# System Archetypes of the Energy Transition

## Feedback loops and levers of change

2025

s-curve economics

Environmental *Change* Institute

eci

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“If you are an investor, a policy maker or an industrialist involved in the energy transition, you need the right tools to navigate a successful path to the future. Mainstream thinking assumes incremental change, simple cause-and-effect relationships, and linear growth. This paper explains why these old tools are not up to the job, and lays out in simple language a set of systems archetypes to be applied by the practitioner who doesn't just want to survive this transition, but thrive by leading it.”

***Nigel Topping, UN Climate Change High-level Champion, COP26***

“Reaching net-zero emissions will involve a structural transformation of the global economy. Feedbacks, coordination games and non-linear dynamics are key to understanding the possible futures ahead. This readable brief clearly explains such dynamics, making great use of causal loop diagrams, and offers valuable policy lessons along the way.”

***Cameron Hepburn, Battcock Professor of Environmental Economics, The University of Oxford***

“So far, the energy transition has advanced not because of what we've constrained, but because of what we've enabled. Governments accelerate innovation when they move beyond pricing externalities and start shaping markets—by understanding the systems in which new technologies emerge, amplifying feedback loops, and removing barriers to scale.”

***Katherine Dixon, Regulatory Assistance Project CEO***


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# Contents

## Introduction

# The clean energy transition is a process of disruptive innovation and structural change.

The clean energy transition is a process of disruptive innovation and structural change. The creation of zero-emissions energy systems entails adopting new technologies and fundamentally reshaping markets, institutions, and industries at a scale and pace hitherto unseen. All the while, governments must balance multiple objectives: improving energy access, keeping prices low, and ensuring energy security, as well as reducing emissions.

Navigating the transition successfully requires an awareness of its dynamics. Change is often non-linear; cause and effect are disproportionate; system interactions can be complex and unpredictable. As a result, interventions can achieve much more, or much less, than their intended outcomes.

These dynamics can be understood in terms of feedback loops. A reinforcing feedback loop exists when an increase in one variable leads to a causal chain that results in a further increase in the same variable, tending to amplify impact or accelerate change. Conversely, a dampening feedback loop exists when an increase in one variable leads to a decrease in the same variable, tending to limit change or preserve stability. The behaviour of a system arises from these feedbacks and the interactions between them.

System archetypes are typical patterns of system behaviour, which may be repeated in diverse settings.[1] In this policy brief we describe ten such archetypes that are already occurring in the energy transition. Governments that recognise these patterns when they arise, or anticipate them before they do, will be better able to understand and manage structural change, to craft policies that achieve their desired effects, and to manage the risks and take the opportunities of the transition.

*1 Kim Daniel, H. (2000). System archetypes I: Diagnosing systematic issues and Designing High-leverage Interventions. Waltham, MA, USA: Pegasus Communication, Inc.*

# Feedback loops

We use causal loop diagrams to illustrate these archetypical feedback loops that influence the transition. In the diagrams, a green arrow indicates that when one variable moves in a certain direction (increase or decrease), it causes the next variable to move in the same direction. A red arrow indicates that change in one variable causes the next variable to move in the opposite direction. The letter 'R' indicates a reinforcing feedback, and the letter 'D' indicates a dampening feedback.

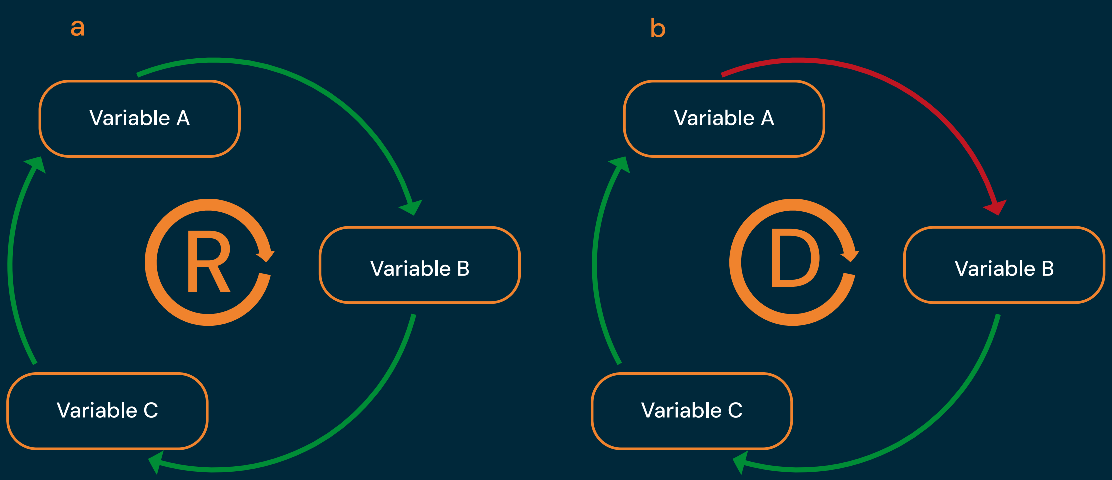



*Figure 1: Example causal loop diagrams (CLDs) showing a reinforcing feedback loop (1a) and a dampening feedback loop (1b). Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions). Loops with an even number of negative causal relationships are reinforcing feedbacks; loops with an odd number of negative causal relationships are dampening feedbacks.*

Reinforcing feedbacks may be helpful or unhelpful for policy objectives, and the same is true of dampening feedbacks. For each system archetype, we describe the relevant feedback mechanisms, examples, and policy implications.

The annex to this brief includes practical guidance on the use of systems mapping with causal loop diagrams, the analytical technique in which feedback loops are identified and used to understand system behaviour.

Report

# Ten system archetypes of the energy transition

## [1] Reinforcing feedbacks of clean technology development and diffusion

### FEEDBACKS

Many technologies benefit from reinforcing feedbacks that drive their development and diffusion. These feedbacks include:[2]

i) **Learning by doing:** as cumulative production and deployment grow, the technology is improved and its costs fall.

ii) **Economies of scale:** as production is scaled up, unit costs decrease, typically through both direct scale economies in units or factories, and through enhanced supply chains

iii) **Network effects and emergence of complementary technologies:** as adoption increases, synergistic relationships develop between the technology, users, institutions, and complementary technologies.

These effects together produce a reinforcing feedback where investment drives innovation and improvement, leading to increased demand, incentivising further investment. This is the core feedback that drives a technology transition.

*2 Arthur, W. B. (1994). Increasing Returns and Path Dependence in the Economy. University of Michigan Press.*

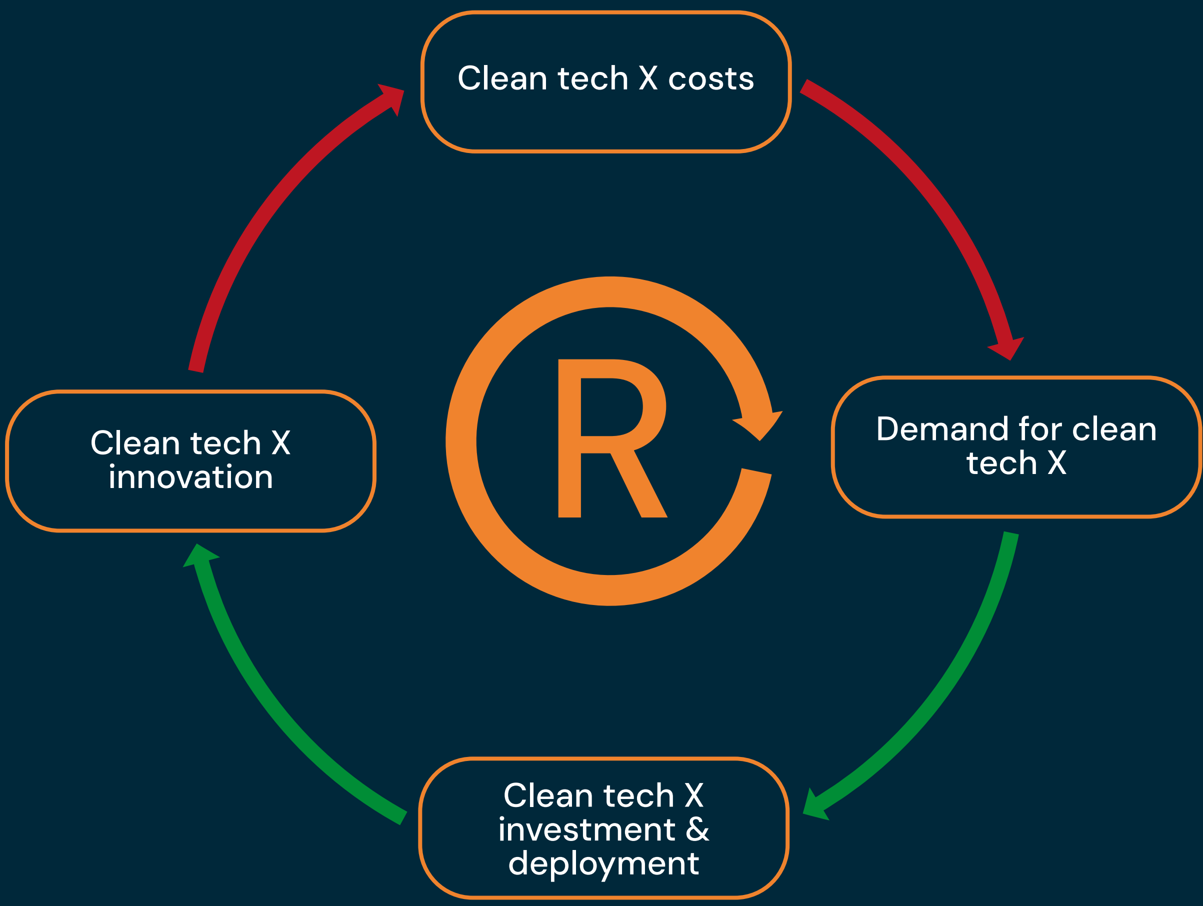



*Figure 2: A reinforcing feedback loop of clean technology development and diffusion. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).*

## EXAMPLES

Solar photovoltaics and wind turbines benefit from these reinforcing feedbacks. This is why growth in their adoption has been non-linear, surprising many governments with its pace. Government targets set in 2006 implied that global solar PV capacity would reach around 50 GW by 2020,[3] but the actual installed capacity in 2020 was over 700 GW,[4] more than ten times the level expected. More recently, China met its 2030 target—1200 GW of wind and solar power capacity—in 2024, six years ahead of schedule.

*3 Beinhocker, E., Farmer, J., & Hepburn, C. (2018). The tipping point: How the G20 can lead the transition to a prosperous clean energy economy. G20 Insights.*
*4 International Renewable Energy Agency. (2021). Renewable Capacity Statistics 2021.*

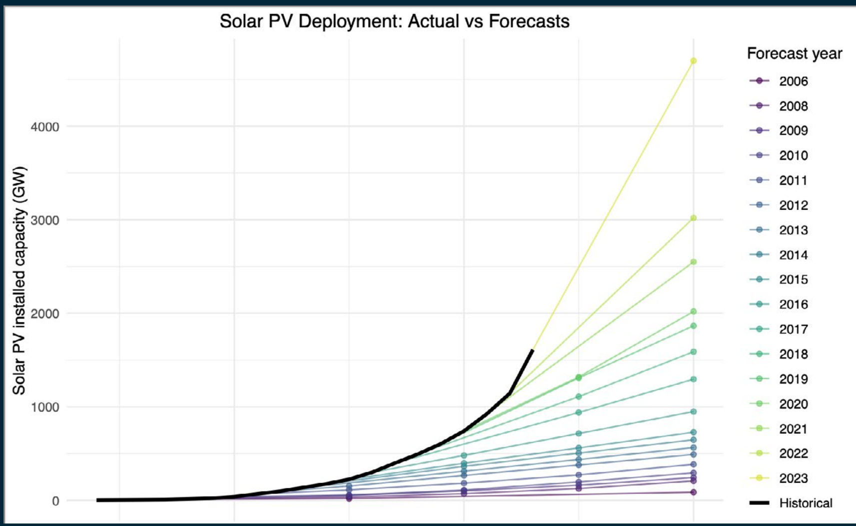



*Figure 3: Comparison of global solar power PV deployment projections against actual deployment. Different coloured curves represent projections made in different years. The black, emboldened line shows historical deployment.*

Batteries and electrolysers also benefit from this reinforcing feedback, as evidenced by the cost reductions that accompany their increasing deployment.[6] For each technology, this feedback will work most powerfully in the sector where it is deployed at the largest scale. For batteries, this is road transport. For electrolysers, it may prove to be fertilisers or chemicals.

Some other clean technologies appear not to benefit from this reinforcing feedback. These include nuclear power[7], hydropower, and biofuels.[8] Some research suggests that a technology's cost-reduction potential may be stronger if it has smaller and more variable unit sizes (implying lower unit costs), and more standardised, replicable production processes; on the other hand, large, complex, and/or site-specific technologies may be less likely to experience sustained cost declines.[9] Technologies that do not experience cost declines may still play useful roles in the transition; for example, hydroelectric power can be valuable for balancing a grid with high volumes of solar and wind; and nuclear power may be particularly useful in countries with high technological capabilities, strong governance, and limited available land area.

