Industrial process flexibility: what is it, and why does it matter?

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As we move to a renewable energy system, understanding flexibility in industrial chemical processes is becoming more and more important. The IChemE Clean Energy SIG is exploring that question in a three-part webinar series, moving from the theory of process flexibility, to what the electricity system needs, and finally to what implementation looks like in practice. But first, what do we actually mean by flexibility?

Our electricity system has to balance supply and demand at every moment, so it has always needed buffers. Traditionally, much of that buffering sat upstream of electricity generation: fuel stocks, gas storage and hydro reservoirs helped generators follow demand. As wind and solar supply more electricity, a growing share of generation follows weather patterns. More of the balancing task therefore moves to the electricity side [1]. Storage shifts electricity through time; flexible demand shifts consumption through time.

How should we design and operate chemical processes when more electricity generation follows the weather rather than demand?

Swaney and Grossmann define operational flexibility as the ability of a process to operate over a wide range of conditions whilst meeting its performance specifications [2]. Dimitriadis and Pistikopoulos extended this idea to dynamic systems [3]. Calvin Tsay and his collaborators have applied these ideas to the scheduling and control of industrial processes responding to electricity-system conditions [4].

Consider a simple system: a variable-speed pump feeds a tank with a minimum and maximum operating limits. Assume the downstream process is flow-controlled and continuously withdraws a constant flow.

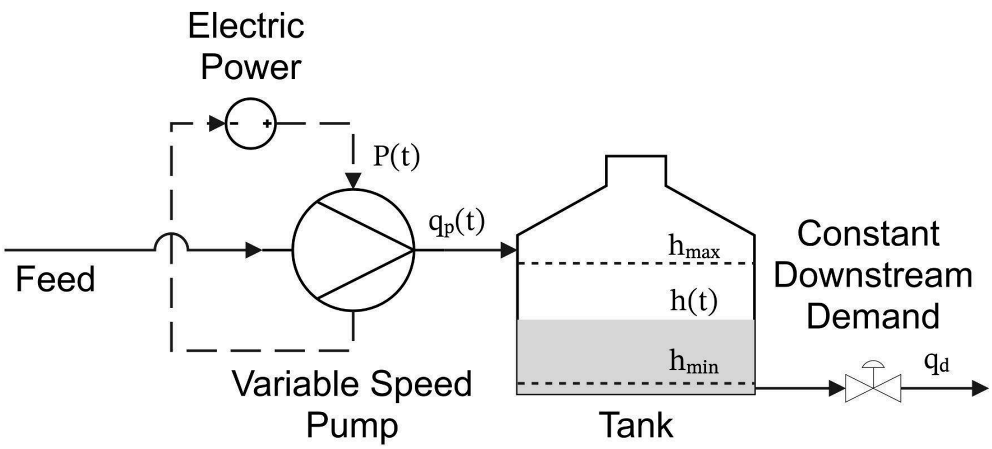

Figure 1: A variable-speed pump and buffer tank allow electrical power and pump inflow to vary while maintaining the required downstream flow.

The material balance is

$$A \frac{dh}{dt} = q_{p(t)} - q_d$$

where A is the tank cross-sectional area, $h(t)$ is the tank level, $q_{p(t)}$ is pump inflow, and q_d is the downstream flow requirement. The left-hand side is the rate of accumulation in the tank.

For a simple pump, let flow be proportional to electrical power:

$$q_{p(t)} = \beta P(t)$$

where $P(t)$ is pump electrical power and β is the flow delivered per unit of power.

The operating limits are

$$h_{min} \leq h(t) \leq h_{max}$$
$$P_{min} \leq P(t) \leq P_{max}$$

If $\beta P = q_d$, the level is steady. At higher power, the tank fills; at lower power, the level drops. The tank acts as the buffer, and its level is analogous to a battery's state of charge.

Even in this simple system, the flexibility available at any moment depends on where the tank starts and how long a change in pump power must be sustained. Let h_0 be the initial tank level and τ the duration of the requested response. For a chosen τ, Figure 2 shows how the tank constraints bound cumulative pump electricity, together with two feasible paths that return the tank to its starting level. The graph reveals three important properties of flexibility.

1. Flexibility is state-dependent. A nearly full tank contains enough water to support the downstream process while pump power is reduced. A nearly empty tank does not.
2. Flexibility is directional. A full tank has substantial ability to reduce pump power, but little ability to increase it without overflowing. An empty tank has the opposite capability.
3. Flexibility is time-dependent. A large change in pump power may be feasible for a few minutes but not for several hours. Increasing the requested duration narrows the feasible region.

