Virtuous and vicious cycles in the energy transition

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Feedback loops shape the pace and direction of the clean energy transition by accelerating or resisting change. Researchers and practitioners can draw on these feedback loops as practical heuristics to understand and manage the transition.

Main

Feedback loops can be virtuous drivers of, or vicious obstacles to, the energy transition. Reinforcing feedback loops amplify small changes, tending to create runaway growth or sudden collapse. Dampening feedback loops resist change, promoting stability despite shocks or intervention.

In this comment, we extend on insights from previous work[1] to describe six feedback loop dynamics as system archetypes[2]—typical patterns of system behaviour that occur repeatedly across different sectors, technologies, and geographies—relevant to the energy transition. These archetypes provide researchers and policymakers with valuable heuristics for understanding change and making decisions across diverse settings.

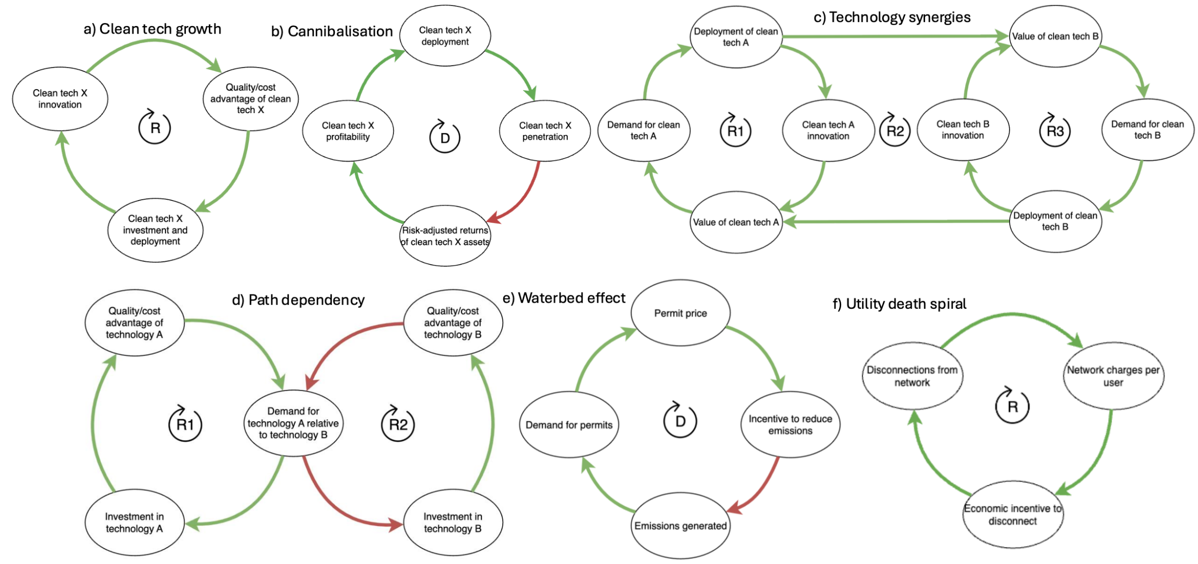

Figure 1: ***Causal loop diagrams depicting six system archetypes***. *A| Clean technology growth. B| cannibalization. C| technology synergies. D| path dependency. E| waterbed effect. F| utility death spiral. Green arrows represent positive causal relationships (variables move in same direction), red arrows represent negative causal relationships (variables move in opposite directions). Reinforcing feedback loops are marked with an "R" and dampening feedback loops are marked with a "D".*

Self-amplifying technology growth

Increasing returns to adoption can lead to non-linear growth in the deployment of many new technologies via a reinforcing feedback loop (*Figure 1a*). As a technology becomes cheaper, it is deployed more widely, driving investment and further cost declines, leading to yet more deployment. This virtuous cycle depends on an inverse relationship between technology adoption and costs, which can arise through economies of scale, learning-by-doing, and network effects[3].

Many technologies, particularly smaller and modular ones, exhibit this feedback, including solar PV, wind turbines, and batteries[4], with their adoption and cost declines outpacing expectations.

This reinforcing effect has been a primary driver of energy transition progress to date, and was ignited by targeted policies—such as feed-in tariffs, public procurement programmes, and deployment subsidies—that supported early adoption of clean technologies despite initial high costs and pushback. Researchers and policymakers should therefore identify nascent clean technologies with cost-reduction potential, then provide support for deployment to kickstart and strengthen this virtuous cycle.

Clean power technology revenue cannibalisation

In the power sector, revenue cannibalisation can act as a dampening feedback loop, slowing down clean technology adoption before full decarbonisation is achieved. This occurs when the increasing deployment of a technology undermines its own risk-adjusted returns, threatening future investment (*Figure 1b*).

Distinct from a technology reaching market saturation, cannibalisation occurs when technologies' falling risk-adjusted returns prevent their deployment reaching the level needed for efficient system-wide decarbonisation. Technologies can therefore become uninvestible, yet undersupplied.

Solar PV and wind power are the most well-known victims of this vicious dampening loop—increasing grid penetration levels have been observed to depress wholesale market revenues of these technologies in markets across the world[5]. This is due to the near-zero short-run marginal costs and temporal correlation in generation patterns of each technology, within the context of marginal pricing in electricity markets. Cannibalisation has also become an emerging threat to battery storage investment[6]. Further research is required to identify cannibalisation effects in other domains beyond the power sector.