## POLICY IMPLICATIONS

Early in the transition to clean power, the most important policies were those that enabled this feedback to start operating, by supporting the deployment of early solar and wind plants. Feed-in tariffs served this purpose in many countries; bulk public procurement played a similar role in others.[10] More recently, governments have used contracts-for-difference (CfDs) to support deployment at larger scale, extending this feedback. As the transition progresses and the cost of renewables becomes lower than that of coal or gas power, the removal of other barriers to deployment—such as through accelerated permitting processes, grid expansion, and market reforms to support renewable power integration—becomes increasingly important to lessen the effect of dampening feedbacks associated with system constraints.

In other greenhouse gas-emitting sectors, policies that directly strengthen reinforcing feedbacks in the development and diffusion of clean technologies—such as deployment subsidies, public procurement, and clean technology mandates—are likely to be particularly effective in driving the transition through its early stages.

*5 Source: Authors. Data from International Energy Agency World Energy Outlook reports. Projections are from the Stated Policies Scenario or equivalent*
*6 Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. Joule, 6(9), 2057-2082.*
*7 Small modular reactors may be an exception, but this is not yet known.*
*8 Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. Joule, 6(9), 2057-2082.*
*9 Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., & Zimm, C. (2020). Granular technologies to accelerate decarbonization. Science, 368(6486), 36–39.*
*10 Nemet, G. F. (2019). How solar energy became cheap: A model for low-carbon innovation. Routledge.*

# [2] Success to the successful: path dependence in technology choice

## FEEDBACKS

Where different technologies compete for market share within a sector, each may benefit from reinforcing feedbacks of development and diffusion, but the growth of one may inhibit the growth of the other (unless they are complementary). This can create a particular form of path dependence: a small initial advantage to one technology can be amplified into dominance.

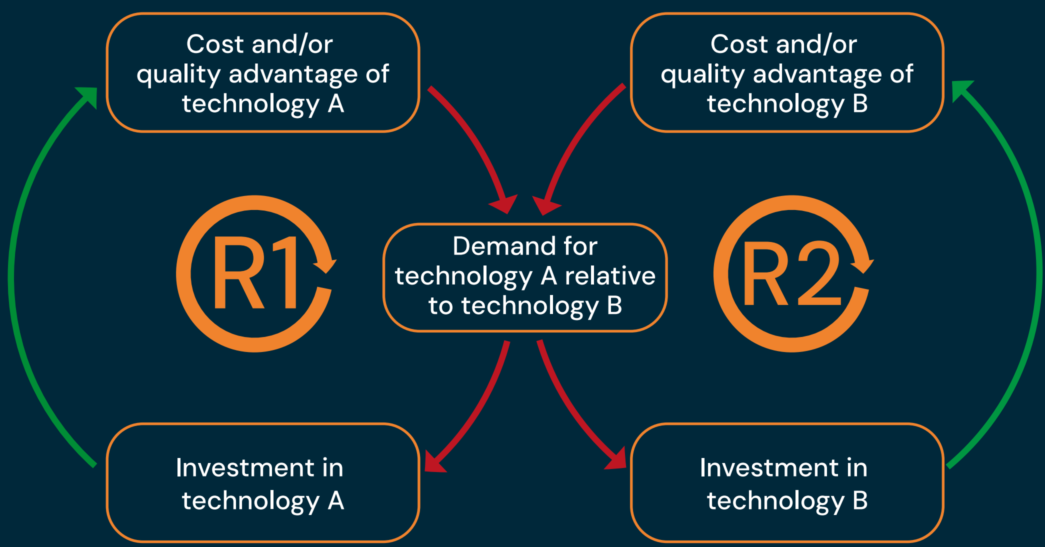
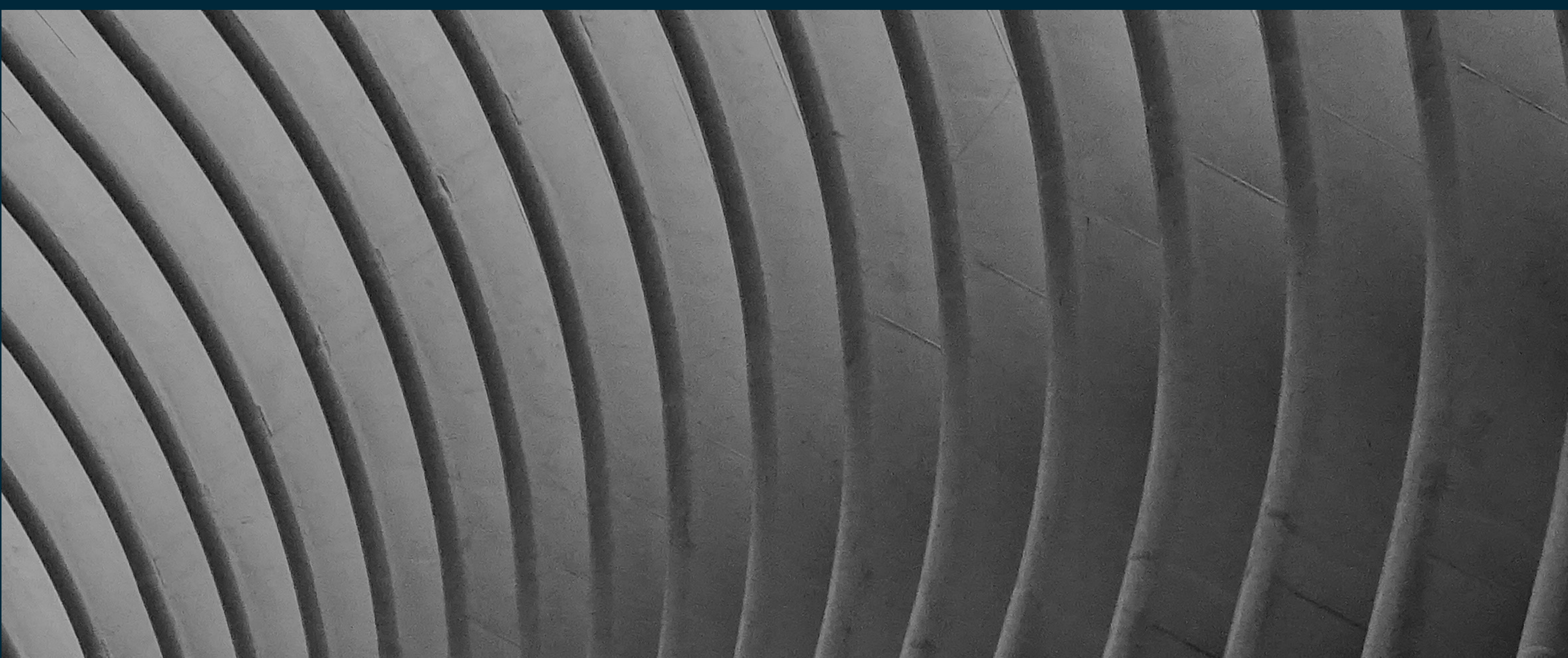



*Figure 4: CLD showing two reinforcing feedback loops that together lead to path dependence in technology choices. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).*



## EXAMPLES

In the road transport transition, battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) have both been developed as zero-emission technologies. Both had a near-zero share of the global car market in 2010, but BEVs had the advantages of inherently superior efficiency, existing infrastructure networks (electricity grids exist in most countries, whereas hydrogen grids do not), and technological improvements from cross-sectoral spillovers[11]. Although governments have supported both technologies, the dynamic of competing reinforcing feedbacks has amplified the advantages of BEVs leading to their dominance as the zero-emissions vehicle technology, and a corresponding decline in the prospects for FCEVs. The former's share of global car sales is now around 20%, whereas the latter's remains near zero.

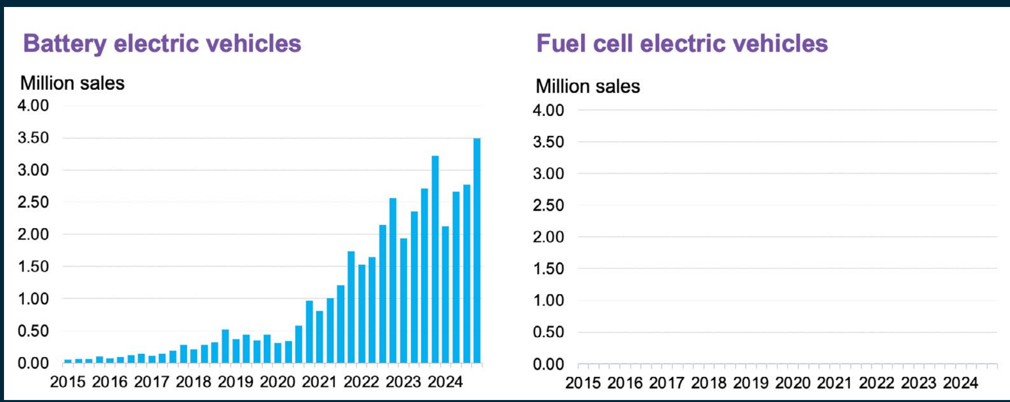



*Figure 5: Comparison of global sales of battery electric vehicle and fuel cell vehicles over 2014-21. Scales are identical in the left and right charts[12].*

For many years, a similar dynamic also served to maintain the dominance of internal combustion engine (ICE) vehicles over low-emissions alternatives. Now, as BEVs approach quality and cost parity with ICE vehicles (following years of investment and active policy support), we may see this dynamic reversed, with technological competition driving a self-amplifying shift to BEVs.

In the power sector, the leading clean technologies of solar and wind have not exhibited this path-dependent competition effect because they are not functionally equivalent (there may be wind at a time when there is no sun, and vice versa). In many systems, indeed, they are complementary, for example in terms of seasonal patterns.

*11 Dugoua, E., & Dumas, M. (2024). Coordination dynamics between fuel cell and battery technologies in the transition to clean cars. Proceedings of the National Academy of Sciences, 121(27).*
*12 Source: BloombergNEF, Liebreich Associates.*

## POLICY IMPLICATIONS

Governments often try to design policies that are technology neutral, but in practice this is usually impossible. A policy intended to be technology neutral will typically advantage whichever technologies are more mature, or more supported by existing infrastructure and market structures. For example, a zero-emissions vehicle mandate is likely to result in the deployment of BEVs, not FCEVs. The reinforcing feedbacks illustrated above will tend to amplify this advantage over time. Instead, governments can aim to identify technologies that are establishing dominance in global or national markets, and align or adjust policies to influence technology outcomes deliberately, rather than accidentally.

In the road transport transition, the dynamic of technology competition operates strongly at a global scale. This creates risks of waste and losses for governments and companies that continue to invest in FCEV, or ICE, technologies.

Active policy support may be necessary when policymakers wish to avoid path-dependent lock-in to incumbent technologies or only those clean technologies with initial advantages. In the UK power sector, if deployment subsidies had been provided at the same level for all clean power technologies, only onshore wind and solar would have been deployed. Offshore wind was initially more expensive; as such, larger subsidies were needed to spur development and activate its feedbacks of investment, innovation, and cost reduction. This had valuable results: the cost of offshore wind fell by two thirds within a decade,[13] becoming cheaper than gas power, and offshore wind now provides 17% of the UK's generation.[14]

In countries with plentiful sunlight, the faster cost reduction of solar PV compared to wind power could lead to solar taking a dominant share of investment and deployment.[15] Modelling suggests that in some cases it may be useful to limit this dominance, since a combination of solar and wind power may be able to balance the power system at lower cost.[16] Furthermore, promoting diversity among generation sources may reduce total system costs once balancing is taken into account, and may also bring other advantages in terms of energy security or non-economic benefits.

Conversely, technological uncertainty may delay clean energy investment when no technology has a clear advantage. Firms and governments may be left unwilling to make bets and invest under such uncertainty, thus slowing the transition. This risk currently exists in sectors such as shipping, aviation, steel, and cement. In these instances, it may be necessary for policy to make clear the technology characteristics that are desired, and then to support investor confidence and network effects necessary to scale up investment, innovation, and deployment.

*13 Jennings, T., Tipper, H. A., Daglish, J., Grubb, M., & Drummond, P. (2020). Policy, innovation and cost reduction in UK offshore wind. The Carbon Trust.*
*14 The Crown Estate. (2024). UK Offshore Wind Report 2023.*
*15 Nijsse, F. J. M. M., Mercure, J.-F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., & Pollitt, H. (2022). Is a solar future inevitable? (Working Paper 2022/02). Global Systems Institute.*
*16 Pasqualino, R., Cabello, A., Pereira, M. D. C., Young, C. E. F., Roventini, A., Martins, A. C., ... & Sharpe, S. (2023). Energy transition in Brazil: innovation, opportunities and risks. p. 42. The Economics of Energy Innovation and System Transition (EEIST).*

# [3] Limits to success: the dampening feedbacks of renewables cannibalisation

## FEEDBACKS

In liberalised power markets, as the share of solar and wind in power generation increases, several dampening feedbacks are likely to make it increasingly difficult for this share to continue to rise.

**i) Merit order effects (loop D2, Figure 7):** as the solar and wind share of generation increases, higher-cost generation sources are increasingly pushed out of the merit order, as they are needed less often. This leads to lower market clearing prices at times of high variable renewables supply, reducing revenues to renewable generators and undermining the case for further investment.

