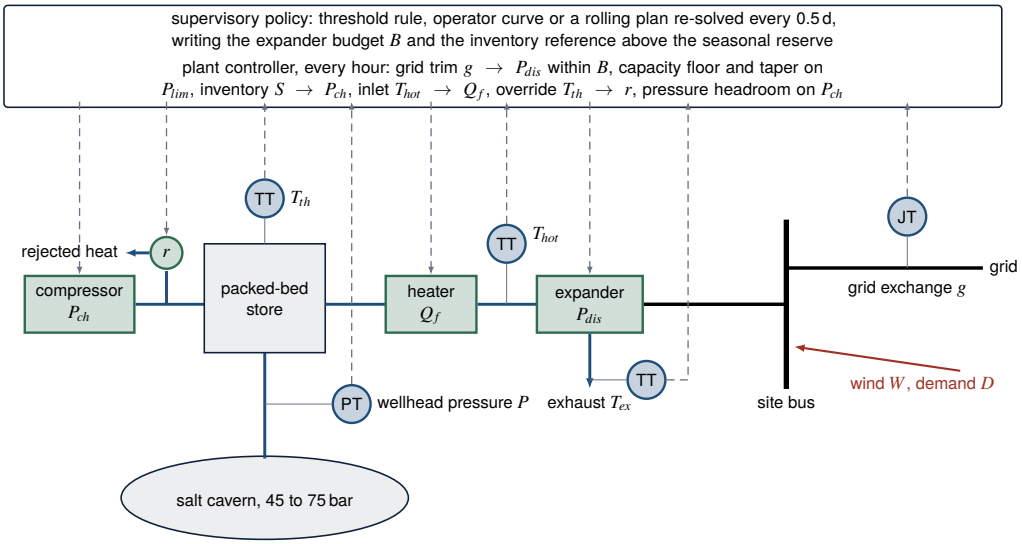


Figure 11.4 The chapter's loops drawn with their hardware. PT reads the cavern pressure at the wellhead, the thermometers TT read the store, the expander inlet and the exhaust, and JT reads the grid exchange at the site's tie. Every hour the plant controller sets the expander load, the compressor load, the supplemental heat and the heat rejection, under a budget that the supervisory policy writes. Wind and demand act on the site bus. Notice that the pressure measures only the gas inventory: the heat inventory is read separately, in the store.

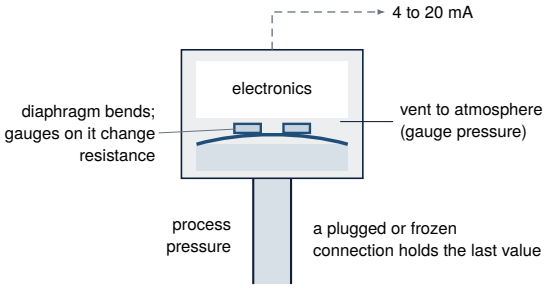


Figure 11.5 Principle of a gauge pressure transmitter. Pressure deflects a diaphragm, strain gauges on it change resistance and the electronics send the reading. Notice that a plugged connection leaves the signal steady while the process moves, which on a cavern looks like an inventory that stopped changing.

What Measures It

The gas inventory is never measured directly. The plant reads the cavern pressure at the wellhead and computes the mass from it and the cavern temperature through Equation (11.1), which is what the chapter's state of charge does. Figure 11.5 shows the principle of the transmitter. The heat inventory needs its own thermometer in the store, and the deliverable power is a calculation from both.

> **TECHNOLOGY** **Sensor: A Pressure Transmitter at the Wellhead**
>
> An electronic pressure transmitter senses the deflection of a diaphragm, with bonded strain gauges or a differential capacitance cell, and sends the pressure as a 4 mA to 20 mA or digital signal [14]. A silicon strain gauge that is overstressed fails completely, while a metal one can drift and still look healthy. A snubber, a small restriction that damps pulsations, can plug with debris, and the reading then responds too slowly or

not at all [14]. On a trend that looks like a cavern pressure frozen while the compressor runs. The chapter's PT is exact, and the inventory is computed from it and the cavern temperature.

