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Outcome Report of IIASA Expert Workshop on

System Dynamics of Social Tipping Processes

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with Franziska Gaupp, Niklas Höhne, Mark S. McCaffrey, Jean-Francois Mercure, Irene Monasterolo, Raya Muttarak, Leila Niamir, E. Keith Smith, Caroline Zimm

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Abstract

Social tipping processes describe how social, political, economic or technological systems can move rapidly into a new system state if cascading positive feedback mechanisms are triggered. Interventions for activating these social tipping processes are promising levers for accelerating progress towards net-zero. This study builds on recent literature in this field by explicitly characterising the feedback mechanisms, interconnections between systems, and monitoring variables, that collectively help explain social tipping processes. Using a participatory system dynamics modelling approach with experts in five specific social systems, we delineated both positive and negative feedback mechanisms in each system: energy, finance, urban infrastructure, norms and values, and education. We then co-developed a conceptual model of relevant feedback mechanisms, and identified the variables that can be used to monitor tipping dynamics. The presence of many coupled positive feedback loops within and between the systems indicate a high potential for social tipping dynamics to help tackle climate change. However, we also identified conditions and countervailing feedback loops that could result in undesirable dynamics. Further work is needed to explore potential tipping dynamics, identify the conditions under which they can be achieved including through interventions, and elaborate tipping processes in other social systems such as food and land use.

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Introduction

Tipping Processes in Social Systems

Scientific evidence repeatedly emphasizes that limiting global warming to Paris Agreement's climate goals require strong, rapid and sustained reductions in global GHG emissions (IPCC 2021). This urgency has drawn the attention of scientific and policy debate to social tipping points and processes, which can trigger accelerated climate action through cascading effects in societies, institutions and economic systems (Moore et al. 2022).

Tipping points describe critical thresholds in complex systems that - if crossed - can lead to qualitatively different system states (Lenton 2020). Tipping points are typically reached when boundary conditions are forced in a direction that strengthens positive (reinforcing) feedbacks and/or weakens negative (balancing) feedbacks. At the tipping point, a small perturbation triggers a large system response driven by such feedback mechanisms (Sharpe and Lenton 2021). Climate tipping points, for instance, refer to critical thresholds in earth systems that - if passed - could lead to nonlinear and often irreversible changes such as shutting off ocean circulation systems, dieback of Amazon rainforest, or decay of Greenland ice sheet (Lenton et al. 2008). Although uncertain, these thresholds become more likely if mean global temperature rises above 2°C on preindustrial levels, which could prevent stabilization of the climate even if emissions are reduced (Steffen et al. 2018). Climate tipping points pose low-probability high-consequence risks to the global economy and strengthen the economic case for stringent climate policy (Dietz et al. 2021; Lontzek et al. 2015).

Growing understanding of these non-linear dynamics in the earth and climate systems has led to a growing body of literature identifying analogous feedback mechanisms in human systems that could help accelerate and amplify progress on climate action (Otto et al. 2020).

'Social tipping processes' describe how social, political, economic or technological systems can move rapidly into a new system state or functioning (Tàbara et al. 2018). Social tipping processes are distinct from those in earth systems as: (1) they involve human agency; (2) they involve social network-related change mechanisms and so do not have to physically co-occur; (3) they have more complex sets of interacting drivers and mechanisms, and do not have a single control variable (Winkelmann et al. 2022). These complexities mean single points or critical thresholds are difficult to isolate, so researchers tend to avoid using the term 'social tipping point', referring instead to processes and dynamics (see Box 1). Social tipping processes also tend to occur over shorter timescales and at more local or regional scales than in the earth system (Winkelmann et al. 2022).

Positive feedback effects that act as amplifiers in social tipping processes include learning curves, economies of scale, and network externalities (in technological systems), or self-fulfilling beliefs, norm cascades, and bandwagon effects (in social systems) (Farmer et al. 2019). Although reversible initially, these processes may become irreversible over time as new feedbacks emerge, such as the political difficulty of reversing support for a new technology sector with associated jobs once it has become established as the incumbent (Sharpe and Lenton 2021). Path dependence in incumbent political institutions can also be dislodged by shifting public opinion, increased activism, more vocal expressions of public concern, and new coalitions of interest around policy change (Winkelmann et al. 2022).

Box 1. Definitions of key terms used in this report.

Following Otto et al. (2020) and Winkelmann et al. (2022), in this report we use the following terminology:

- **'Social tipping processes'** = positive feedback mechanisms associated with the potential tipping of a social system into a new state. Note that 'social system' is used as a shorthand for all human systems (as distinct from 'natural' earth and climate systems).
- **'Social tipping elements'** = social, political, economic or technological systems in which tipping processes can occur. (Also referred to as 'subsystem' in this report.)
- **'Social tipping interventions'** = active changes made to social systems in order to trigger or activate tipping processes.
- **'Social tipping dynamics'** = changes in socioeconomic systems over time that result from social tipping processes.
- **'Control parameters' =** forcing variables that can trigger tipping processes once they cross a threshold.
- **'Monitoring variables' =** operational variables that represent the tipping dynamics and for which quantitative data is available or can be obtained.

In system dynamics terms, 'social tipping processes' refer to system structure, and 'social tipping dynamics' refers to system behaviour. In this report, the system behaviour of interest is accelerated decarbonisation through a decline in the fossil fuel energy supply.

These working definitions are based on more formal and extensive definitions from the literature as follows*:*

" *'**Tipping**' describes the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system which is often irreversible*" (Milkoreit et al. 2018).

"*A '**social system**' can be described as a network consisting of social agents (or subsystems) embedded within a social-ecological environment. Such a social system is called a '**social tipping element**' if under certain critical conditions, small changes in the system or its environment can lead to a qualitative macroscopic change, typically via cascading network effects such as complex contagion and positive feedback mechanisms … The resulting transient change process is called the '**social tipping process**"* (Winkelmann et al. 2022).