**ii) Price volatility (loop D1, Figure 7):** an increasing share of solar and wind in generation is likely to increase the volatility of electricity spot market prices, reducing the predictability of revenues. This could increase the cost of capital, undermining further investment.

**iii) Volume risk (loop D3, Figure 7):** the expansion of solar and wind power makes it more likely that there will be periods when generation is curtailed, either due to technical constraints, market processes, or surplus supply. This risk weakens incentives for further investment in renewables. However, at the same time it may provide new opportunities for energy storage—see archetype no. 4.

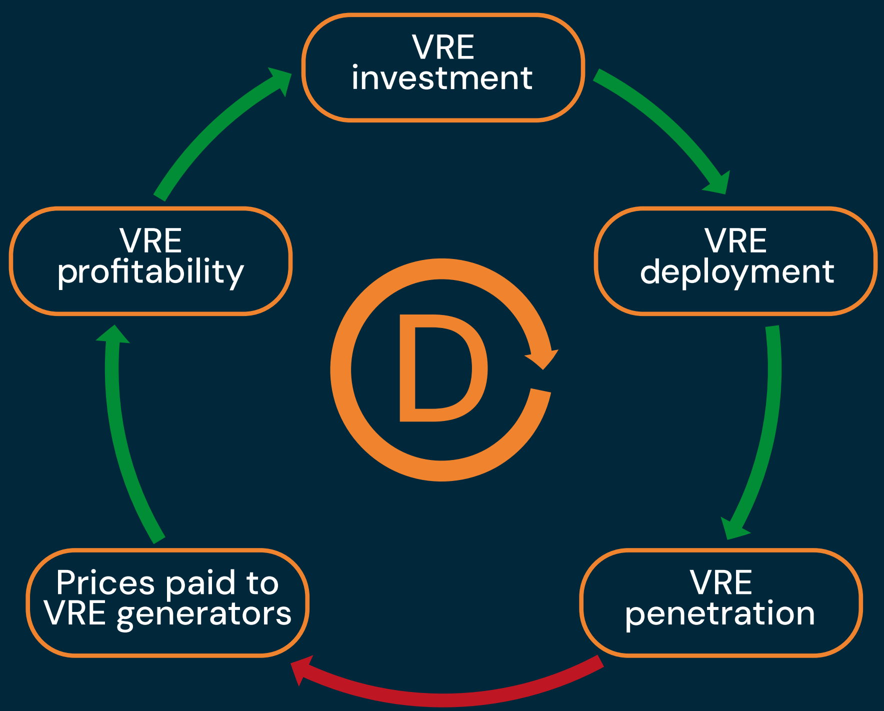



*Figure 6: The dampening feedback loop of VRE (variable renewable energy) revenue cannibalisation. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).*

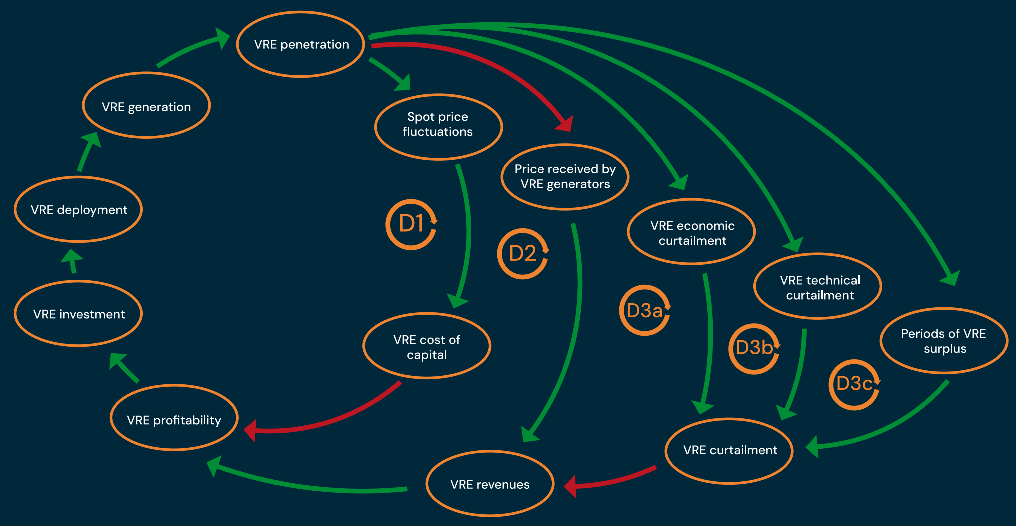



*Figure 7: CLD showing the multiple channels through which VRE (variable renewable energy) cannibalisation can occur. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).*

Inevitably, more volatile and/or (on average) lower wholesale prices associated with such cannibalisation would tend to deter investors if they depend on these for revenues, hence the policy responses as noted below.

In any technology transition, there is inevitably a point where the dampening feedback of market saturation becomes more powerful than the reinforcing feedbacks of technology development and diffusion. The interaction of these feedbacks is what creates the S-curve of technology adoption that is typical of transitions past and present.[17] The problem in the power sector is that the specific characteristics of its technologies and markets could result in the case for investment in solar and wind being undermined long before they are deployed at the scale required in a zero-emissions energy system.

## EXAMPLES

Merit order effects (loop D2, Figure 7) have been observed to depress capture value of variable renewables in electricity markets across the world.[18] For example, researchers estimate that solar power unit revenues fell by $1.30/MWh for each percentage point increase in solar penetration in California over the years 2013–2017.[19]

In the UK, before the introduction of CfDs in 2014, wholesale electricity price volatility discouraged investment in capital-intensive renewable energy assets (loop D1, Figure 7),[20] despite the revenue boost provided by Renewable Obligation Certificates. CfDs stabilised revenue expectations, which attracted bank finance, reducing financing costs and supporting ongoing renewables investment, enabling the continuation of related positive feedback loops.

As for volume risk (loop D3, Figure 7), analysis of the UK system suggests that without any sources of storage or flexibility, renewable power generation would exceed electricity demand for more than 50% of the time by 2030,[21] potentially leaving generators unable to sell their power. This threatens to undermine the case for investment now, despite variable renewables currently accounting for only 35% of generation.[22]

*17 Speelman, L., & Numata, Y. (2022). A Theory of Rapid Transition: How S-Curves Work and What We Can Do to Accelerate Them. RMI.*
*18 Halttunen, K., Staffell, I., Slade, R., Green, R., Saint-Drenan, Y.-M., & Jansen, M. (2020). Global Assessment of the Merit-Order Effect and Revenue Cannibalisation for Variable Renewable Energy (SSRN Scholarly Paper 3741232). Social Science Research Network.*
*19 López Prol, J., Steininger, K. W., & Zilberman, D. (2020). The cannibalization effect of wind and solar in the California wholesale electricity market. Energy Economics, 85, 104552.*
*20 Maximov, S., Rickman, J., Gross, R., & Ameli, N. (2024). Policy, Risk and Investment in UK Offshore Wind Capacity. UK Energy Research Centre.*
*21 Brown, C., Maximov, S., Price, J., & Grubb, M. (2024). Generating surplus: the challenges and opportunities of large-scale renewables deployment. UCL Institute for Sustainable Resources Electricity Market Series Working paper #6.*
*22 NESO. (2025). Britain's Electricity Explained: 2024 Review. National Energy System Operator (NESO).*

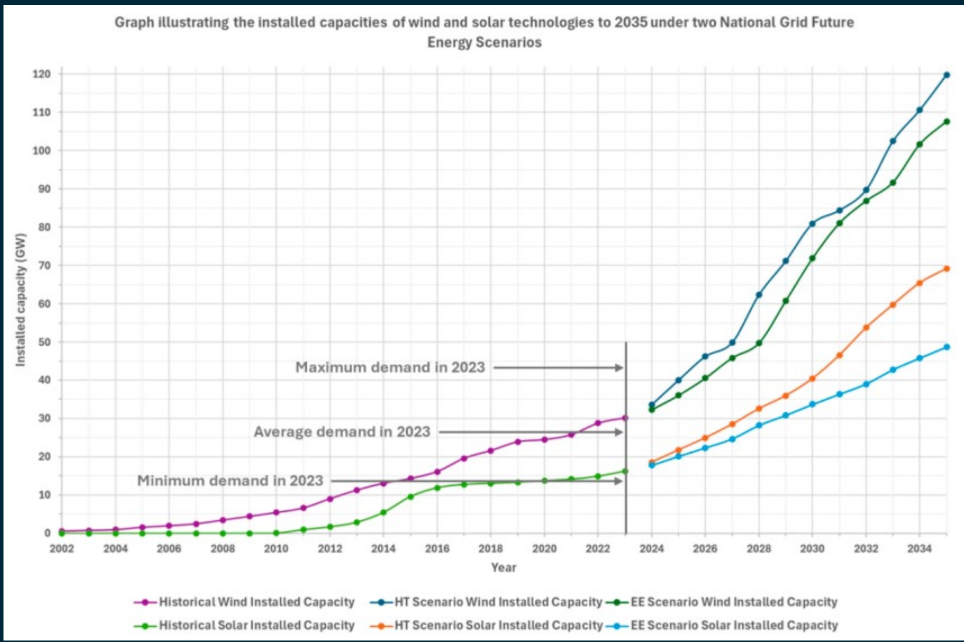



*Figure 8: Evolution and projections of solar and wind installed capacity in the UK compared to demand (grey vertical line). Historical installed capacities of solar and wind shown to 2023, followed by the projected installed capacities under National Grid Future Energy Scenarios over 2024-35. "EE Scenario" and "HT Scenario" refer to NESO's Electric Engagement and Holistic Transition future scenarios, respectively.*[23]

## POLICY IMPLICATIONS

Contracts for difference (CfDs), where renewable generators receive a fixed price for each unit of electricity they supply, can greatly weaken the dampening feedbacks (i) and (ii) (loops D2 and D1, respectively, in Figure 7) by breaking the relationship between wholesale market price and renewable power revenues. This can be an effective way to maintain investment in renewables in countries where the prospect of renewable supply exceeding total demand is still relatively far off.

The long-term prospect of cannibalisation may still lessen the weight investors give to potential post-contract generation;[24] and when renewable surplus becomes a near-term prospect, alternative policies may be needed to limit the operation of dampening feedback (iii) (loop D3, Figure 7). These could include CfD designs that guarantee revenues rather than prices, based on a renewable plant's capacity or its potential generation, though these may have other drawbacks.[25] The underlying economic challenge is to manage co-evolution with other technologies such as energy storage or hydrogen production that can make economic use of surplus generation.

*23 These capacity projections are based on the Energy System Operator's (2024) Future Energy Scenarios. The two scenarios used—Electric Engagement (EE) and Holistic Transition (HT)—represent different pathways for meeting net zero by 2050 in the UK. EE assumes most demand is met via electrification, while HT uses a mix of hydrogen and electrification.*
*24 Since CfDs are generally only valid for a fixed period of time (e.g. 15 years in the UK), investors must also take into account post-contract sales in their revenue projections. Expectations of growing cannibalisation effects in the mid- and long-term would imply lower projections of post-contract revenues, which may push up strike prices for CfD auctions in the present day.*
*25 Department of Energy Security and Net Zero. (2024). Review of Electricity Market Arrangements: Second Consultation Document.*

# [4] Technology synergies: mutual reinforcement of complementary technologies

## FEEDBACKS

Technologies can be complementary when the deployment of one technology expands the market for deployment of another, and vice versa. This mutual reinforcement can arise from a combination of technical, social, and institutional channels. In this way, a reinforcing feedback can exist between the deployment of two technologies, whose coevolution can drive forward the transition. The emergence of complementary technologies can be one of several reinforcing feedbacks of clean technology development and diffusion—see archetype no.1.