What Moves It

Four final elements act on the plant. The compressor's motor sets the charging load, and the chapter's override closes it over the last 1.5 bar below the maximum pressure. A valve rejects compression heat when the store reaches its material limit. A fired heater lifts the expander inlet when the store is too cold, which is the design the two commercial plants use all the time: they burn fuel in the air withdrawn from storage, partly because air expanded without reheating would leave the turbine cold enough to risk icing on its blades [5]. The fourth element, the expander, carries the chapter's lesson about deliverable power.

TECHNOLOGY **Final Element: The Expander and Its Inlet Throttle**

A compressed-air plant sets its output by the air flow through the expander while it holds the inlet temperatures of both stages constant, which keeps the efficiency high at part load [5]. Both commercial plants throttle the cavern air to a fixed turbine inlet pressure, 46 bar at Huntorf and 45 bar at McIntosh, because the turbine is more efficient at a constant inlet pressure, at the cost of a larger cavern. The other option lets the inlet pressure follow the cavern and accepts a falling output [5]. The chapter's expander takes that option, which is why its deliverable power falls with the pressure.

Where the Controller Runs

The four loops of Table 11.4 and the two overrides run in the plant's own controller, and the inventory policy runs above it in supervisory software. Supervisory and lower-level loops of this kind run with cycle times from milliseconds to minutes [15]. The chapter's loops scan once an hour on a thirty-minute physics step and the plan re-solves every half day, because the inventory moves over days. At Huntorf the switch between compressing and generating is fully automated and takes at least twenty minutes, with the plant neither generating nor compressing [5], which the chapter's rule that keeps only the larger of a charge and a discharge command does not represent.

IN PRACTICE **Written Procedures and Integrity Management**

In the United States a solution-mined salt cavern that stores natural gas must meet the recommended practice API RP 1170 under 49 CFR 192.12 [16]. Its operator keeps written manuals for operations, maintenance and emergency response, reviews them at intervals of no more than 15 months and at least once each calendar year, and runs an integrity management program with risk assessments of every cavern and every well, wellhead included [16]. Huntorf itself was built beside a natural gas storage facility of four solution-mined caverns [5].

What Is Modernizing It

Three developments touch this plant. The first is the heat store. Advanced adiabatic designs keep the heat of compression in a thermal store and use it in place of fuel. One concept reached a round-trip efficiency of about 70 % with no fuel, and the stores studied for it range from beds of natural stone and ceramics to molten nitrate salt and oil [5]. The second is the machine train. Separating the compressor and expander, which share one shaft through a clutch at both existing plants, would allow direct switching between charging and generating and standard production compressors [5]. The third is the network. Operational systems increasingly resemble information systems as they adopt standard computers, operating systems and protocols for remote access, which leaves them less isolated and in greater need of security [15]. A plant that sells a capacity commitment depends on that network every time it is called.

11.9 Limitations

The first-stage supplemental heater has a 650 K firing limit rather than a burner model. Ideal interstage reheaters reach the same fired temperature, and their additional duty is charged at the fuel price. The rating and the actuator apply to the first-stage heater, while the Fuel tile and the margin include both it and the additional interstage duty. The model has no separate interstage burner dynamics or heat-transfer limits, and its thermal-store and reheat laws are reduced-order approximations.

The price model makes the forecast-based policy look worse than it should. Price is affine in the net load, so the quantity a price threshold responds to and the quantity the water value forecasts are the same variable, and the comparison in Table 11.8 is therefore a weak test of forecasting. A price model with scarcity events decoupled from the net load would separate them, and the result reported here should be read as a statement about this price model rather than about forecasting in general.

The thermal store is one temperature where a packed bed has a thermocline. The modeled store cools from the first hour of a discharge, by 30 K in the first 2.5 h of the third scenario, where a real bed's exit temperature follows the position of its thermocline [6], so where the icing constraint of Equation (11.10) binds in a real plant depends on the bed's design and not on its mean temperature. A store too cold to warm the air above ambient gives no heat, and the inlet is then held at ambient, an idealization of the air-side exchangers that would be needed.

Salt mechanics are limits rather than a model. The cyclic stress accumulator counts pressure slew beyond the rated 6 bar per day and feeds back into nothing, so a reader can cycle the cavern as hard as the machines allow and see a number rise without consequence. Cavern closure by creep, which sets the minimum pressure in the first place, is absent [11].