Social Tipping Elements, Interventions, and Interactions

Social tipping elements or subsystems

Using expert elicitations, workshops and literature review, Otto et al. (2020) identified six key social tipping elements for accelerating progress on climate change mitigation. These social tipping elements are specific subsystems of human activity (Box 1) in which relatively small disruptions or 'tipping interventions' can activate non-linear dynamics of change. The six social tipping elements from Otto et al. (2020) are:

- *Energy production and storage:* Increasing the relative price of clean energy technologies through subsidy programs and decentralized production can trigger reinforcing feedback mechanisms in the energy system for a rapid transition towards clean technologies.
- *Human settlements:* Choosing clean technologies in new urban infrastructure triggers both cost reductions and consumer interest in environmental technologies and can lead to rapid decarbonization.
- *Financial markets:* Divestment from fossil fuel assets can rapidly reinforce investors' belief in the risks of carbon-intensive assets and lead to a shift of financial support from fossil fuels to clean technologies.

- *Norms and value systems:* Advocacy by a small group of thought leaders can lead to a large fraction of the population recognising the immoral character of fossil fuels, hence a shift in norms and values, and increased pressure on policymakers to restrict the use of fossil fuels.
- *Education system:* Coverage of the causes and effects of climate change in school curricula leads to increased public knowledge and awareness, which can trigger sustained widespread engagement in climate action.
- *Information feedbacks:* Both in the public consumption domain and in financial markets, disclosure of information on carbon emissions can trigger rapid behavioural change. Corporate disclosures are expected to enhance investors' belief in the risks of carbon-intensive assets. Disclosure on consumer products can induce widespread engagement in climate action and lifestyle changes.

In this study, we include corporate disclosures in the finance system and combine the 'education system' and 'information feedbacks' of carbon labelling on consumer products. Therefore, we focus on five social tipping elements.

Social tipping interventions

Others have identified similar or related social tipping elements and interventions. For example, Farmer et al. (2019) define 'sensitive intervention points' as relatively small changes that can trigger a large change in systems that sit at a critical threshold or boundary between qualitatively different types of behaviour. They distinguish two types of interventions: 'kicks' or 'shifts'. Kicks push the system onto a new trajectory without changing underlying system dynamics (e.g., financial disclosure, technology investment, political mobilisation). Shifts change the rules of the system and its dynamics (e.g., institutional structures) (Farmer et al. 2019). Sharpe and Lenton (2021) show how targeted investment and pricing policies in small groups of countries can bring clean technologies below the threshold of cost-parity with fossil fuel technologies, and trigger shifts in global markets. Similarly, Climate Action Tracker (2019) identify targeted investments, incentives, and regulations to drive down the costs of energy storage (for grid integration of intermittent renewable power), electric vehicles, and decarbonised cement production. Winkelmann et al. (2022) discuss how a single schoolchild's protest which led to the Fridays For Future school strikes has triggered a strong response in the German socio-political system evident in an upward shift in public concern, strong electoral support for Greens, and a new federal climate neutrality law that could potentially lead to wider shifts in the EU climate policy landscape. Similarly, Smith, Christie, and Willis (2020) caution against an over-reliance on policy actions as social tipping interventions. They argue that civil society and social movements create the constituency for government-led interventions (which are effect not cause). They also emphasise the importance of local clusters of strong ties for building and expanding social mobilisation.

More revolutionary direct action is also a social tipping intervention, as in Andreas Malm's calls for fossil capital[1] to be destroyed on grounds of immorality, and evidenced in hundreds of place-based protests against fossil extraction (Temper et al. 2020). Outcomes of interventions are uncertain given the interactions between reinforcing (positive) and dampening (negative) feedback loops. In the case of radical direct action, value polarisation is an example of a countervailing process. Temper et al. (2020) show how protest movements against both fossil and low-carbon energy projects have stopped, suspended, or slowed new

[1] http://www.theguardian.com/commentisfree/2021/nov/18/moral-case-destroying-fossil-fuel-infrastructure

developments but have also led to violence, with 10% of 649 cases analysed involving assassination of activists.

Polarisation also leads to a loss of diversity in opinion, ideas and solutions, undermining system resilience. Axelrod, Daymude, and Forrest (2021) and Macy et al. (2021) show computationally how changing public opinion can lead to irreversible partisan division if there is low tolerance for disagreement and strong within-group identification. This value polarisation even persists in response to a universal exogenous threat (like Covid-19). Both these papers are part of a special issue edited by Levin, Milner, and Perrings (2021) that explores value polarisation in the political sphere in a variety of contexts, emphasising interactions between processes at multiple scales in complex adaptive systems. Common strategies for mitigating value polarisation include network heterophily (linking or interacting with dissimilar others), public goods provision (or other means of wealth redistribution), higher tolerance for risk and reduced exposure to oppositional views (Levin, Milner, and Perrings 2021).

Interconnections between social tipping elements

Although analysis of social tipping processes tends to be domain or subsystem specific, these subsystems are strongly interconnected. Otto et al. (2020) highlight potential interactions between the six social tipping elements that can further accelerate tipping processes. As an example, more emphasis on climate change in the *Education system* can lead to wider advocacy activities that trigger shifts in the *Norms and value systems*, which in turn leads to more demand for climate change coverage in school curricula while also creating a higher sensitivity to carbon-emission disclosures on consumer products and triggers in the *Information feedbacks* social tipping element.