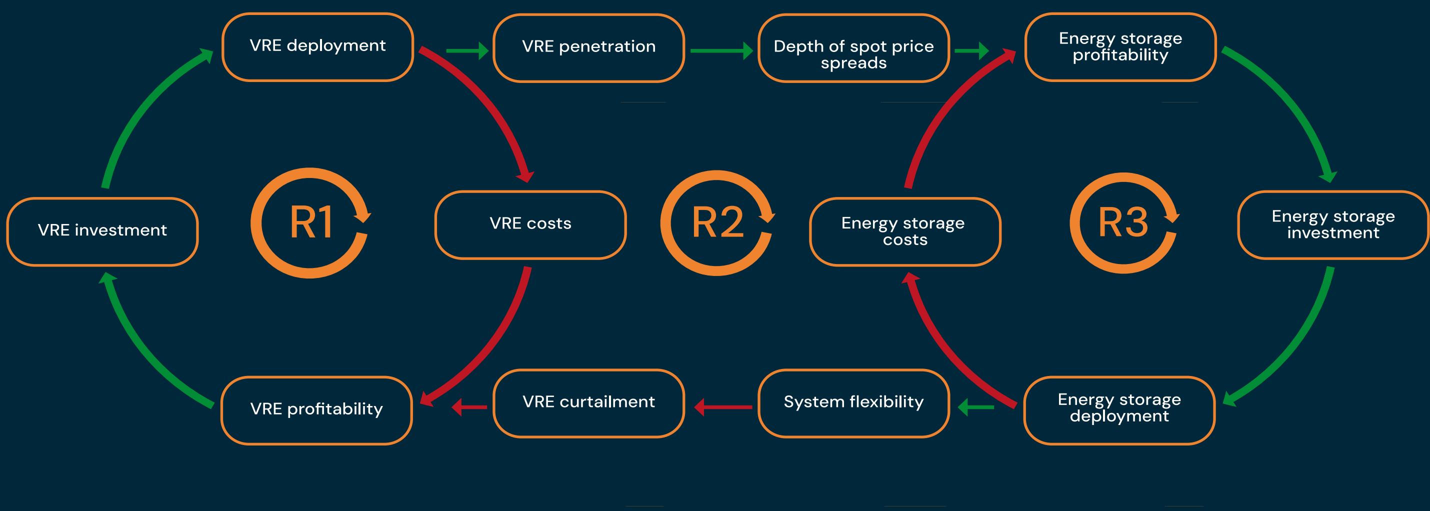



*Figure 9: CLD showing the synergistic dynamic between variable renewable energy (VRE) and energy storage deployment. Each technology is subject to its own learning-by-doing reinforcing loop (R1 and R3), but the complementarity between the technologies links these loops to create a larger reinforcing loop (R2). Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).*

## EXAMPLES

Perhaps the most important example of this feedback in the low carbon transition is the relationship between variable renewable power technologies and energy storage. As variable renewable energy (VRE) generation increases, so do fluctuations in spot prices that (in a liberalised market) reflect the balance between supply and demand. This increases the potential profits available to energy storage, tending to increase its deployment. Higher levels of energy storage deployment can reduce curtailment, and allow more renewables to be profitably deployed, further increasing renewable power generation. This reinforcing feedback between renewables and storage interacts positively with the reinforcing feedbacks of development and diffusion that each of those technologies has individually.[26]

*26 As noted above, for battery energy storage, the reinforcing feedback of development and diffusion occurs primarily in the road transport sector; deployment in the power sector makes a smaller contribution.*

## POLICY IMPLICATIONS

This set of feedbacks can be helpful for driving the transition to a power system with high levels of low-cost renewable generation, but certain steps may need to be taken to allow it to operate. Energy storage must be allowed to operate in the spot market, and its deployment will grow faster if it can also operate in the ancillary services market and—if there is one—the capacity market. Double taxation of energy storage, as a generator and as a consumer, can weaken this feedback, and should generally be avoided.

Requiring all renewables to install co-located energy storage may be inefficient, and can increase the costs of renewable deployment. It is likely to be more effective to recognise energy storage as a desirable property of the power system, not as a necessary property of each power plant, and allow its costs to be spread across all users of the system. Adequate and timely investment in energy storage may be impeded by the intrinsic uncertainty of its revenues, so there is a key role for coordination of investment incentives.[27]

*27 Watson, J., Gross, R., Bell, K., Waddams, C., Temperton, I., Barrett, J., Rhodes, A., Gill, S., & Bays, J. (2017). Cost of Energy Review: Call for evidence. Response by the UK Energy Research Centre (UKERC). UK Energy Research Centre.*

# [5] Fixes that fail: administrative limits on electricity prices

## FEEDBACKS

All governments want to keep electricity prices low to protect consumers, support industrial competitiveness, and increase economic productivity. Setting administrative limits on electricity prices can achieve low prices in the short term, but may achieve the opposite in the long run. This can happen as a result of one, or both, of two reinforcing feedbacks. The first of these occurs when artificially low prices cause some plants or retailers to become loss-making, forcing them out of the system. This concentrates market power, eroding the potential for competition to keep prices low in the long run. The second occurs when prices are set at a level that is too low to enable ongoing investment in the new technologies, capacity expansion, or capital maintenance necessary to keep unit costs low. Without functional price signals, artificially low prices could therefore starve firms of capital, leading to underinvestment and long-run price increases.

Besides price controls, energy subsidies can also have counterproductive effects in the long run as they may encourage inefficient energy use, which leads to higher energy demand, putting upwards pressure on energy prices.

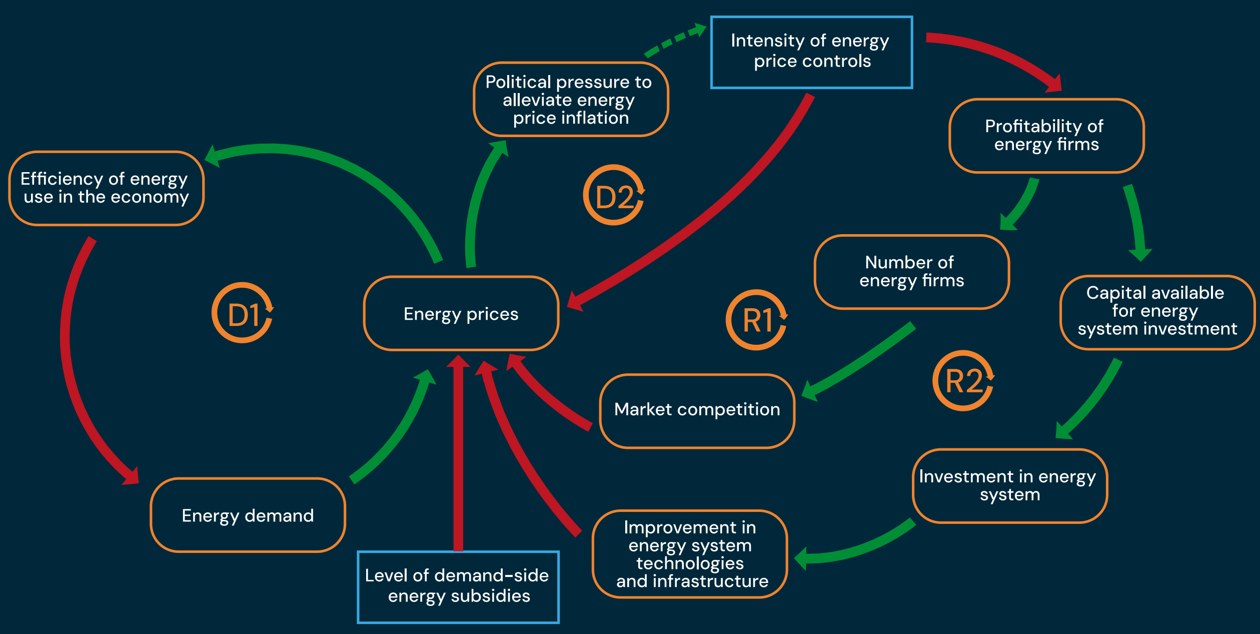



*Figure 10: CLD showing the interactions between different feedbacks and policies affecting energy prices. The dampening loop D1 represents the relationship between energy demand and prices; the dampening loop D2 represents governments responding to political pressure to keep energy prices low via price controls; the reinforcing loop R1 represents a longer-term effect whereby price controls can cause industry consolidation and drive up prices in the long run; the reinforcing loop R2 represents another longer-term effect whereby lack of price signals can preclude energy firms from recovering the costs necessary to invest in new technologies and capital maintenance, leading to higher prices in the long run. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions). Dashed lines indicate weak/conditional relationships. Orange nodes represent variables within the system, blue rectangular nodes represent policy inputs.*

## EXAMPLES

Many countries have experienced undesirable effects arising from controls on electricity prices. In South Africa, state-set electricity tariffs were fixed at a level that starved Eskom, the state-owned power utility, of the capital required to maintain and improve power system infrastructure. This, along with other institutional and political factors, has led to South African power prices increasing at rates drastically outpacing inflation since 2007, having previously been among the lowest in the world in the 1970s. In India, price controls have contributed to widespread financial difficulties among distribution companies, limiting their ability to invest.[28] In 2021, many Chinese coal power plants shut down temporarily to limit losses when price controls left them unable to pass on coal price increases. These shut downs, along with other factors, led to power rationing and blackouts in 20 provinces.[29]

East European countries in which energy was heavily subsidised in the Soviet era became extremely inefficient in their use of energy, leaving them highly exposed to energy costs when they could no longer afford subsidies and moved to market pricing. Indeed, there is strong evidence that given sufficient time, countries adjust to higher energy prices with greater energy efficiency, in ways which create roughly constant overall long-run national expenditure on energy.[30]

The multiple feedbacks linking energy prices with innovation, efficiency, and economic structure mean that higher energy prices are ultimately offset by equally higher efficiency; and conversely, general consumer energy subsidies (as opposed to carefully targeted subsidies for innovation) may impede progress of this kind.

## POLICY IMPLICATIONS

The aim of reducing electricity prices is more likely to be achieved in a sustainable way by policies that support the large-scale deployment and efficient integration within power systems of solar and wind power. In 2023, solar power on average cost 56% less than fossil-fuelled power globally, and the cost of new onshore wind projects was on average 67% less than that of fossil-fuelled alternatives.[31] The cost advantage of the clean technologies will only widen in future, as solar and wind benefit from the reinforcing feedbacks of learning by doing and economies of scale, whereas coal and gas power do not.

*28 Ahluwalia, S. (2024). DISCOMs: The weak link in India's energy transition. Observer Research Foundation.*
*29 Zhang, J., 2022. Understanding China's 2021 power crunch. Insight.*
*30 Bashmakov, I., Grubb, M., Drummond, P., Lowe, R., Myshak, A., Hinder, B., 2024. "Minus 1" and Energy Costs Constants: Empirical Evidence, Theory and Policy Implications. Struct. Change Econ. Dyn.*
*31 IRENA. (2024). Renewable Power Generation Costs in 2023. International Renewable Energy Agency.*

# [6] Locational signals: the dampening feedbacks of locational electricity pricing

## FEEDBACKS

Compared to a power system based on coal or gas, a renewables-based power system relies on generation assets that are more numerous, more geographically dispersed, and whose location is more strongly dependent on factors other than the location of demand (such as natural resources, and land availability). This can increase the difficulty of geographically balancing supply and demand, and can result in curtailment of renewables in areas of plentiful supply. It can mean higher electricity prices in areas of high demand, either through transmission charges or explicit (dynamic) locational prices in wholesale markets. With locational prices, there are several dampening feedbacks that could potentially lower overall costs across the system, although in some regions, prices may rise. As noted above, dampening feedbacks are not always unhelpful to policy objectives; this is an example of where they may play a helpful role. These feedbacks are:

i) **Inter-regional power trading (loop D4, Figure 12):** larger locational price differences increase the incentive for power trading between regions, which reduces the price differences.

ii) **Demand migration (loop D3, Figure 12):** larger locational price differences can incentivise industry to locate closer to areas of plentiful renewables supply, reducing the geographical imbalances and price differences.

iii) **Renewables investment (loops D1 and D2, Figure 12):** larger locational price differences tend to encourage more renewable investment in high-price zones (likely demand centres), and less investment in areas with abundant supply (likely in remote areas or behind transmission bottlenecks), tending to reduce the differences.

iv) **Transmission investment (loops D5, Figure 12):** larger price discrepancies between regions can strengthen the case for investment in transmission assets, particularly in cases where the depth of price spread determines the revenues of that asset. This linking of different regions can allow demand to be met by lower-cost power, reducing overall costs.

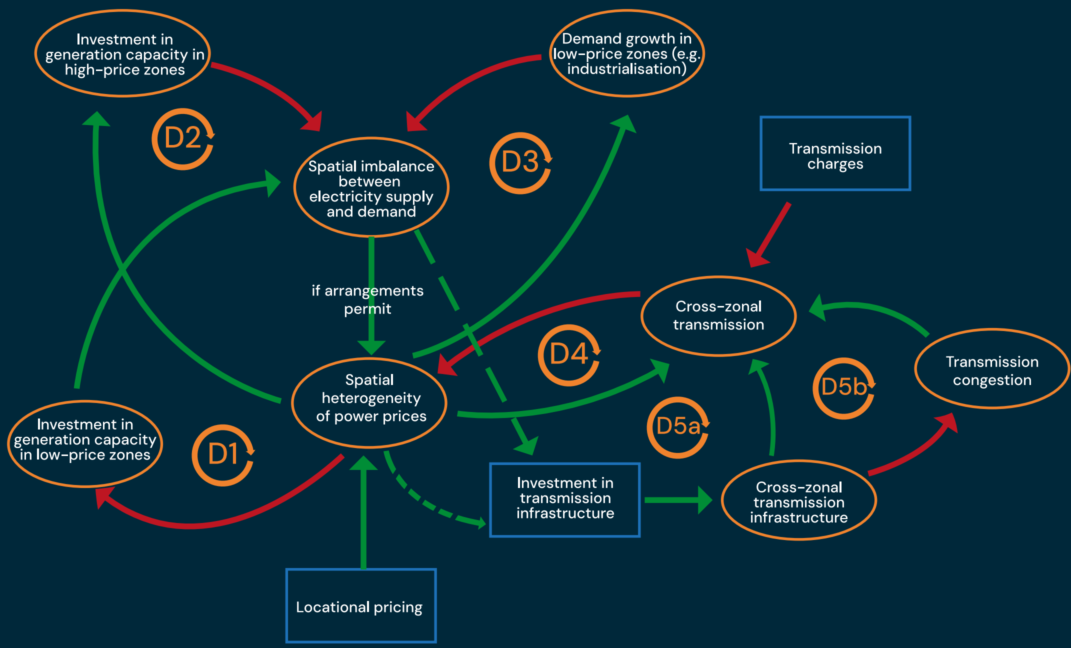



*Figure 12: CLD showing multiple dampening feedback loops that act to limit the differences in electricity prices across a certain geographical area. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions). Dashed lines indicate weak/conditional relationships. Orange nodes represent variables within the system, blue rectangular nodes represent policy inputs.*

## EXAMPLES

In China, there are large imbalances between western provinces rich in renewable energy resources where power supply exceeds demand, and highly populated eastern provinces where demand exceeds supply. Separate provincial electricity markets create significant heterogeneity of prices across the country: prices in some eastern provinces were around 35% higher than in the northwest, in 2023.[32] This difference is driving an increase in cross-provincial power trading and a westward migration of some industrial activity, both of which contribute to reducing the imbalance.