The year is one seeded realization. The wind variability reproduces exactly, which is what makes the paired comparisons in this chapter meaningful, and it is a single sample from a distribution. Over seven other seeds the challenge margins move by about \$6 M and the heater-off default of the rolling plan ranges from 0.02 GWh to 0.59 GWh, with 0.47 GWh on the shipped seed. Halving the physics step from 30 to 15 minutes changes the suggested challenge's fuel heat from 23.08 to 22.25 GWh and its margin from \$15.28 M to \$15.36 M, while preserving all four verdict clauses. The hourly controller scan is unchanged; these default-step measurements should not be interpreted as numerically converged energy predictions. Nothing here supports a statement about expected value across weather years.

> ⚠ **OPEN CHALLENGE** **Keeping the Heat of Compression**
>
> A 2022 feasibility study named the energy lost as heat a significant gap. A plant that dissipates the heat of compression is limited to about 50 % efficiency, while recovering it could raise that to about 80 %. A molten-salt store helps, but its finite heat capacity limits the storage and adds cost [17]. Early studies found adiabatic plants too costly unless fuel was very expensive [5]. Progress would be a heat store large and cheap enough to outlast the gas, which is the gap this chapter's drought exposes.

11.10 Conclusion

A salt cavern holding 24.6 GWh is three and a half days at the expander rating, and calling it seasonal storage describes the calendar rather than the plant. What the plant is actually asked to do is be in the right state on the worst fortnight of the year, and the state that matters is not the one on the inventory gauge. Spending 84 % of the stored energy costs 38 % of the deliverable power, and a store cooled to its 320 K useful limit costs another third with the cavern full.

The measured comparison has two results and both are about heat. With the heater armed, every inventory policy and every reserve peak from 25 % to 85 % reports zero default over the hundred and fifty days, at a cost of 13 GWh to 27 GWh of heat, and a pair of price thresholds books \$0.77 M more than the rolling plan because in this price model the threshold responds to the same variable the plan forecasts. With the heater off, the threshold rule and the plan default on 0.56 GWh and 0.47 GWh while the operator curve, which holds the most gas, misses by 2 MWh, and the percentage reserve

reduces the plan's default without removing it. A floor written in megawatts is in the right units and computed at the wrong time, because a drought spends the heat before it spends the gas, and the reserve that protects the commitment is the one held before the store goes cold.

KEY POINTS

- A salt-cavern plant holds two inventories, air in the ground and heat in a packed bed, and the heat runs out first.
- Spending 84 % of the stored energy costs only 38 % of the deliverable power, so a commitment in megawatts is not a percentage of the cavern.
- With the supplemental heater armed every inventory policy keeps the commitment, and with it off the threshold rule and the plan default.
- A floor written in megawatts is in the right units but computed at the wrong time, because a drought spends the heat before the gas.

Where else this applies. An inventory held against a commitment also sets the policy of Volume 9, Chapter 7, and Chapter 10 tapers the limits of a store with two inventories in the same way.

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11.11 Exercises

11.1 Concept check · 2 min

The thermal store is held at 470 K while the cavern pressure falls from 75 to 50 bar, and the deliverable power falls from 282.6 to 175.2 MW. Which explanation is right?

(a) The well flow limit of 820 kg/s binds at low pressure and caps the flow

(b) The expander swallows less air and each kilogram yields less work, and both fall with the pressure

(c) The thermal store cools as the cavern empties, so the expander inlet falls with the pressure

(d) The compressibility correction removes more air at low pressure than at high pressure

11.2 Concept check · 1 min

With the supplemental heater armed, every inventory policy keeps the challenge year's commitment with zero unserved energy, and the capacity floor reads zero at every store temperature. What keeps the commitment?

(a) The capacity floor, which holds back enough gas to make the commitment at any store temperature

(b) The seasonal reserve, which holds enough gas in the cavern to carry the plant through the drought

(c) The supplemental heater, which lifts the expander inlet so the capability stays above the commitment

(d) The threshold rule, which stops selling before the drought because the price follows the net load

11.3 Concept check · 2 min

The plan's forward simulation in Equation (11.25) lets the seasonal floor stop the plant selling. Suppose it were written instead as a clamp that lifts the state back up onto the floor whenever a block ends below it. What would the bisection for the water value report?