Stadelmann-Steffen et al. (2021) argue that social tipping dynamics emerge from interactions between three specific subsystems - technological, behavioural, and political. They use the historical phaseout of ozone-depleting chemicals as an example of interacting political tipping dynamics (e.g., Montreal Protocol), technological tipping dynamics (e.g., non-CFC substitutes), and behavioural tipping dynamics (e.g., concern over UV radiation and skin cancer). But they note that analogous dynamics for the phaseout of fossil fuels are more complex, uncertain, and hard.

A recent paper by Moore et al. (2022) formalises a similar set of interconnected social tipping elements in a quantitative global model of coupled social-climate systems. Their model components capture a wide range of feedback processes governing the interactions between public opinion, individual action, climate policy, climate impacts (and their effects on opinion), and endogenous technological change. Stylised runs of the model show how positive feedbacks in distinct model components generate tipping dynamics. For example, Moore et al. (2022) show that individual action is ineffectual unless the social credibility of costly behavioural change is high such that others are persuaded to join the early climate policy supporters, triggering a cascade of positive feedback processes through conformity and technological learning.

Interconnections between scales

Sharpe and Lenton (2021) further emphasise how tipping processes in interconnected systems can propagate up through scales of impact. They call this an "upward-scaling tipping cascade". As an example, if the EU, China and California (which account for 50% of new car sales) were to follow Norway-style policies for reducing the cost premium of electric vehicles (EV) relative to conventional vehicles, this could trigger an irreversible shift in the global automotive market. Sterl et al. (2017) similarly argue that the transformational changes observed over the past decade in the renewable power and electric vehicle sectors have been triggered by concerted policy efforts in a handful of frontrunner countries who have transformed global markets and enabled the transition to spread more widely.

Bernstein and Hoffmann (2019) similarly use the solar PV and EV success stories: from German feed-in-tariffs and Norwegian purchase incentives to global solar and EV market expansion respectively alongside policy diffusion as later adopters learn from the frontrunners as to what works. For a third example related to information feedbacks rather than technological innovation, they point to early CDP engagement with select large corporates which catalysed many different national, sectoral, and central bank initiatives for disclosing carbon liabilities. (CDP was formerly the Carbon Disclosure Project).

In each subsystem, human agency (or directed interventions) can have cascading effects up through scales (Stadelmann-Steffen et al. 2021). In the behavioural subsystem, for example, a single schoolchild's protest has led to a global Fridays for Future movement. The conditions under which this leads to social tipping dynamics depends on interconnections with other subsystems: will Fridays for Future legitimise radical collective climate action led by policymakers in response to the window of opportunity created by rapidly falling renewable energy and battery costs against a backdrop of geopolitical energy insecurity?

Linkages across scales can support positive cascades, but can also lead to carbon lock-in or what has been termed the 'fractal trap' (Bernstein and Hoffmann 2019). Interconnected political, social, economic, and technological systems from municipal up to national and global scales create inertias that climate action needs to unlock.

From their extensive analysis of emission-reduction strategies in Project Drawdown, Bhowmik et al. (2020) identified the 'meso scale' of 10^4 - 10^5 people as the 'sweet spot' for interventions with maximum leveraging effect across scales - from individuals (10^1) through communities (10^4) up to countries (10^6 - 10^9) and the world (10^10). These meso-level scale of communities and social networks has the highest number of implementable climate actions, and the largest reductions in carbon emissions.

McCaffrey and Boucher (forthcoming) link these insights on cascading cross-scale effects with both fractal entanglement concepts, and with the importance of pedagogy for agency and action, as "radical means" of societal transformation.

The fractal metaphor steers intervention strategies away from single agents or arenas (like national governments and carbon taxes) and towards diverse, multilevel, catalytic action at different scales. This distributed approach needs mechanisms of 'contamination' or spill over between specific fractal traps so that new actions, policies and institutional forms are taken up in different parts of the overall system. Bernstein and Hoffmann (2019) describe this as the "*politics of overcoming the fractal carbon trap*". O'Brien (2021) further argues that language, shared meanings, and values are all contamination mechanisms that can cause ripples of effect up through scales.

The success of 'catalytic' interventions (here, social tipping interventions) is measured not in emission reductions but in impacts on social, cultural or institutional dynamics for escaping carbon lock-in. Pamlin (2020) makes a similar argument about the importance of catalytic interventions and platforms for transformative change both generally and specifically in response to Covid-19. Activating tipping points to deliver on needs fulfilment (a 'dynamic' framing of the opportunity) is a transformative shift away from emission-reduction solutions offering incremental improvements (a 'static' framing of the problem) (Pamlin 2021).

Aim of this study

The aim of this study is to develop a conceptual system model of social tipping elements so that the effectiveness of social tipping interventions can be evaluated once this model is formalized with empirical evidence and quantitative data. The key outcome indicator is the global GHG emissions, and fossil fuel energy supply is the proxy variable we use in this study to measure this outcome indicator.

Monitoring variables are additional metrics that reflect the progress of social tipping dynamics and indicate the effectiveness of interventions. In the conceptual system model, we aim to capture the feedback mechanisms that underlie the tipping dynamics in each social tipping element, as well as the interconnections between the social tipping elements discussed in the previous section.

Figure 1 illustrates how the key concepts used in this study - social tipping elements, processes and interventions (Box 1) - are aligned with the systems analytical problem structuring framework. Systems analysis starts with problem structuring (Quade and Miser 1985; Thissen and Walker 2013) in line with the objectives operationalized in outcome indicators, of which (dynamic) behaviour is determined by the system structure captured in a system model. This model is then used to evaluate the effectiveness and consequences of policy (intervention) options by propagating their impacts on the outcome indicators through the system interactions. This system model is also used to explore the effects of uncertainties alongside interventions, which are not shown in Figure 1.