## POLICY IMPLICATIONS

Locational pricing can strengthen each of the dampening feedbacks mentioned above. Location-related pricing can take different forms, including zonal or nodal wholesale pricing, and transmission charges with locational elements. Investment in transmission infrastructure is also crucial to enable feedback (i) (loop D4 in Figure 12) to operate effectively. Time-variable transmission pricing can further improve the operational efficiency of the system, by encouraging supply and demand to be balanced locally at times when there is the greatest risk of transmission congestion nationally.[33] In the long run it seems likely that stronger locational price signals should aid the transition overall, but this is far from certain. The many different feedbacks involved, and the distributional and transitional impacts, make locational pricing exceptionally complex, and its overall effects difficult to predict.

*32 Per data collated and published by North Star Electricity Network (www.bjx.com.cn).*
*33 Morell-Dameto, N., Chaves-Ávila, J. P., Gómez San Román, T., & Schittekatte, T. (2023). Forward-looking dynamic network charges for real-world electricity systems: A Slovenian case study. Energy Economics, 125, 106866.*

# [7] Cross-sectoral synergies: reinforcing feedbacks through shared technologies

## FEEDBACKS

When a certain technology is used across multiple sectors, there is potential for reinforcing feedbacks to operate such that the transition in each sector helps to advance the transition in other sectors.

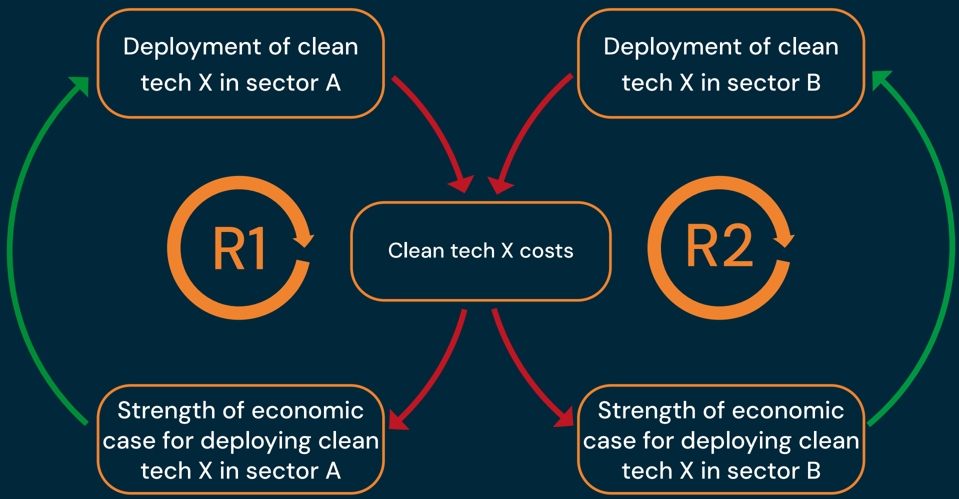


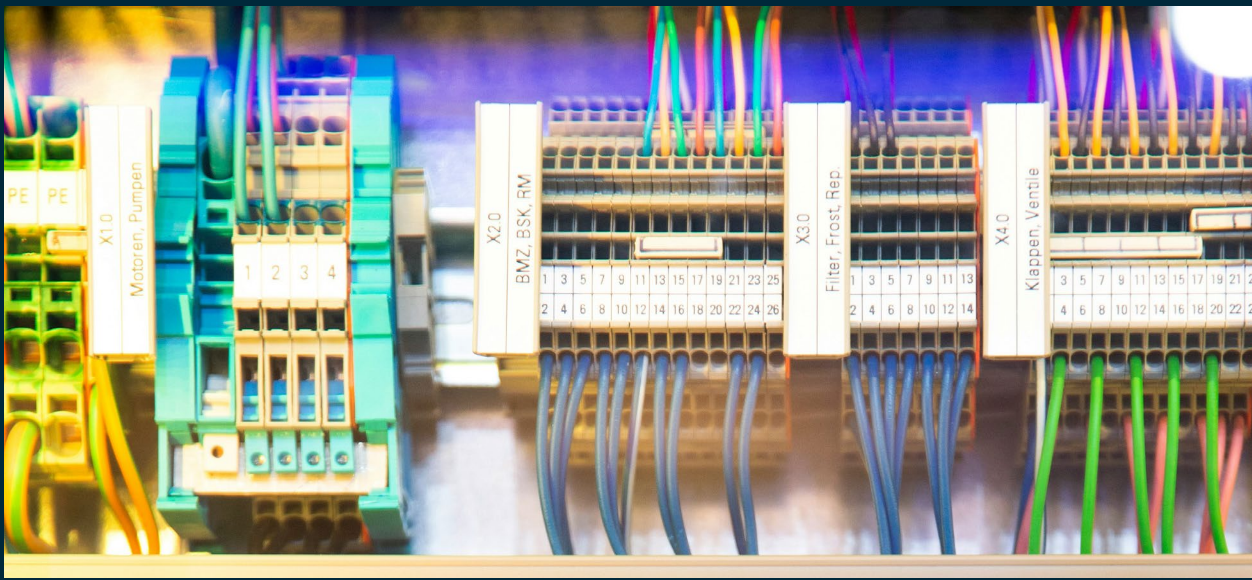

*Figure 13: CLD of dual reinforcing feedback loops illustrating the cost-reduction synergies associated with clean technology deployment across sectors. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).*

## EXAMPLES

Reinforcing feedbacks are likely to exist between the transition to clean power and the transitions in sectors where electrification is the main way to achieve decarbonisation, based on the shared technologies of renewable power and batteries. Deployment of batteries in light road transport decreases their costs (through feedbacks of investment and innovation, learning by doing and economies of scale), enabling greater deployment in heavy road transport and the power sector, which contributes to further cost reduction. Greater deployment of batteries in the power sector can potentially reduce the cost of electricity by enabling greater use of low-cost renewable power. Lower-cost electricity increases the incentives for electrification of road transport, heating, and light industry. Electrification of those sectors increases demand for power, driving further deployment and deeper cost reduction in solar and wind power. It also increases potential capacity for demand-side response, helping to balance the power system more cost-effectively.[34]

*34 Nijsse, F., Sharpe, S., Sahastrabuddhe, R., & Lenton, T. M. (2024). A positive tipping cascade in power, transport and heating. Economics of Energy Innovation and Systems Transition.*

Reinforcing feedbacks are also likely to exist between sectors where green hydrogen is used, which could include fertilisers, shipping, steel, and the power sector (for energy storage and peaking plants). Deployment in any one of these sectors will contribute to reducing the cost of electrolysers, helping to enable deployment in the other sectors.[35]




## POLICY IMPLICATIONS

There is no need to wait for decarbonisation of the power sector to advance further before beginning the electrification of transport, heating, or industry. In most countries, the superior efficiency of electric vehicles compared to petrol cars and heat pumps compared to fossil fuel boilers means that deploying EVs and heat pumps saves emissions immediately, despite power systems being carbon intensive;[36] but even where this is not the case, it is of minor importance.[37] Pursuing these transitions in parallel, globally, is likely to be the best way to activate cross-sector feedbacks to enable deep reductions in both costs and emissions.

Cross-sectoral reinforcing feedbacks can be strengthened by policies that increase the technological linkages between the sectors. These include electricity tariffs and market structures that reward smart charging and vehicle-to-grid charging, the participation of industry in demand-side response, and the installation of integrated home energy systems.

These cross-sectoral interactions strengthen the path-dependence of the energy system both within and across major energy-using sectors, amplifying the benefits of early investment in the transition.[38]

*35 SYSTEMIQ. (2023). The Breakthrough Effect: how tipping points can accelerate net zero. SYSTEMIQ.*
*36 Knobloch, F., Hanssen, S. V., Lam, A., Pollitt, H., Salas, P., Unnada Chewpreecha, Mark, & Mercure, J.-F. (2020). Net emission reductions from ele ctric cars and heat pumps in 59 world regions over time. Nature Sustainability, 3(6), 437–447.*
*37 Lam, A., Mercure, J.-F., & Sharpe, S. (2023). Policies to Pass the Tipping Point in the Transition to Zero-Emission Vehicles. Economics of Energy Innovation and System Transition (EEIST).*
*38 Grubb, M., Lange, R.-J., Cerkez, N., Sognnaes, I., Wieners, C., & Salas, P. (2024). Dynamic determinants of optimal global cli-mate policy. Structural Change and Economic Dynamics, 71, 490–508.*

# [8] Waterbed effects: the dampening feedbacks of emissions trading systems

## FEEDBACKS

A carbon price increases the cost of using fossil fuels relative to clean technologies. If clean technologies are available, close enough to fossil fuels in relative cost, and enabled by market structures to compete with fossil fuels, carbon pricing can support their further deployment. An emissions trading system (ETS), however, creates a new dampening feedback. In a typical ETS with a fixed emissions cap, any reduction in emissions (whether by enhancing efficiency or deploying clean technology substitutes) leads to a decrease in demand for emissions permits. Since the supply of permits is fixed, lower demand leads to lower permit prices. Lower permit prices then reduce the incentive for further emissions reductions. In this way, the typical ETS has a self-limiting effect. Any progress it makes in decarbonisation will weaken its ability to drive further progress.

If an ETS encompasses more than one sector, then this dampening feedback will operate across sectors, such that any progress in the transition in one sector weakens the incentive for progress in others.

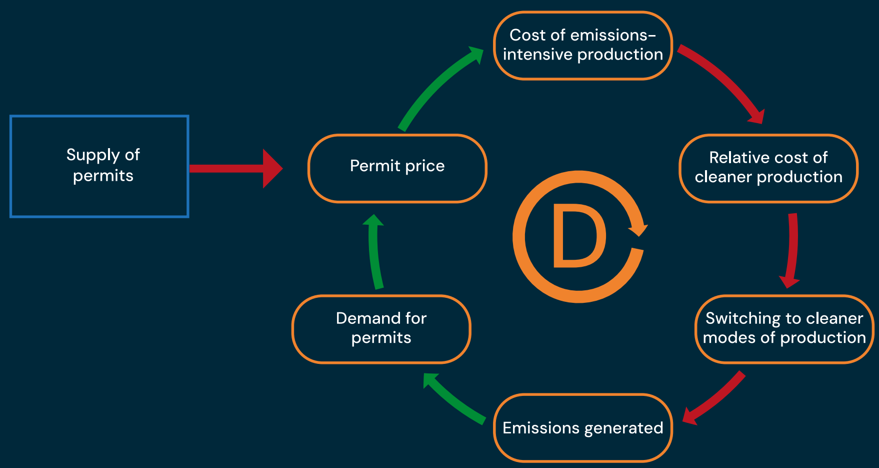



*Figure 14: Dampening feedback loop representing the waterbed effect in emissions trading schemes. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions). Orange nodes represent variables within the system, blue rectangular nodes represent policy inputs.*

## EXAMPLES

In the European Union between 2008 and 2018, as subsidies drove the deployment of renewables and lower-than-expected economic growth at times constrained demand, the dampening feedback of the ETS kept the carbon price so low that it could make little contribution to driving the transition.[39] In 2019, the EU reformed the ETS by introducing a market stability reserve, a way of managing the number of emissions permits in the market that has an effect similar to that of a carbon price floor. The carbon price then rose significantly, although it was also influenced by other factors, including a tightening of the emissions cap.