(a) A higher threshold, because the plan would then keep more gas in the ground

(b) The same threshold, because the floor binds only in the last days of the horizon

(c) A threshold that swings between re-solves, because the lifted state moves every twelve hours

(d) The price floor, because the end-of-horizon inventory would no longer depend on the threshold

11.4 Theory and calculation · 8 min

Use Equations (11.9) to (11.11) with $n_e = 2$, $\eta_t = 0.88$, $c_p = 1005\,\mathrm{J/(kg\,K)}$, $\kappa = 0.2857$, $P_{amb} = 1\,\mathrm{bar}$, a swallowing capacity of 780 kg/s at $P_{max} = 75\,\mathrm{bar}$, a store-to-air approach of 25 K, an expander rating of 300 MW and no supplemental heat.

(a) The cavern is at 60 bar and the store at 470 K. Find the swallowing capacity, the specific work and the deliverable power. *Checkpoint:* 624 kg/s, 348.6 kJ/kg and 217.5 MW.

(b) Scenario 2 starts at 53.9 bar with the store at 500 K. Find the deliverable power. *Checkpoint:* 204.5 MW, within 0.5 MW.

(c) At 60 bar, find the exhaust temperature with the store at 590 and at 450 K, and say whether the 260 K icing limit or the 150 MW commitment binds first as the store cools. *Checkpoint:* 345 K and 259 K, the icing limit, with 207.7 MW still deliverable.

11.5 Theory and calculation · 6 min

The plant holds two inventories with their own clocks. Use $C_r = 9.0 \times 10^{12}\,\mathrm{J/K}$, $UA_r = 2.6 \times 10^{6}\,\mathrm{W/K}$, $UA_\infty = 2.0 \times 10^{5}\,\mathrm{W/K}$, $C_{th} = 6.1 \times 10^{10}\,\mathrm{J/K}$ and $UA_{th} = 7.0 \times 10^{3}\,\mathrm{W/K}$.

(a) Find the time constants of the gas-to-rock and rock-to-far-field exchanges of Equation (11.5), in days. *Checkpoint:* 40.1 d and 521 d.

(b) Find the heat the packed bed holds between its limits of 320 and 590 K, and how long it lasts against the 332 MW that rated discharge draws. Compare with the 81.9 h of gas at rating. *Checkpoint:* 4.58 GWh and 13.8 h, about a sixth of the gas duration.

(c) Find the standing-loss time constant of the store and say which of the two drains empties it in practice. *Checkpoint:* 101 d. The expander's draw empties it.

11.6 Theory and calculation · 6 min

The loops scan every $\Delta t_c = 1/24$ d with a tracking time $T_t = \tau_I$, and the plant step is $h = 1/48$ d.

(a) While an output is clipped and the error and the running sum are held, Equation (11.20) is a first-order recursion in I with pole $1 - \Delta t_c/T_t$. Find the smallest τ_I for which it is stable and the τ_I below which it oscillates. *Checkpoint:* 0.0208 d (half an hour) and 0.0417 d (one hour).

(b) Find the pole for $\tau_I = 0.02$ d and for the override's slider minimum of 0.04 d. *Checkpoint:* -1.083 and -0.042.

(c) The heater lag is $\tau_{fuel} = 0.004$ d. Find the ratio h/τ_{fuel}, say whether classical Runge-Kutta, whose real-axis stability limit is 2.785, could carry this lag as a state, and find the share of a commanded step the exact solution reaches after one step. *Checkpoint:* 5.21, no, and 99.5 %.

11.7 App challenge · 7 min

Load scenario 2, A full cavern that cannot make its rating, and change no setting: the plant is in Manual with Expander power at 300 MW. Use the default seed.

(a) Before pressing Run, read the Deliverable tile and compare it with part (b) of Exercise 11.4. *Checkpoint:* 205 MW.

(b) Run one simulated day at speed 1 and export the CSV file. Read `dis_MW` in the row at `time_d` 0.0417 (one hour), then find the first row with `dis_MW` below 150 and read its time, `P_bar` and `Tth_K`. *Checkpoint:* 199.2 MW; 11 h (0.458 d), 50.5 bar and 399 K, within 1 MW, 0.1 bar and 1 K.