Breaking this vicious dampening cycle requires reshaping markets to better align new technologies' profitability with their contributions to desired outcomes. In practice, this can entail de-risking and/or diversifying assets' revenues. For wind and solar, policymakers can de-risk projects by decoupling revenues from volatile wholesale markets, at least partially. Different kinds of contracts, such as power purchase agreements, contracts for difference, and revenue cap-and-floor mechanisms have proved effective to this end[7].

Technology synergies

A synergistic, reinforcing relationship between two (or more) technologies can drive down costs and promote diffusion for both (*Figure 1c*). These synergies—technical, economic, and/or institutional—mean that deployment of one technology strengthens the case for deploying the other.

A prominent example is the relationship between renewables and energy storage: growth in intermittent renewables generation enables storage arbitrage, and storage deployment can fortify the economic value of renewables. Other pairs of synergistic technologies include electric vehicles and charging infrastructure[8], and distributed renewables and smart grid technologies[9].

To leverage these synergies, policy should aim to enable a co-evolution of technologies, ensuring that lagging deployment of one does not constrain deployment of the other. Government support is needed to overcome chicken-egg dilemmas; for example, insufficient charging infrastructure can constrain battery electric vehicle (BEV) adoption, and vice versa.

Path dependency and lock-in

When two or more technologies or technology systems are in competition with each other, an initial advantage to one can allow it to more effectively acquire the resources necessary for further growth—like capital, social acceptance, and political support. This creates path dependence, whereby a head start to one or the other can be amplified and result in entrenched market dominance (*Figure 1d*).

Examples of this archetype exist in many sectors, at the levels of both clean technology choice and disruption of incumbent fossil fuel regimes. In road transport, proponents of BEVs and hydrogen fuel cell vehicles competed for investment and policy support until around 2008, when BEVs took a clear lead and swiftly became the dominant zero-emissions vehicle technology[10]. At the system level, a lock-in dynamic has maintained the dominance of internal combustion engines over zero-emissions alternatives for decades. This is now starting to be unwound as the quality, cost advantage, infrastructure, and public perceptions of BEVs improve.

Sectors that are strongly locked-in to incumbent systems present first mover risks, deterring early investments in clean technologies. Policies to create new markets and/or de-risk projects, such as capital subsidies or offtake agreements, coupled with R&D support to bring clean alternatives to maturity, can begin to shift investment[11]. As confidence in the transition grows, first-mover risk gives way to late-mover risk—the risk that firms (or producer countries) could lose market share by transitioning too slowly. Inverting the risk paradigm is key to channelling finance towards clean technologies and breaking lock-in.

Waterbed effects in carbon markets

An emissions trading scheme (ETS) aims to drive efficient decarbonisation by pricing carbon, but its effectiveness can be constrained by waterbed effects, in which reducing emissions in one firm or sector can lead to emissions growth elsewhere in the system.

In a typical ETS with a fixed emissions cap, any cuts to emissions—whether by improving efficiency or deploying zero-emissions technologies—weaken demand for emissions permits. Since permit supply is fixed at any moment in time, weaker demand puts downwards pressure on permit prices. Lower permit prices then reduce incentives for further decarbonisation, creating a self-limiting effect (*Figure 1e*). Any progress that an ETS makes in cutting emissions would thus erode its ability to drive further progress.

When an ETS covers multiple industries and/or geographies, this dampening feedback acts across sectoral and jurisdictional boundaries, exacerbating the waterbed effect. Policies that constrain this dampening feedback, such as a market stability reserve[12], can make the ETS more effective.

The utility death spiral

Many energy systems rely on centralised grids with high fixed costs that are spread across a large user base. As distributed and/or low-carbon solutions become increasingly cost-competitive with traditional centralised options, users may leave the network, forcing fixed network costs to be shared across ever fewer users. This can become a reinforcing feedback loop in which remaining users' bills increase, strengthening the cost advantage of grid disconnection and driving further disconnections (*Figure 1f*).

If risks are not managed, snowballing disconnections could lead to the stranding of utilities' network assets. This dynamic looms in various settings, from the UK's gas network[13] to Pakistan's electricity grid[14]. To manage network decommissioning, regulators must devise clear plans and timelines, set appropriate asset depreciation rates, and support vulnerable ratepayers by funding disconnections[15].

This loop could also work in reverse: migration of new customers to the electricity grid via electrification could spread network costs across a wider user base, putting downwards pressure on standing charges and making further electrification more attractive.

Using these archetypes

Effective decisions and analysis in the energy transition must be sensitive to feedback effects that drive, or resist, structural change. The feedback loops described above capture patterns of system behaviour that occur across different sectors, technologies, and geographies. These analytical tools are flexible—they can be used in communication, evaluation, and to directly inform policymaking, modelling, and other analyses. Researchers, analysts, and policymakers need to start using these powerful heuristics to improve their shared understanding and drive rapid progress in the energy transition.

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Competing interests

S.S. is Managing Director and M.C. is a Research Associate at S-Curve Economics CIC, a non-profit think tank dedicated to advancing understanding of the transition to clean technologies.