*39 See Grubb, M. (2012). Carbon pricing after Copenhagen: an updated assessment. Climate Strategies.; and Koch, N., Fuss, S., Grosjean, G., & Edenhofer, O. (2014). Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence. Energy Policy, 73, 676–685.*

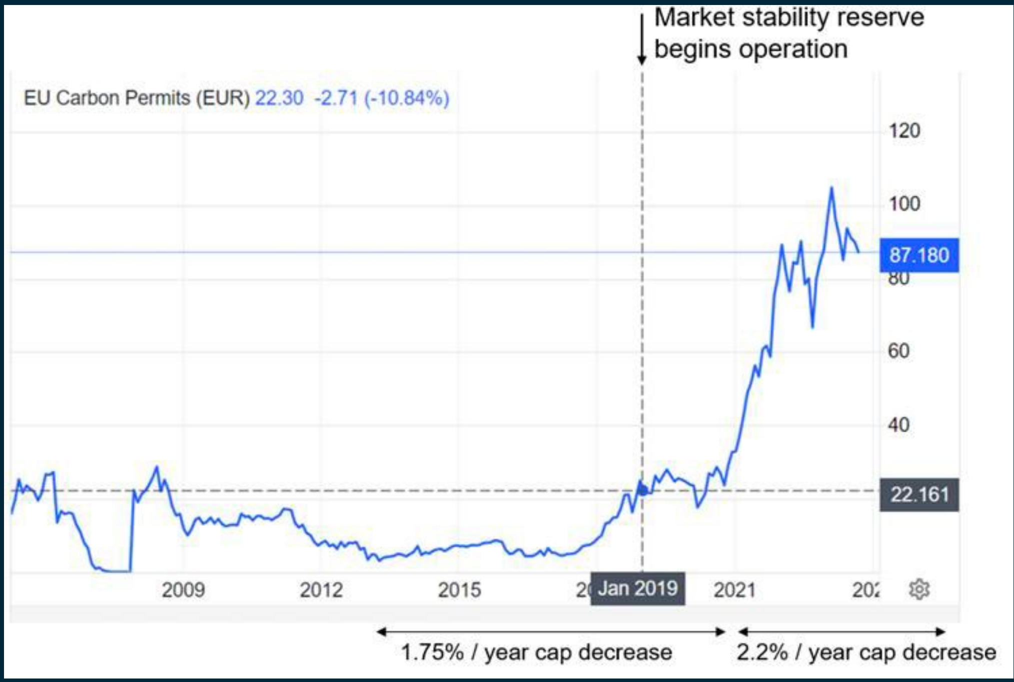



*Figure 15: Chart showing the evolution of the EU carbon price in relation to the introduction of the market stability reserve and declining cap policies.*[40]

## POLICY IMPLICATIONS

A carbon price floor can limit the effect of the dampening feedback within an ETS by constraining the relationship between demand for permits and the permit price. There are various ways in which a price floor can be implemented, including as a reserve price in the auction for emissions permits, a top-up tax that brings the permit price up to a specified level, or a fixed tax that adds to the permit price.[41] In an ETS that covers more than one sector, setting different floor prices in each sector (reflecting differences in relative cost between clean technologies and fossil fuels) could limit the extent to which the dampening feedback operates across sectors. An alternative approach to limiting the effect of the dampening feedback is to frequently adjust the emissions cap after emissions reductions have been achieved, tightening it to prevent the carbon price falling to very low levels.

Reinvesting carbon pricing revenues to support clean technology deployment or energy efficiency improvements can strengthen reinforcing feedbacks associated with those processes, although the dampening feedback of the ETS will continue to have an offsetting effect.

*40 Source: Trading Economics. Annotations by authors.*
*41 On Climate Change Policy. (2024). Carbon price floors and ceilings. On Climate Change Policy.*

# [9] Tipping points in the transition

## FEEDBACKS

While the reinforcing feedbacks of technology development and diffusion drive a transition forward, resistance from incumbents can often hold it back. This can take the form of lobbying governments against policies that would enable the transition, shaping public discourse with narratives that discredit the new technologies, and investing in incremental innovations that extend the life of the old technology system.[42] Since this resistance only arises due to the possibility of transition, and is likely to strengthen in response to an increase in the incumbents' perception of a threat, it can be understood as a dampening feedback.

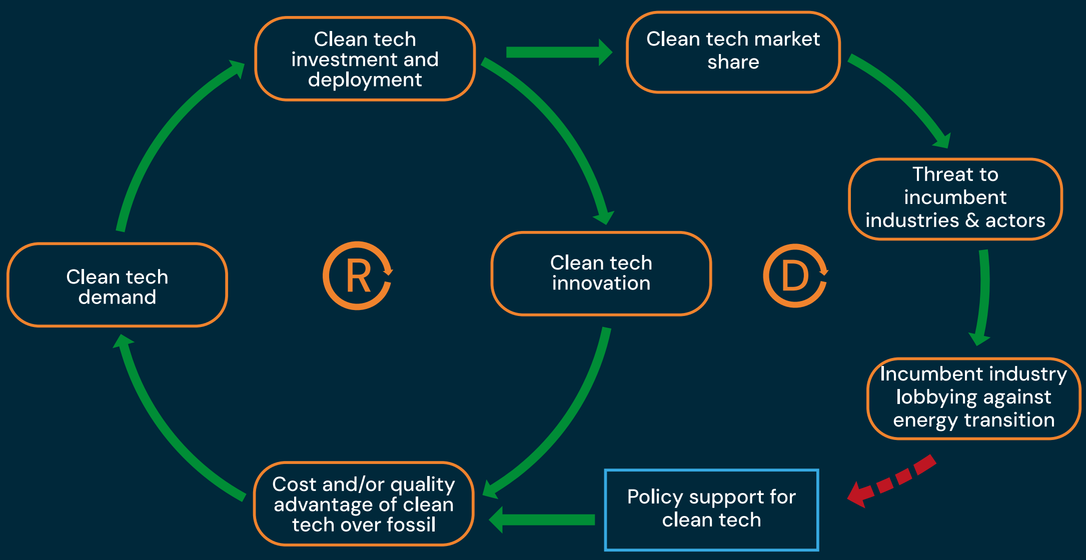



*Figure 16: CLD with two interacting feedback loops showing the tipping point dynamic. The reinforcing loop (R) represents the self-amplifying effect of clean tech diffusion and development, but this diffusion is offset by the dampening loop (D), in which incumbents seek to protect their position by resisting policies that support clean technologies. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions). Dashed lines indicate weak/conditional relationships. Orange nodes represent variables within the system, blue rectangular nodes represent policy inputs.*

In the progress of a transition there is usually a tipping point—a point at which the reinforcing feedback of technology development and diffusion becomes more powerful than the dampening feedback of incumbent resistance.[43] This may happen because consumers decide they prefer the new technology, producers decide it is more profitable, investors decide it has better growth prospects, or any combination of those factors. Beyond this point, the transition is increasingly self-propelling, and is more difficult to hold back.

*42 Geels, F. W. (2014). Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. Theory, Culture & Society, 31(5), 21–40..*
*43 Sharpe, S., & Lenton, T. M. (2021). Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. Climate Policy, 21(4), 421–433.*

## EXAMPLES

Norway has used a combination of a purchase subsidy for EVs and a tax on sales of ICE cars to make the former cheaper at the point of purchase. Together with a range of other supportive policies, this decisively shifted consumer preference towards the new technology: in 2019, EVs were only 2-3% of car sales globally, but over 50% in Norway. Without its own car industry, Norway was not held back by the dampening feedback of incumbent resistance. As EVs now make up nearly a fifth of car sales globally,[44] and their total cost of ownership has fallen below that of petrol cars in leading markets,[45] evidence is growing that tipping points in major markets may be either fast-approaching, or already passed.[46]

In the power sector, solar and wind already generate electricity at lower cost than coal or gas in most countries, and this cost advantage is driving rapid growth in renewables' market share. However, since current electricity market designs make it difficult for consumers to directly access the cost advantages of renewable technologies, the threat to incumbents' position (both economic and reputational) remains weaker than it otherwise might be.[47]

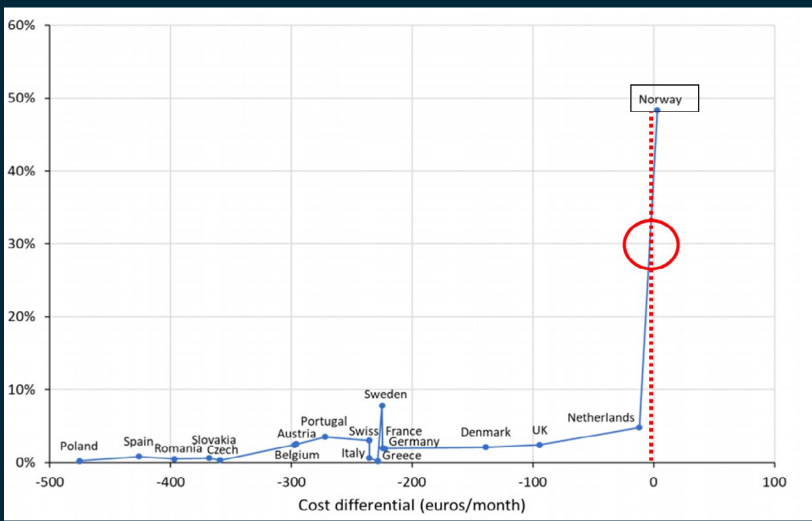



*Figure 17: Chart of electric vehicle market share as a function of cost differential across various European countries.[48]*

## POLICY IMPLICATIONS

Governments can design policies to cross tipping points in the transition by focusing on the relative costs, profitability, attractiveness or accessibility of clean technologies compared to fossil fuel alternatives, rather than the absolute values.

Early in the transition, a subsidy high enough to make the clean technology cheaper than the fossil fuels can usually be funded by a very small tax on each fossil fuel product, since at that stage the clean technology accounts for only a small share of the market.[49] Clean technology mandates can be effective in forcing a reallocation of investment towards the new technology, accelerating its reduction in cost.[50]

Tipping points can also usefully serve as the focus for diplomacy on the low carbon transition, since they bring into play a broader range of interests than emissions reduction. This approach is central to the Breakthrough Agenda process, in which countries have agreed to work together to make clean technologies and sustainable solutions the most affordable, attractive and accessible option in each of the emitting sectors before the end of this decade.[51]

# [10] The complex feedbacks of fossil fuel decline

## FEEDBACKS

While the market share of the new technology in a transition increases along an S-curve trajectory, that of the incumbent technology decreases along an inverse S-curve. Some of the same reinforcing feedbacks that drive the growth of the new also act in reverse to drive the decline of the old. This dynamic can play out through three major channels:

**i) Reverse economies of scale (loop R1, Figure 18):** as demand falls for products that rely on fossil fuels for their production or use, companies that supply these products can be left with overcapacity (for example, in coal power plants, blast furnaces, or factories for the manufacturing of internal combustion engine cars). This causes asset utilisation rates to fall and unit costs of production to rise, eroding profitability and leading to further contraction.[52] Fossil fuel distribution networks may be affected in a similar way.

**ii) Capital flight (loop R2, Figure 18):** as the profitability of the fossil fuel industry begins to fall, whether due to policy changes or being outcompeted by new technologies, investor confidence in it is likely to decrease, pushing up the cost of capital, and further reducing its profitability; this may lead to fossil fuel assets becoming stranded.

**iii) Weakened lobbying power (loop R3, Figure 18):** as fossil fuel industries contract, their ability to influence political and policy decisions is likely to wane. Reductions in employment, tax contributions, profitability, and social approval relative to clean technologies erode the industry's credibility in political debate, leaving it less able to resist policies that lead to its further weakening.[53]

At the same time, however, a dampening feedback involving reductions in fossil fuel prices (loop D, Figure 18) is likely to come into play as the transition advances. By lowering demand for fossil fuels, the transition is likely to lower their traded price. This trend could work against the competitiveness of clean technologies in some sectors, whilst reducing energy costs across the board.

*44 International Energy Agency. (2024). Global EV Outlook 2024.*
*45 Nijsse, F., Sharpe, S., Sahastrabuddhe, R., & Lenton, T. M. (2024). A positive tipping cascade in power, transport and heating. Economics of Energy Innovation and Systems Transition.*
*46 Lam, A. and Mercure, J-F., (2022). Evidence for a global electric vehicle tipping point. University of Exeter Global Systems Institute.*
*47 For example, in wholesale electricity markets with marginal pricing, prices are often set by fossil fuel generators, even under conditions of relatively high wind and solar penetration, and therefore tend to be much higher than the low marginal cost of renewable power. See Grubb, M., Ferguson, T., Musat, A., Maximov, S., Zhang, Z., Price, J., & Drummond, P. (2022). Navigating the crises in European energy: Price Inflation, Marginal Cost Pricing, and principles for electricity market redesign in an era of low-carbon transition (Working Paper 3; Navigating the Energy-Climate Crises). University College London.*
*48 Source: Adapted from Figure 1 in Sharpe, S., & Lenton, T. M. (2021). Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. Climate Policy, 21(4), 421–433.*
*49 Lam, A., Mercure, J.-F., & Sharpe, S. (2023). Policies to Pass the Tipping Point in the Transition to Zero-Emission Vehicles. Economics of Energy Innovation and System Transition (EEIST).*
*50 Nijsse, F., Sharpe, S., Sahastrabuddhe, R., & Lenton, T. M. (2024). A positive tipping cascade in power, transport and heating. Economics of Energy Innovation and Systems Transition.*
*51 Breakthrough Agenda. (2024). Breakthrough Agenda.*
*52 Ibid.*
*53 Butler-Sloss, S., Bond, K., and Benham, H. (2021). Spiralling disruption: the feedback loops of the energy transition. Carbon Tracker.*