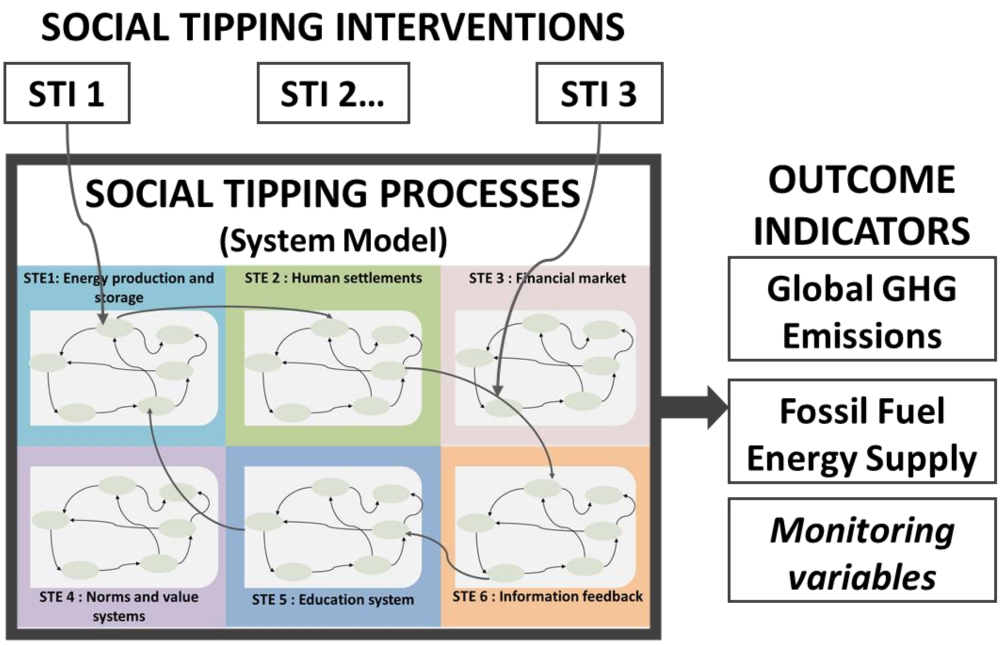


Figure 1: Systems analytical structuring of social tipping processes and interventions

Participatory System Dynamics Modelling to Conceptualize Feedback Mechanisms

Tipping dynamics are triggered by strong feedback mechanisms. To explicitly identify these feedback mechanisms, we adopted a participatory system dynamics (SD) modelling approach.

System dynamics is a modelling method for complex systems that implements the core concepts of systems thinking: Feedback loops, delays and nonlinearities. Being closed chains of causal relationships, feedback loops govern the dynamics of a system, that is, its behaviour over time. Therefore, even though a model composed of feedback loops is a static representation of a system, it conceptualizes the system's dynamic behaviour over time.

Systems thinking and causal loop diagrams

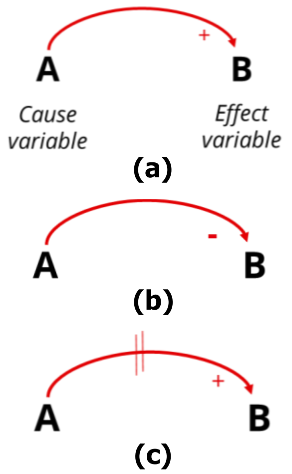


*Figure 2: Illustration of a positive relationship (**a**), a negative relationship (**b**), and a delayed relationship (**c**).*

In this report, we use *causal loop diagrams* to visualize feedback loops. In a causal loop diagram, a relationship is represented by an arrow and a polarity sign (Figure 2). A positive relationship implies that a change in the cause variable changes the effect variable in the same direction. For instance, if *A* decreases, *B* decreases. A negative relationship means that a change in the cause variable changes the effect variable in the opposite direction. For instance, if *A* decreases, *B* increases. A double line passing through the arrow perpendicularly indicates a delay between the cause and effect.

Closed chains of causal relationships form feedback loops as shown in Figure 3 and the polarity of a loop is determined by multiplying the polarities of individual links. A positive (reinforcing) feedback loop emerges if a change in any of the variables cascades through the loop and changes that variable in the same direction, hence reinforces the dynamic behaviour. A negative (balancing) loop returns a change in the opposite direction, hence balances the dynamic behaviour. Positive feedback loops create exponential behaviour, growth or decline, and negative feedback loops create logarithmic growth or decline.