(c) Find the first row with `dis_MW` below 5 and read `soc_pct` and `floor_pct`. Explain why the expander stops with the inventory still above the floor. *Checkpoint:* 17 h (0.708 d), 15.0 % against 13.9 %.

11.8 App challenge · 8 min

Load scenario 3, The second inventory, and it empties first, and change no setting: Manual, Expander power 280 MW, Supplemental heater on Manual and Supplemental heat at 0 MW. Use the default seed and speed 1.

(a) Run one simulated day and export the CSV file. Find the first row with `Texh_K` below 260, and read `dis_MW` in the row at 15 h (`time_d` 0.625) and `metric_discharge_MWh` in the last row. *Checkpoint:* 7 h (257.7 K), 184.3 MW and 3820 MW h, within 1 MW and 10 MW h.

(b) Pause, press Reset, set Supplemental heat to 60 MW and run one day again. Read `metric_discharge_MWh` in the last row and the Fuel tile, and find the extra energy delivered per unit of fuel heat. *Checkpoint:* 4780 MW h, 1.74 GWh and 0.55.

(c) The chapter reports 1.20 GWh of first-stage heat for this run. Use $Q_{total} = Q_f[1+(n_e-1)(1-x)]$ with the cavern between 70 and 64 bar to explain the Fuel tile. *Checkpoint:* The factor is about 1.45, and $1.20 \times 1.45 = 1.74$.

11.9 App challenge · 9 min

Load the Challenge, From September to the far side of winter. Use the default seed and speed 30, at which a 150-day run takes about five seconds.

(a) Run all 150 days as shipped. Read the Unserved and Margin tiles, read `metric_minsoc` in the last row of the CSV file, and count the rows with `in_firm` equal to 1 and `available_MW` below 150. Say which of the four clauses fail. *Checkpoint:* 1.11 GWh, $14.36 M, 0.195 and 602 rows (25.08 d). All four fail.

(b) Reload, press Reveal suggested tuning and run 150 days. Read the same four values and the Fuel tile. *Checkpoint:* 0.00 GWh, $15.28 M, 0.249, 0 rows and 23.08 GWh.

(c) Reload, apply the suggested tuning, set Supplemental heater to Manual before pressing Run, and run 150 days. Read the Unserved and Margin tiles and count the short rows again. *Checkpoint:* 0.47 GWh, $14.55 M and 368 rows (15.33 d).

11.10 Application area · 4 min

The Huntorf and McIntosh plants are diabatic and burn gas before expansion, while the plant of this chapter is adiabatic with a supplemental heater.

(a) Explain why the supplemental heater turns the adiabatic plant into a hybrid when the store is cold, and what it costs at the challenge's suggested settings at the fuel price of $46 per megawatt-hour of heat. *Checkpoint:* About $1.06 M for 23.08 GWh.

(b) Name two consequences of an exhaust below its icing limit for a real expander, and explain why a lumped store temperature misplaces the moment the limit binds. *Checkpoint:* Ice from the moisture in the air on the last stage, and a thermocline that a lumped model cannot follow.

11.11 Application area · 3 min

A plant owner proposes to protect the winter commitment with a seasonal percentage reserve alone and to retire the supplemental heater.

(a) Use Table 11.9 to say what the reserve achieves with the heater off. *Checkpoint:* The default falls from 1.15 to 0.13 GWh for $1.70 M, and no setting meets the commitment.

(b) Say what a reserve would have to measure to protect a commitment written in megawatts, and why salt mechanics also limit how the cavern is worked. *Checkpoint:* The deliverable power, through gas and heat together, and creep-based pressure and slew limits.

11.12 Review the agent · 5 min

On day 5 of scenario 7, A two-week winter wind drought, an AI assistant reviews the screen and replies as follows. "The cavern sits on its floor at 24 % and the Deliverable tile reads 207 MW, which is 57 MW above the 150 MW commitment. The plant has headroom, so set the Supplemental heater to Manual at zero for the rest of the drought and save the fuel." Find the flaw in the advice and say how it could be checked in the app.