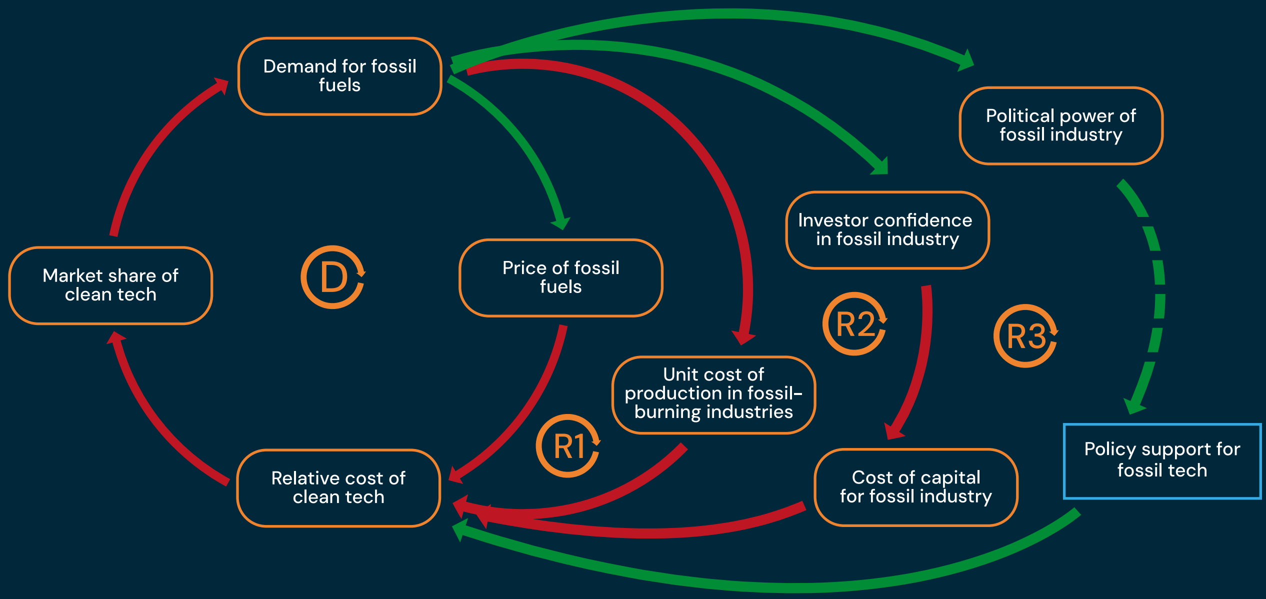



*Figure 18: CLD showing multiple interacting feedback loops that represent potential effects of changes in fossil fuel demand. The dampening loop (D) depicts the effect whereby a decline in demand could lead to prices falling, which may slow the transition. The reinforcing loops (R1, R2, R3) represent effects whereby a fall in fossil fuel demand may hasten the decline of the fossil fuel techno-economic regime. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions). Dashed lines indicate weak/conditional relationships. Orange nodes represent variables within the system, blue rectangular nodes represent policy inputs.*

## EXAMPLES

As recently as 2011-12, the share of coal in the UK's power generation was increasing. After that time, the growth of renewable power, combined with a carbon tax that made coal less competitive than gas, led to coal becoming unprofitable. Together with a clear policy direction of decarbonisation, this caused investor confidence in coal power to collapse. Plants closed more swiftly than anticipated, with coal's share of generation dropping from 40% in 2012 to 2% in 2019.[54] In 2015, the government set a date of 2025 for the complete phaseout of coal power; by 2021 this was brought forward to 2024; and in September 2024 the UK's last coal power plant was closed (Figure 19).

*54 Mayo. (2024). The UK's journey to a coal power phase-out. Ember.*

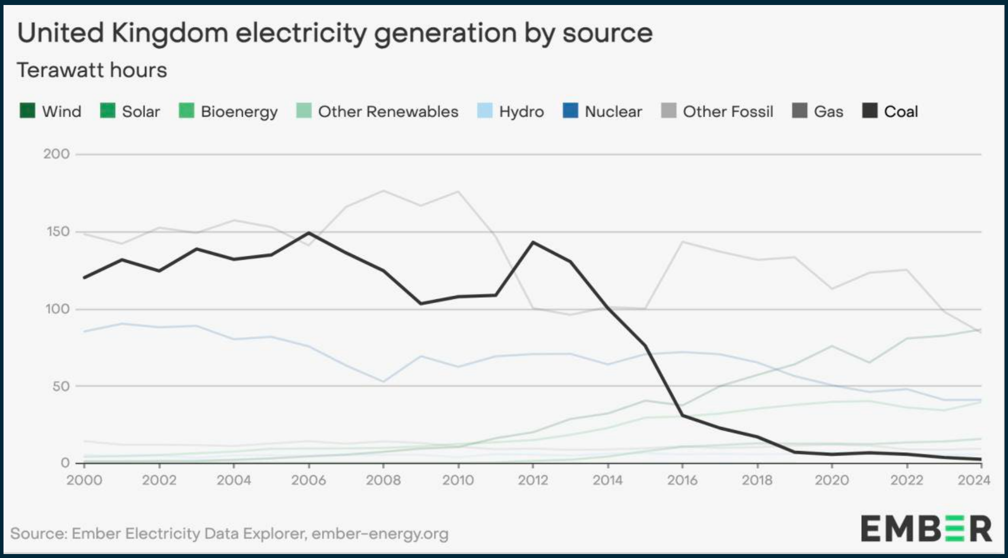



*Figure 19: Chart showing evolution of UK power generation mix over 2000-24. Line representing coal-fired power generation is bolded in black.*[55]

## POLICY IMPLICATIONS

The feedbacks of fossil fuel decline are a natural part of the transition to clean technologies and in many ways desirable, but they also carry some risks. Governments may not want to be surprised by the speed of fossil fuel decline in the same way that they were surprised by the rapid growth of renewables. In the power sector, a capacity market or a strategic reserve can be used to manage the declining role of coal or gas plants, keeping enough capacity available to ensure security of supply. If capacity markets allow the participation of energy storage and demand-side response, not only thermal plants, this can also strengthen the reinforcing feedbacks driving the diffusion of those technologies.

Governments will need to look out for economies of scale going into reverse in infrastructure networks. In countries with gas networks for residential heating, as consumers switch to heat pumps, the costs of maintaining these networks will be shared among an ever smaller number of households, pushing up bills and incentivising more to make the switch.[56] As the cost of maintaining the network becomes increasingly difficult to meet, measures may be needed to ensure heating services are available to households that for any reason have difficulty switching to the new technology. In the power sector, although grids are expected to expand rather than contract, growth of distributed renewables could lead to a similar dynamic, with grid costs being shared among a smaller number of electricity consumers.

More generally, the potential for rapid decline in fossil fuel industries means that governments should start early in planning and implementing just transition strategies for the most affected regions and communities.

Finally, a fall in traded fossil fuel prices could increase the political space for stronger carbon pricing, which may help governments offset any loss of carbon pricing revenues brought on by declining demand.

*55 Source: Ember Electricity Data Explorer.*
*56 Rosenow, J., Lowes, R. and Kemfert, C., 2024. The elephant in the room: how do we regulate gas transportation infrastructure as gas demand declines?*

Annex

# Practical guidance on using causal loop diagrams and participatory systems mapping approaches for policy analysis

## 1. Introduction

This brief has used causal loop diagrams to illustrate dynamics that are frequently encountered in the energy transition. In this annex, we present practical guidance on how you can start using these methods to inform your work, whatever the topic. This advice is intentionally short. For more information, we recommend referring to detailed guides.[57]

The next two sections explain what causal loop diagramming and participatory systems mapping are, and how they differ. We then explain how you can use them in different project contexts. Finally, we list some useful resources and software.

## 2. Causal loop diagramming

Causal loop diagramming is a systems mapping method in which one creates diagrams made up of factors and arrows that describe the causal relationships and feedback loops within the system of focus. Systems mapping is the broader name given to a variety of methods in which diagrams are used to describe the operation, causal structure, and/or stakeholders, in a particular system.[58]

Causal loop diagrams, or CLDs, almost always focus heavily on feedback loops. This is the defining difference between them and other systems mapping methods.

Feedback loops are causal dynamics whereby a change in one variable triggers a causal chain that eventually acts again on that initial variable. These may be reinforcing feedback loops in which the initial change is amplified (or reinforced); or they may be self-limiting feedbacks, in which the initial change is countered or dampened. A classic example of a reinforcing feedback loop is learning by doing (see Figure 2 in the above brief, reproduced below); a classic example of a dampening feedback loop is homeostasis; another example is a thermostat. The focus on feedback loops means that for most CLDs, the visualisation is organised to highlight the feedbacks, which are often labelled.

CLDs have been used for some time, so practice varies. They come in various sizes and shapes, but are all made up of factors (represented as boxes or nodes) and their causal relationships (represented as arrows). Factors always represent variables. These variables do not necessarily have to be quantifiable, but must be able to increase or decrease. For example, factors could range from the price of a banana to the strength of a friendship.

Causal relationships can have positive or negative polarity, meaning that a change in one variable influences another to change in the same (positive) or opposite (negative) direction.

The direction of each causal relationship should be determined by drawing on the best available information, and not arbitrarily or speculatively. This could include quantitative evidence, expert knowledge, other research findings, or a relationship being logically true by necessity. Documenting the basis on which the direction of each relationship has been determined can increase the transparency of the analysis and make it easier to change if new information is discovered.

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*57 E.g. see Barbrook-Johnson, P., & Penn, A. S. (2022). Systems Mapping: How to build and use causal models of systems. Springer International Publishing; and Penn, A., & Barbrook-Johnson, P. (2020). Participatory systems mapping: A practical guide. Centre for the Evaluation of Complexity Across the Nexus.*
*58 Barbrook-Johnson, P., & Penn, A. S. (2022). Systems Mapping: How to build and use causal models of systems. Springer International Publishing.*

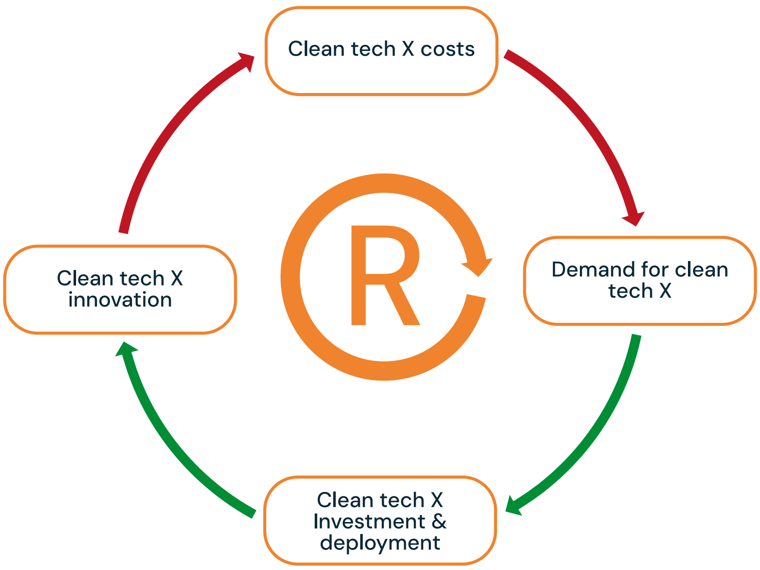


Figure 20: Example of a CLD showing a reinforcing feedback via technology development and diffusion. Green arrows represent positive causal relationships (variables move in the same direction) and red arrows represent negative causal relationships (variables move in opposite directions).

After individual relationships between variables have been established, feedback loops can be identified, although working in reverse—thinking of feedback loops first then sketching out their mechanisms—is also common. The nature of the feedback can be known from the number of opposite causal links: an even number of opposite links indicates a reinforcing feedback; an odd number of opposite links indicates a dampening feedback. The identification can be checked by walking through the set of relationships.

Feedbacks in the system can be identified as helpful or unhelpful to policy objectives. Policy options can then be considered in terms of the likely effect they will have on these feedbacks: whether they will strengthen them, weaken them, break them, or create new ones. This is one way to judge the dynamic effectiveness of a policy option.

CLDs often represent a first step towards building a quantitative system dynamics model. However, there are many CLDs developed where the main output is the qualitative diagram and associated narratives. Equally, there are many system dynamics models built where there was not first a CLD. CLDs can be built by individual researchers, small teams, or through larger participatory exercises.

## 3. Participatory systems mapping

Participatory systems mapping, or PSM, is a separate, but related, systems mapping approach. It involves building large maps with groups of stakeholders, then looking for subsections within the map to address specific questions of interest.

The maps generated by PSM are made up of factors and causal connections, as with CLDs, but they tend to have more of both and therefore look messier. The visualisations are not typically organised around feedback loops, so they can appear more overwhelming at first glance. To address this, the structure of causal links within PSMs is almost always analysed (manually or using software) to look for useful insights.

PSM analysis involves extracting submaps from a larger overall map and using these to explore questions of interest. Questions are often developed with the same stakeholders that built the map, so the analysis becomes participatory too. Common questions include: what impacts might our policy have? What (else) is affecting the outcomes we care about? Are there trade-offs between our outcomes, or between our actions and other outcomes? What are the causal paths between our interventions and outcomes we and/or others care about? How might our actions cause deleterious or unintended consequences?