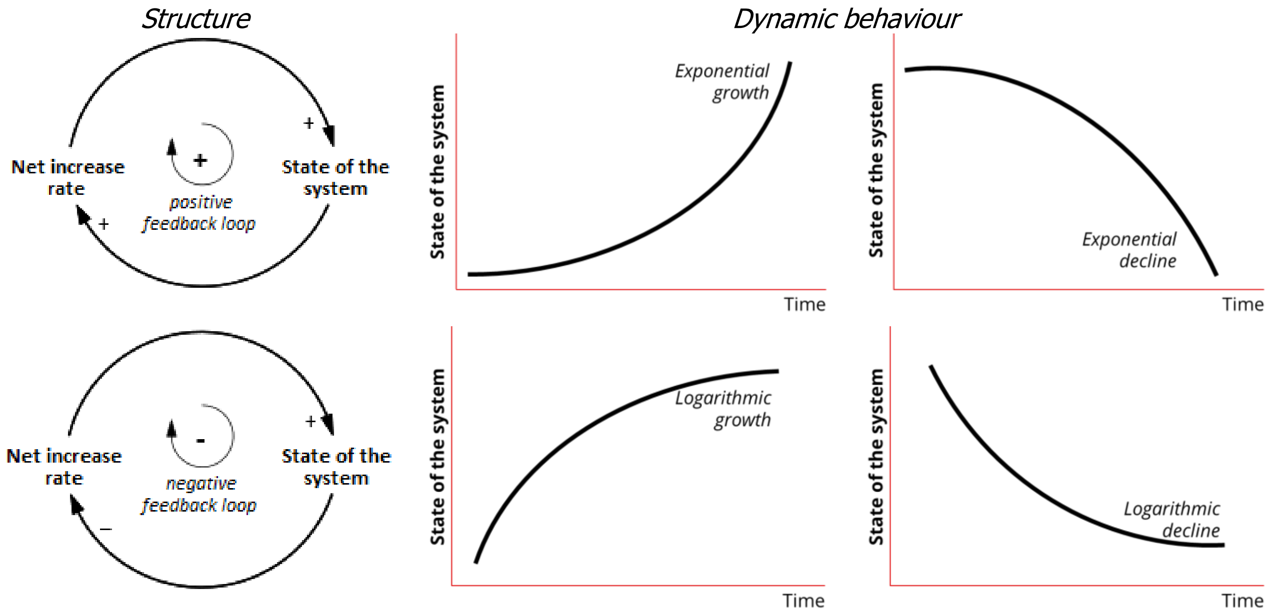


Figure 3: Illustration of a single positive (reinforcing) and a negative (balancing) feedback loop and dynamic behaviour modes they can generate in the top and bottom row, respectively.

Participatory modelling

To identify the feedback loops governing social tipping dynamics, we adopted a participatory modelling approach in this study. Participatory modelling (also named 'group model building') is involving stakeholders, experts and clients in various phases of the modelling process to elicit different model components such as variables, causal relationships and parameter values (Vennix 1999). Participatory modelling combines scientific and local expert knowledge about a system by representing a shared understanding of stakeholders (Andersen et al. 2007). In addition to co-production of scientific knowledge, participatory modelling helps stakeholders to understand a system's structure and behaviour resulting from these relationships; to create a shared ownership of the problem, analysis, and consensus and commitment about decisions; and to reduce conflict and build trust to each other (Andersen, Richardson, and Vennix 1997).

In this study, we used participatory modelling to elicit expert knowledge on the systemic relationships and feedback loops that can drive social tipping dynamics. We held an in-person workshop on 18-19 November 2021 with thirteen experts in energy innovation, climate policy, finance, demographics, education, behaviour change, social dynamics and food systems. During the workshop, we first focused on each subsystem (social tipping element) separately, and then discussed the interactions between them. The participants were divided into two groups according to the match between their expertise and these subsystems, yet they were asked to reflect on the models created by the other group in order to ensure coherence of interactions between the subsystems. The first subsystem on *norms and values* was discussed by the entire group due to the relevance of their expertise to the subject and to introduce the modelling convention followed in the workshop.

Following an orientation on the nomenclature of causal loop diagrams, we introduced a 'concept model' for each subsystem and listed relevant factors that can be an enabler or barrier for tipping dynamics. A 'concept model' is a small and simple model that focuses on the core of the problem and deliberately lacks detail. Its function in a co-modelling process is to familiarize the participants with SD modelling, to confirm and disconfirm thinking around the subject, and to stimulate and structure the discussion if it gets suspended or diverted. We prepared the concept models for each subsystem based on the description of tipping mechanisms by Otto et al. (2020). These concept models can be seen on the full diagram of each subsystem (Figure 6, Figure 9, Figure 12,Figure 15, Figure 18) as the segments marked by grey lines. They are also included in their original form in the Appendix.

Following the on-site modelling during the workshop, we cleaned, clarified and refined the model diagrams to ensure coherence, avoid redundancies and add missing factors discussed during the workshop. This report presents the final versions of the causal loop diagrams that depict our conceptual model of social tipping mechanisms.

Feedback Mechanisms within Social Tipping Elements

This section presents the systems maps of each STE, developed by co-modelling with domain experts. The maps depict: (i) the main factors affecting rapid decarbonization in each STE as identified in the literature review and elicited from experts; (ii) the interactions of these factors; and (iii) feedback loops emerging from these interactions, as the catalysers of or barriers to accelerated social transformation. The maps presented in this section are refined versions of the workshop outcomes, where redundancies are removed and missing links are added based on the workshop discussion to ensure consistency.

Norms and Values

Social tipping processes in the norms and values subsystem relate to the support for and the opposition to fossil fuel exploitation. Figure 4 illustrates the feedback loops of norm change that function symmetrically against and in support of fossil fuel exploitation.