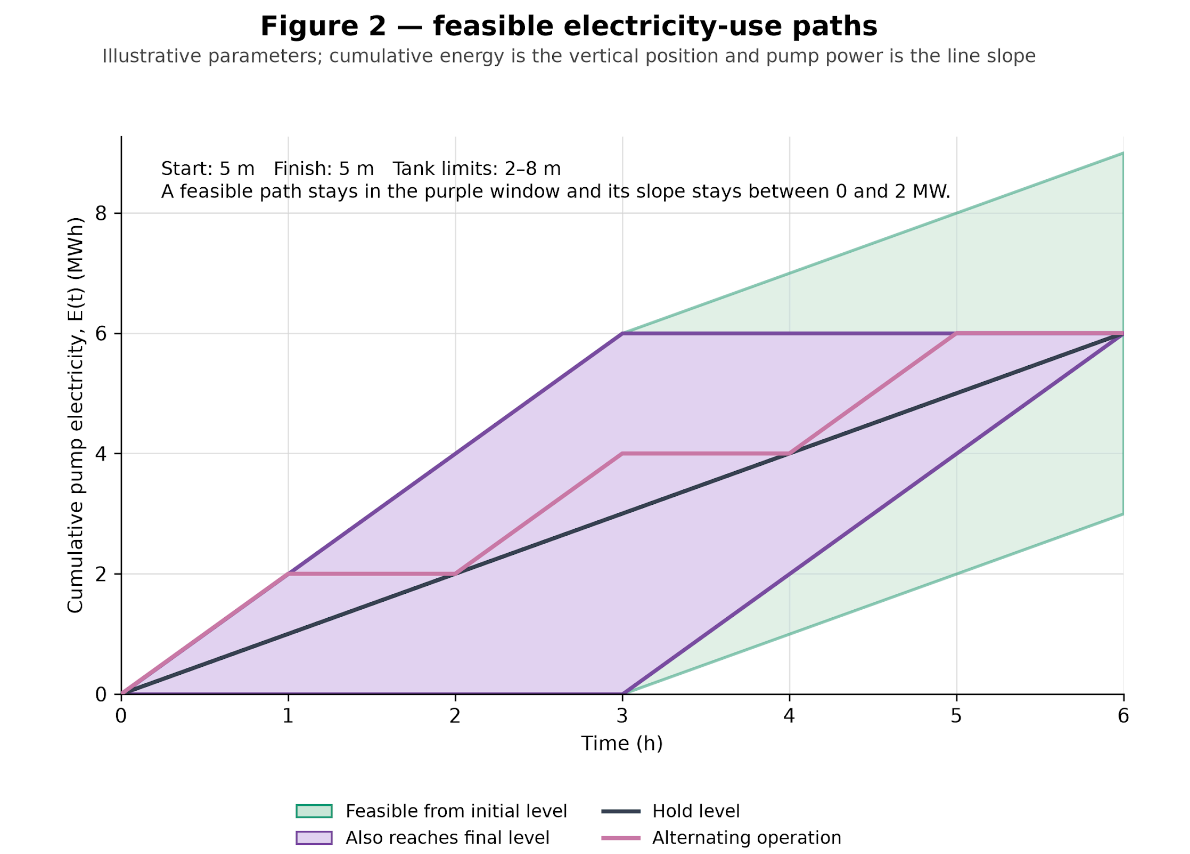

Figure 2: Feasible cumulative electricity-use paths for the pump and buffer tank. Each path respects the tank-level and pump-power limits and returns the tank to its initial level.

Let $c(t)$ be the electricity price at time t. Over a scheduling horizon of length H, we could choose the pump-power trajectory $P(t)$ to minimise electricity cost:

$$min \int_0^H c(t)P(t)dt$$

With the constraint, $h(H) = h(0)$

In this simplified model, the strategy is intuitive: pump more when electricity is cheap, store water in the tank, and pump less when electricity is expensive. At the same time, the tank supplies the downstream process. The tank and pump limits determine how far the load can be shifted and how early the pump must begin preparing.

Process engineering creates flexibility. Electricity prices determine how that flexibility is used.