Submaps can be identified by first deciding a factor of interest based on our question—perhaps a policy, an important outcome, or a variable that is expected to change imminently. Once a starting factor is chosen, one must decide how to construct the submap around it. There are three broad options in this respect: (i) downstream maps, (ii) upstream maps, and (iii) path maps.

**i)** If focussing on a policy intervention or a variable which is expected to change imminently, one can use a downstream map to focus only on the factors that are causally downstream from that factor (i.e. the factors which are affected by a change in the initial variable). Researchers can delete the arrows and factors that are not immediately flowing away from the starting point to reduce the size and complexity of the diagram. This helps narrow the focus towards the question of interest.

**ii)** If focussing on an outcome, one typically creates an upstream map, focussing only on the factors and arrows that are upstream of the outcome (i.e. the factors which affect the outcome of interest), deleting all others.

**iii)** If focussing on causal path(s) between an intervention and outcomes (useful for examining theories of change), one may extract the causal paths between them, either manually or using software. This involves removing all factors and arrows that are not involved in the causal chain from the intervention to the outcome of interest.

Creating submaps is often an exploratory process in which researchers explore different framings of and perspectives within the system, building up a richer understanding of the shared mental model co-created with stakeholders. Analysing PSMs often clarifies logical inconsistencies in them, which can then be corrected. Iteration in analysis—refining the map, doing more analysis, asking stakeholders to give us feedback on preliminary analysis—is usually useful.

# 4. Using these methods

There is no one definitive way to use these approaches in your work. They can be useful for starting to think about a new topic, developing and disciplining ideas, and/or communication with others. They can be useful both in group settings, to facilitate exchange and consensus building, and when used as an individual researcher, to develop or illustrate one's own system model. They can be analysed in isolation or connected to other analysis.

## 4.1. In short exercises

If you want to run a short exercise (e.g. in a one-day workshop) or brainstorm ideas in a small team, we recommend the following processes for CLDs and PSMs:

*Table 1: Procedures for creating causal loop diagrams and participatory systems maps.*

| Step | CLDs | PSMs |
|---|---|---|
| Setting the system boundary | In both methods, one should start by deciding the scope and purpose of the mapping exercise. These will inform many other decisions in the process. Researchers should be clear about the creation of (artificial) system boundaries, as well as the intended purpose of the process and map. | |
| Seeding the map | One starts CLDs by identifying the feedback loops that are deemed to be important in the system and drawing these. This is often the hardest part of using CLDs, it is not always obvious if there are feedback loops in the system. | One starts PSMs by identifying the 1-3 focal factors which define the system of interest. This can be very easy if our system boundary is easily definable—e.g. we might use the three legs of the energy trilemma for the power sector—but can be harder if when the boundaries, purpose, or nature of the system is unclear. |
| Brainstorming | Next, one can begin brainstorming the other factors which affect the core feedbacks, and how they feedbacks might connect. This should be drawn and illustrated. | The most important factors that affect, or are affected by, our focus factors should be brainstormed and listed. |
| Reviewing and synthesising | By this point, an initial version of the CLD should be taking shape, with focus loops emerging and their connections becoming clearer. | Only now does one start connecting focus factors and the brainstormed factors. This process can be done however feels best. Try to build up as many connections as you want, but err on the side of only including the most important. |
| Refining and iterating | In both methods, one should build in time to iterate and refine the emerging map. Redrawing the map (especially in CLDs where layout is key), or annotating it (especially in PSM) can be useful. | |
| Analysing | As the CLD becomes clearer and researchers/participants begin to feel like it may serve its intended purpose, they can start to think through what it tells you about the dynamics in the system, and implications for policy interventions. Look for examples of people using CLDs to do analysis or develop narratives, like we have done in this brief. | Even in a short exercise, one can start to think about what submaps might be pulled out from the PSM to illuminate specific questions and dynamics. |

## 4.2. In longer research projects

When more time and resources are available to use these methods, research processes should be designed to:

**i)** Speak to a wide range of stakeholders on the topic. Interviews and multiple workshops can be used to build the map up. Different opportunities can be used to iterate and develop the map in alignment with the project's purpose and stakeholders' intentions. There is no perfect research design.

**ii)** Review relevant academic and grey literature to sense check and validate the map(s), compiling supporting evidence for causal relationships, and/or identifying sources of data and evidence that support the map and analysis.

**iii)** Develop professional visualisations to aid communication and use of maps. Better visualisations can make a huge different to how others view maps.

**iv)** Develop richer analysis and insights, connecting to other pieces of analysis, modelling and data.

Figure 21 portrays a step-by-step process for conducting PSM. For CLDs it is much the same, but there is slightly less emphasis on stakeholders, and instead of focusing on factors, the emphasis is more on feedbacks.

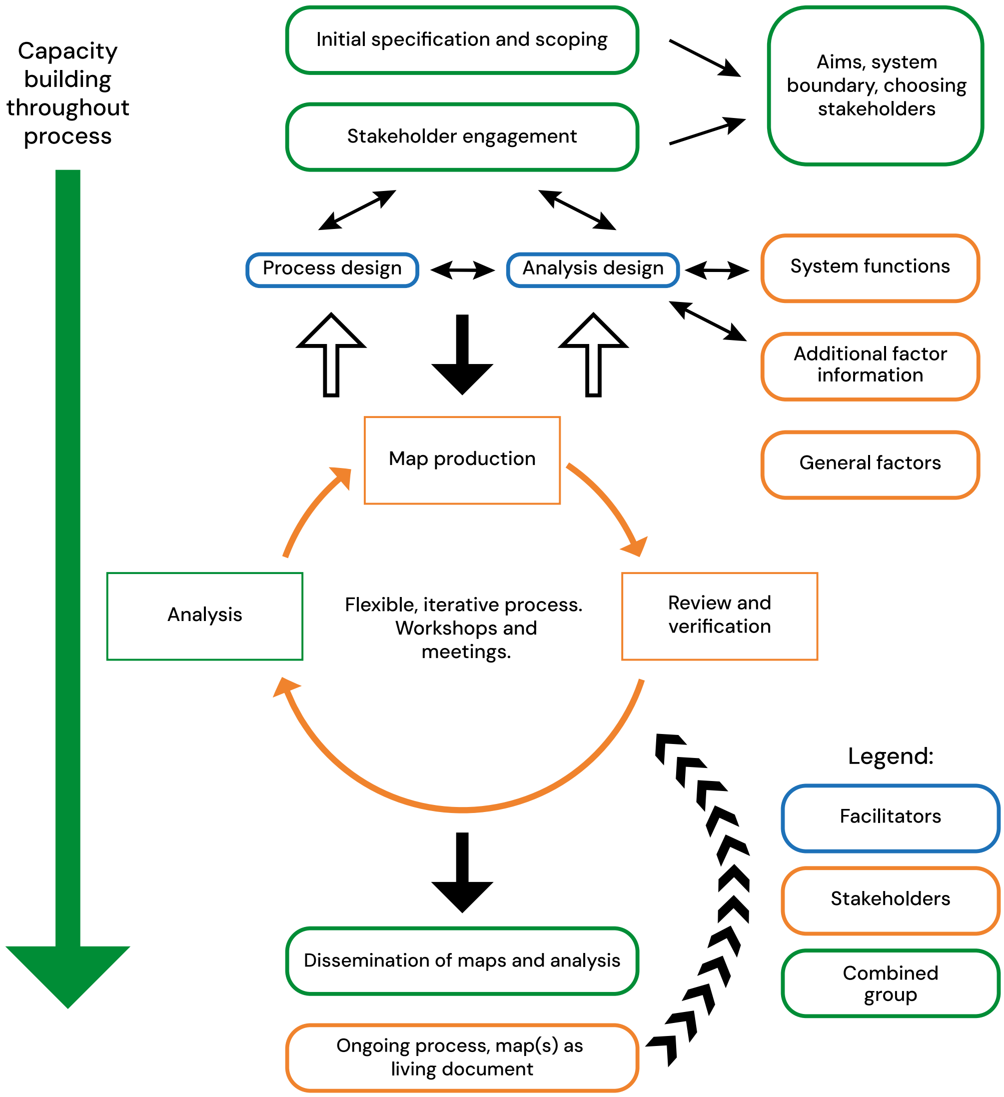


*Figure 21: Research process for PSM. The diagram reads from top to bottom, and shows the iterative stages of a PSM process and who tends to lead them.*[59]

*59 Source: Penn and Barbrook-Johnson (2022). How to design a participatory systems mapping process. CECAN (Centre for the Evaluation of Complexity Across the Nexus).*

# 5. Useful tips and common challenges

Using these methods involves a fair amount of tacit knowledge, and your practice will improve and change as you use them more. Our experience has enabled us to develop the following list of tips and common pitfalls.

*Table 2: Tips and challenges associated with creating CLDs and PSMs.*

| Method | Useful tips | Common challenges |
|---|---|---|
| CLD | •Think about what might drive change in the system, or what creates inertia. These processes are often feedback loops<br><br>•Create 'behaviour over time' plots to think through individ-ual loops and how they interact with others<br><br>•Use system archetypes and existing CLDs to help brain-storm loops<br><br>•Tune the exercise to the visual literacy of your audience<br><br>•Allocate a significant time to improving visualisation and communication before publishing or sharing | •It is hard to identify feedback loops<br><br>•People mix up reinforcing and balancing feedback loops<br><br>•The exercise loses focus and becomes more of a generic systems mapping exercise, or a PSM exercise, because you stop focussing on the loops<br><br>•People confuse positive and negative causal connections |
| PSM | •Always ask participants to explain their thinking when they add things to map to avoid vagueness or confusion<br><br>•Position yourself as a non-expert when facilitating, allow people to disagree if it is constructive, and capture differ-ences of opinion in the map and annotations<br><br>•If facilitation is overwhelming, as it often is, ask participants how they would build things into the map and discuss how to implement their ideas, rather than trying to decide there and then or positioning yourself as the "mapping expert"<br><br>•Regularly reflect on boundaries and focus of the map; adapt them as you go to suit your purpose<br><br>•Do not put pressure on finishing within an allotted time or arriving at a final version of the map; maps rarely feel completely finished<br><br>•Introduce analysis early on to help with refinement and make applications clearer | •There is often a slow start to mapping workshops, especially when they include brainstorming system boundaries and focal factors<br><br>•There may be a lack of conviction in where the exploratory process is going; be clear about your goals and immediate outputs you are aiming at<br><br>•People confuse positive and negative causal connections<br><br>•People get bogged down in tangential discussion; this can be fantastic and part of the exercise, but may be a distraction from the project purpose |

# 6. Resources and software

The resources listed in Table 3 are useful guides to systems mapping techniques.

*Table 3: Helpful resources to guide and inform the use of systems mapping.*

| Reference | Type | Notes |
|---|---|---|
| Barbrook-Johnson, P., & Penn, A. S. (2022). Systems Mapping: How to build and use causal models of systems. Springer International Publishing. https://doi.org/10.1007/978-3-031-01919-7 | Book | Open-source book on a range of systems mapping methods, including causal loop diagrams and participatory system maps. |
| Kim, D. H. (2000). System archetypes I: Diagnosing systematic issues and Designing High-leverage Interventions. Pegasus Communications. https://thesystemsthinker.com/wp-content/uploads/2016/03/Systems-Archetypes-I-TRSA01_pk.pdf<br>Also subsequent guides in the series. | Series of preprints | This suite of guides is invaluable for getting into the most important details of CLD. There is a wealth of information in each one, but the eight archetypes, and the discussion around them really gives a sense of what the core engine of a system might look like.. |
| The Systems Thinker. (2018). The Systems Thinker; Leverage Networks Inc. https://thesystemsthinker.com/ | Website | This is a website version of the original 'The Systems Thinker' publication which has run since the early 1980s. There are hundreds of short and accessible articles on all sorts of topics, including dozens for CLDs. We recommend using the search function to find CLD articles, as there is not a stand-alone category for browsing. Daniel Kim's Systems Archetypes are particularly valuable. |
| CECAN. (2022). The Participatory Systems Mapping Toolkit. CECAN. Available at: https://www.cecan.ac.uk/resources/toolkits/the-participatory-systems-mapping-toolkit/. | Series of reports | CECAN PSM toolkit, including guidance on running workshops and designing research processes. |

We regularly use the following software and recommend you check them out and see which you like.

For general drawing of maps:

i) **Draw.io:** free, open source, and very flexible drawing software. Not specifically for systems mapping and is hard to export maps in other formats, but very easy to use and well-supported.
ii) **PRSM:** free software specifically for systems mapping, very good at live online workshops and doing some basic analysis. Small team developing it so a few minor bugs remain.
iii) **Vensim:** well-established, commercial system dynamics and CLD software, with a free academic version.

For analysis of maps:

i) **Gephi:** free and open-source network analysis software, good for automated layouts and computing network statistics, as well as handling very large maps.

s-curve economics

scurveeconomics.org

RAP REGULATORY ASSISTANCE PROJECT

UCL Institute for Sustainable Resources
Centre for Net Zero Market Design

INSTITUTE FOR NEW ECONOMIC THINKING AT THE OXFORD MARTIN SCHOOL

Environmental *Change* Institute
eci
UNIVERSITY OF OXFORD