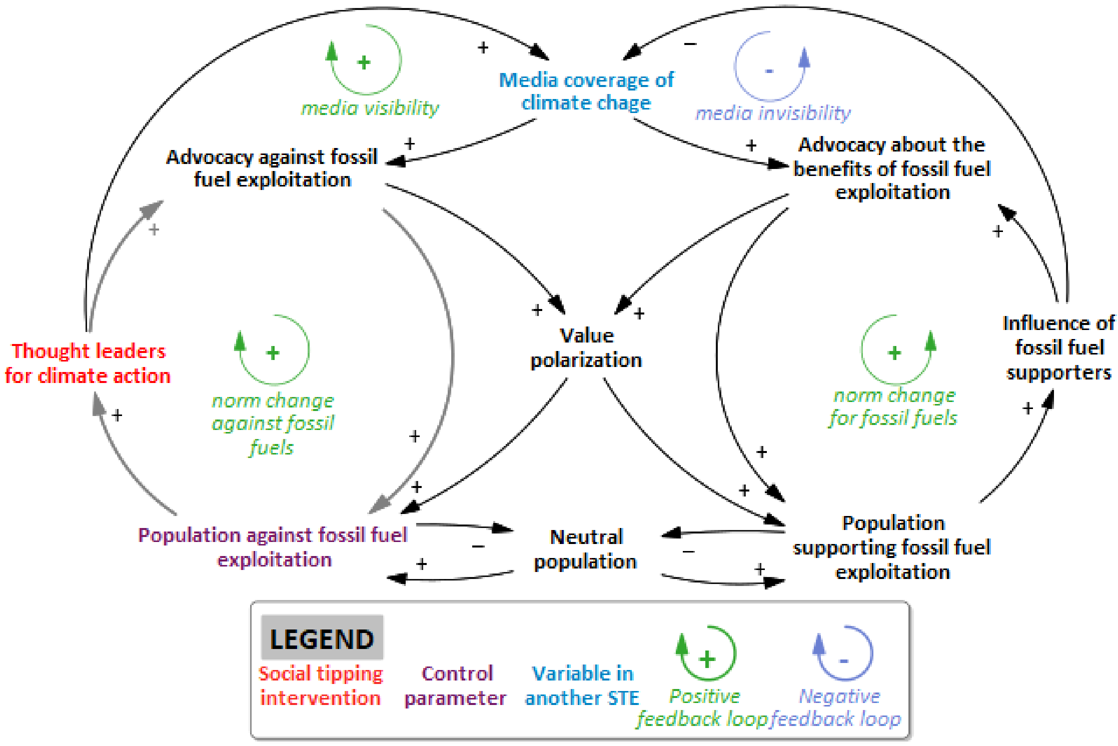


Figure 4: Feedback loops of norm changes against and for fossil fuel exploitation. (Grey arrows in this figure and all subsequent figures refer to the concept model used to initiate the participatory modelling workshop.)

Norm change against fossil fuels describe a reinforcing feedback loop: An increasing population against fossil fuel exploitation creates more thought leaders, more advocacy activities and more people recognizing the damage caused by fossil fuel exploitation. A similar mechanism, **norm change for fossil fuels**, describe the norm change through advocacy that lead to a higher population supporting fossil fuel exploitation. The advocacy activities on both sides lead to a higher value polarization, which further reinforces the norm change loops. Besides this direct effect, value polarization also impedes the increase in 'population against fossil fuel exploitation' since it incites the fossil fuel supporters, and reduces neutralization and the number of opponents to fossil fuel exploitation. A similar counter-effect of polarization also impedes the increase of pro-fossil-fuel population.

Media visibility is another reinforcing loop that strengthens the norm change against fossil fuels. Thought leaders for climate action, or public figures and celebrities, lead to a wider coverage of climate change either in the mass or social media, and this further increases the advocacy activities. The higher the influence of fossil fuel supporters, though, the more limited the media coverage of climate change. This leads to a dampening effect on the positive loop of norm change against fossil fuels, and forms the negative loop of **media invisibility** that balances the norm change for fossil fuel exploitation.

Figure 5 shows the effect of policy and fossil fuel industry on these norm change dynamics. **Social legitimacy of regulations restricting fossil fuels** is a negative loop that balances the increase of population against fossil fuel exploitation, because as public support stimulates regulations against fossil fuels , these regulations reduce the fossil fuel energy supply, hence reduce the climate change impacts in the long-term. Climate change impacts lead to more regulations restricting fossil fuel use not only through direct public support shown in Figure 5, but also through green voting (Hoffmann et al. 2022).

Fossil fuel advocacy describe the balancing effect of a weakening fossil fuel industry on value polarization and subsequently on population against fossil fuels. The lower the fossil fuel energy supply, the lower the market power of the industry, and their advocacy activities. Through the lessening effect of value polarization, though, the decline in the fossil fuel industry can reinforce the rise of population against fossil fuels. As the market power of the fossil fuel industry declines, increasing grievance leads to more aggressive advocacy activities of the industry. In contrast to a declining influence, this grievance effect creates the reinforcing loop of **fossil fuel industry fights back**.

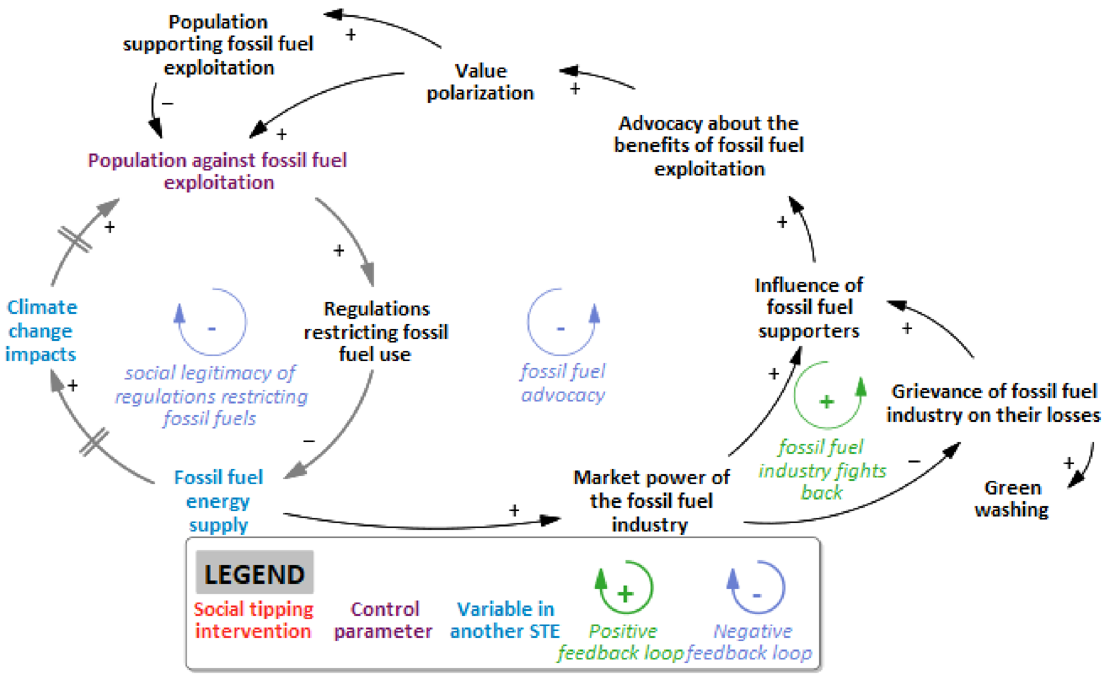


Figure 5: Feedback loops in the policy and fossil fuel industry affecting norm changes

The combination of norm change loops and the effects of policy and industry on them (Figure 6) highlights the complexity of norms and values subsystem: While the thought leaders and advocacy activities can trigger an accelerating increase in the population against fossil fuel exploitation, counter-advocacy on the fossil fuel side can hinder possible tipping dynamics.