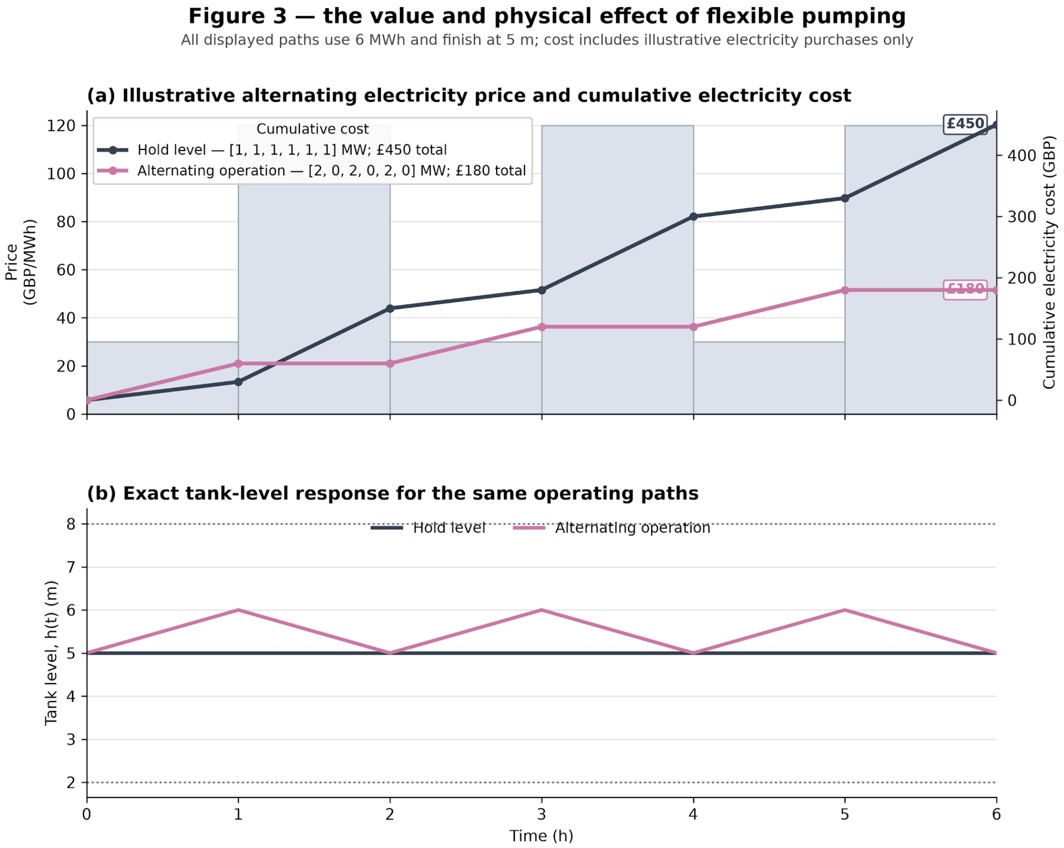

Figure 3: Two pumping schedules use the same total electricity and finish at the same tank level, but shifting pumping to lower-price periods reduces the illustrative electricity cost from £450 to £180. The lower panel shows the corresponding tank-level trajectories.

The tank example is deliberately simple. A chemical plant has many state variables: temperatures, pressures, compositions, inventories, equipment conditions and product states, which we collect in $x(t)$.

We describe the operating variables we can adjust: flow rates, setpoints, compressor loading and production rate, as $u(t)$.

External conditions: ambient temperature, feed conditions and product demand, $w(t)$.

The process dynamics can then be written compactly as

$$\frac{dx}{dt} = f(x(t), u(t), w(t))$$

Here, f represents the material and energy balances, and the other equations that govern how the process changes over time.

The process must remain within its operating limits:

$$g(x(t), u(t), w(t)) \leq 0$$

Here, g captures its physical, safety, equipment, product-quality and production constraints.

The plant's electrical power demand depends on its state, our operating choices and external conditions:

$$P(t) = P(x(t), u(t), w(t))$$

We can now ask the same question as for the tank: from its present state, which electrical-power trajectories can the plant follow without violating its constraints?

A real plant is more complex, but the underlying logic remains the same. Moreover, our simple example already hints at some representative challenges: dynamically coupled decisions, satisfying physical constraints, and making decisions under uncertainty. Understanding how process equations and constraints define flexibility empowers industry professionals to optimise plant operation and energy use effectively.

This is the problem Calvin Tsay has been working on: how process dynamics, constraints, scheduling and control can help maximise the flexibility an industrial plant can provide.

In the first webinar of our series, Calvin will take us deeper into the theoretical foundations of process flexibility. In the second session, NESO will explain what the electricity system needs from industrial processes and how organisations can get involved, including routes to participation and where to find further information. A final case study will then bring both perspectives together, showing what implementation looks like in actual industrial settings.

In other words, the series follows the problem from **process capability** → **system need** → **real-world delivery**.

How to get involved
To take part in the series, visit the IChemE Clean Energy SIG events page for session dates and registration details. The first webinar, led by Calvin Tsay, is on 15 September; James Kerr will lead the NESO and Power Responsive session on 13 October. Bring questions about your site's operational constraints and what you would need to know before participating in flexibility services. NESO will share links during its session for those who wish to get involved or receive further information.
https://www.icheme.org/knowledge-networks/communities/special-interest-groups/clean-energy/events/

References

[1] Parliamentary Office of Science and Technology, Timothy Capper, and Josh Oxby. *Demand Side Response: A Tool for Lowering Household Energy Bills*. Parliamentary Office of Science and Technology, 2024. https://doi.org/10.58248/PN715.
[2] Swaney, R. E., and I. E. Grossmann. 'An Index for Operational Flexibility in Chemical Process Design. Part I: Formulation and Theory'. *AIChE Journal* 31, no. 4 (1985): 621–30. https://doi.org/10.1002/aic.690310412.
[3] Dimitriadis, Veniamin D., and Efstratios N. Pistikopoulos. 'Flexibility Analysis of Dynamic Systems'. *Industrial & Engineering Chemistry Research* 34, no. 12 (1995): 4451–62. https://doi.org/10.1021/ie00039a036.
[4] Tsay, Calvin, Ankur Kumar, Jesus Flores-Cerrillo, and Michael Baldea. 'Optimal Demand Response Scheduling of an Industrial Air Separation Unit Using Data-Driven Dynamic Models'. *Computers & Chemical Engineering* 126 (July 2019): 22–34. https://doi.org/10.1016/j.compchemeng.2019.03.022.