Following Otto et al. (2020) who identified the 'recognition of the immoral character of fossil fuel exploitation' as the social tipping intervention in the norms and values subsystem, we consider 'thought leaders for climate action' who can facilitate such a recognition process as a proxy for this intervention. The control parameter in this subsystem is 'Population against fossil fuel exploitation', which lies in the intersection of several key feedback loops in this subsystem.

The norms and values subsystem is connected to the others through the following variables:

- 'Media coverage of climate change' (links to education and information feedbacks)
- 'Thought leaders for climate action' (links to education and information feedbacks)
- 'Climate change impacts' (links to education and information feedbacks and financial markets)
- 'Fossil fuel energy supply' (links to energy production)

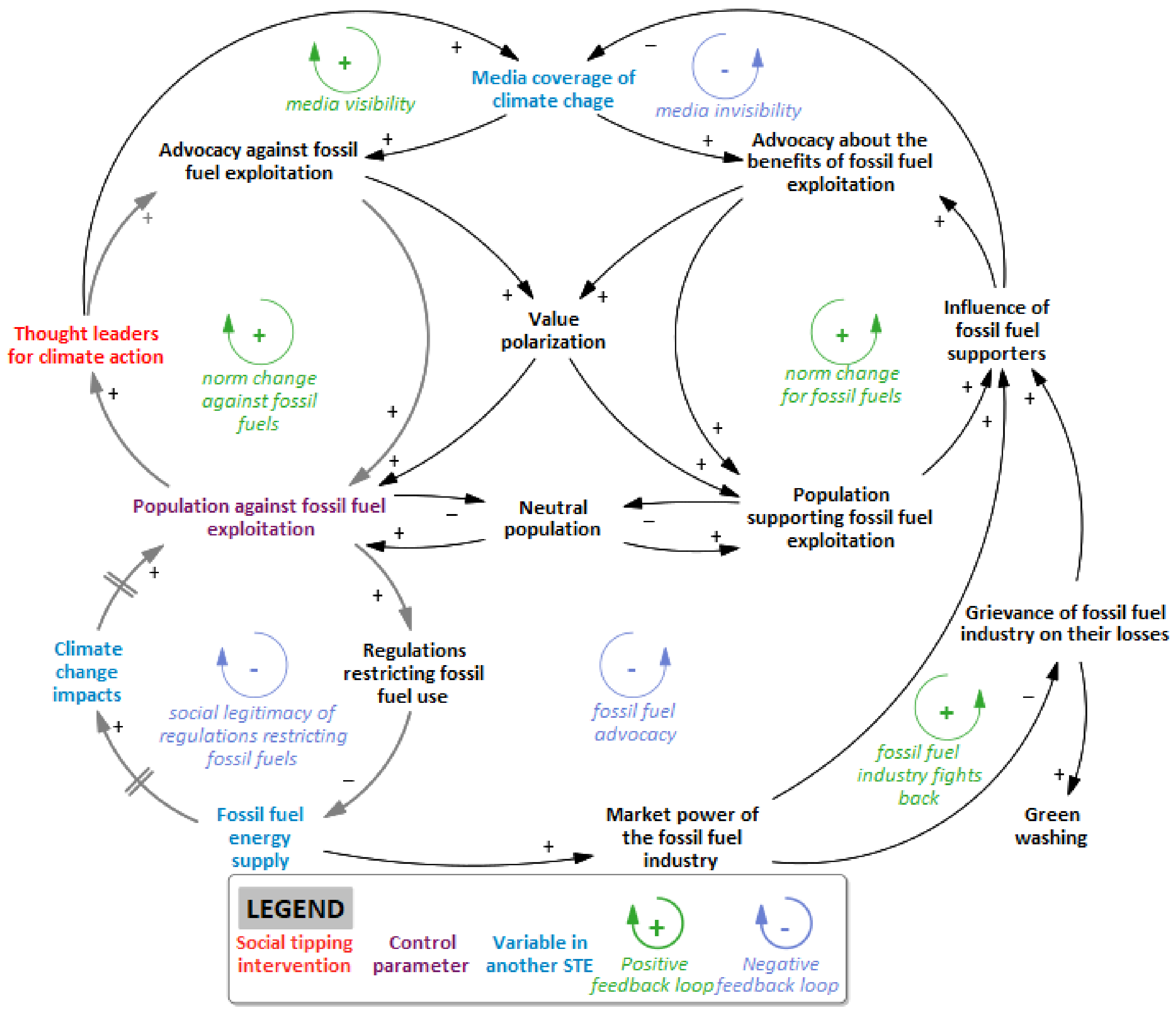


Figure 6: Social tipping processes in the norms and values subsystem

Energy Production

Social tipping processes in the energy subsystem relate to inter-related processes of decarbonization and decentralization. We explain each in turn, before presenting the full subsystem.

There are three feedback loops characterizing decentralization dynamics shown in Figure 7.

Diseconomies of scale is a positive feedback loop through which growing demand for decentralized energy undermines the profitability and materialization of centralized energy production which in turn further undermines the viability of large-scale energy infrastructure. This loop captures the diseconomies or disadvantages of scale as energy markets become more decentralized, flexible, and heterogeneous, and as consumers 'defect' from centralized suppliers - the so-called "utility death spiral".

Economics of decentralized energy is a positive feedback loop through which increased demand for decentralized energy stimulates market growth, economies of scale, and learning effects which in turn improve profitability and further stimulate market growth. This loop can both be direct in terms of improving economics, or also indirect through its stimulating effect on local institutions which respond to new market opportunities. Examples of the 'local institutional innovation' variable include community financing, social purpose companies, local entrepreneurs, new service providers, business models capturing new local value streams, and public-private partnerships backed by local authorities.

Utilities lock-in is a negative feedback loop through which governments intervene to protect the weakening market position of centralized utilities in order to maintain market stability and continuity. Also discussed in the workshop, but not included in the diagram, is whether an additional dampening regulatory intervention is needed in the economics of decentralized energy loop to protect against grid blackouts if progress is too fast.

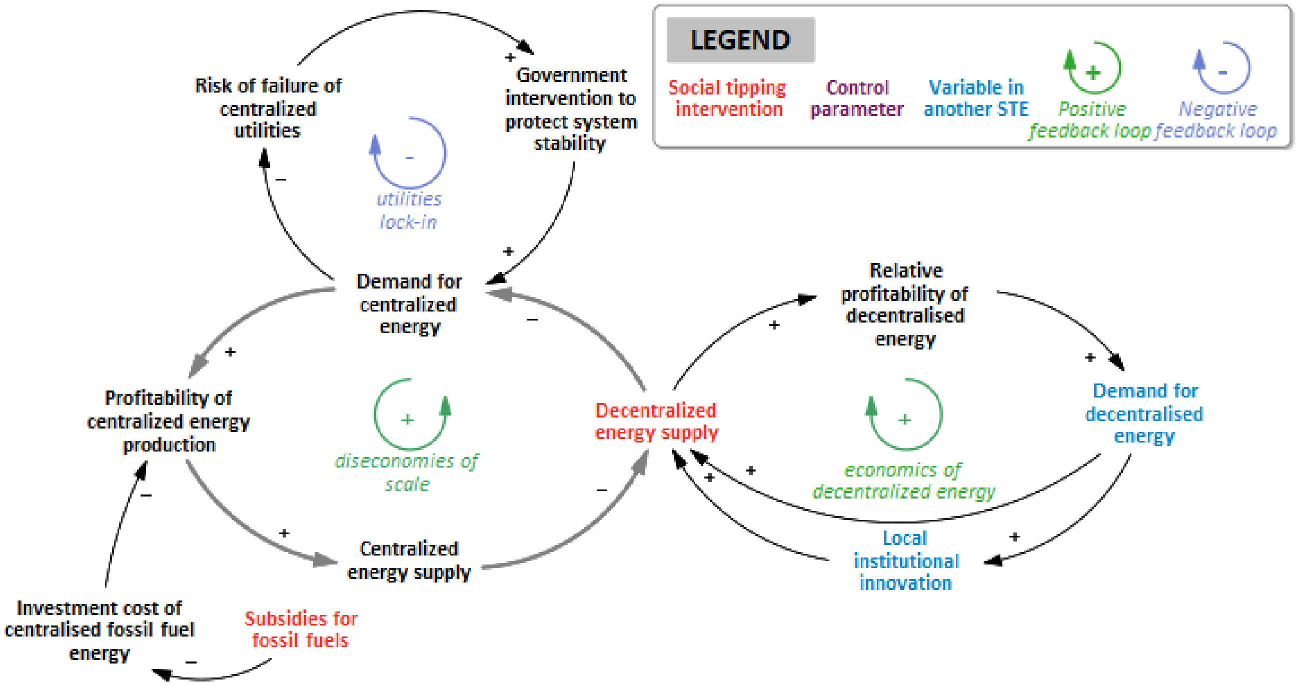


Figure 7: Feedback loops governing decentralization of energy supply

Utilities lock-in acts as a dampening response to the positive feedback loops of **diseconomies of scale** and **economics of decentralized energy** that combine to erode the continued viability of traditional, centralized energy infrastructure and utility business models. Together these three feedback loops capture the main dynamics of change discussed in the workshop in relation to decentralization - one of the '4Ds' driving change in the energy system alongside decarbonization, digitalization, and democratization.

Decentralized energy is strongly associated with solar PV, but also includes diesel generators, micro-generation and combined heat and power, urban heat networks, distributed storage (including electric-vehicle-to-grid). Some of these technologies or business models involve fossil fuels, so we treat 'low-carbon energy supply' as a distinct but related variable in order to capture four feedback looks characterizing decarbonization dynamics.

Decarbonization path-dependence is a positive feedback look through which continued demand for, and profitability of, fossil-fuel energy supply sustains its dominant market position and dampens the materialization of alternative 'low-carbon energy supply'. Also discussed during the workshop, but not included in the diagram, is whether this feedback loop should also include a dampening effect from diseconomies of scale or un-learning (forgetting-by-not-doing).

Working against this sustaining dynamic of a fossil-fuelled energy supply are two positive feedback loops on the **economics of low-carbon energy** and on **learning on low-carbon energy**. These capture the basic economic relationships between demand, profitability and supply which are strengthened further by a virtuous learning cycle of experience enabling cost reductions and performance improvements that further improve the cost competitiveness of low-carbon energy and so stimulate diffusion.

As the main forms of low-carbon energy (solar, wind) are intermittent, one negative feedback loop that dampens the self-reinforcing growth of low-carbon energy concerns **grid integration** which can be addressed or overcome through enabling regulatory structures.

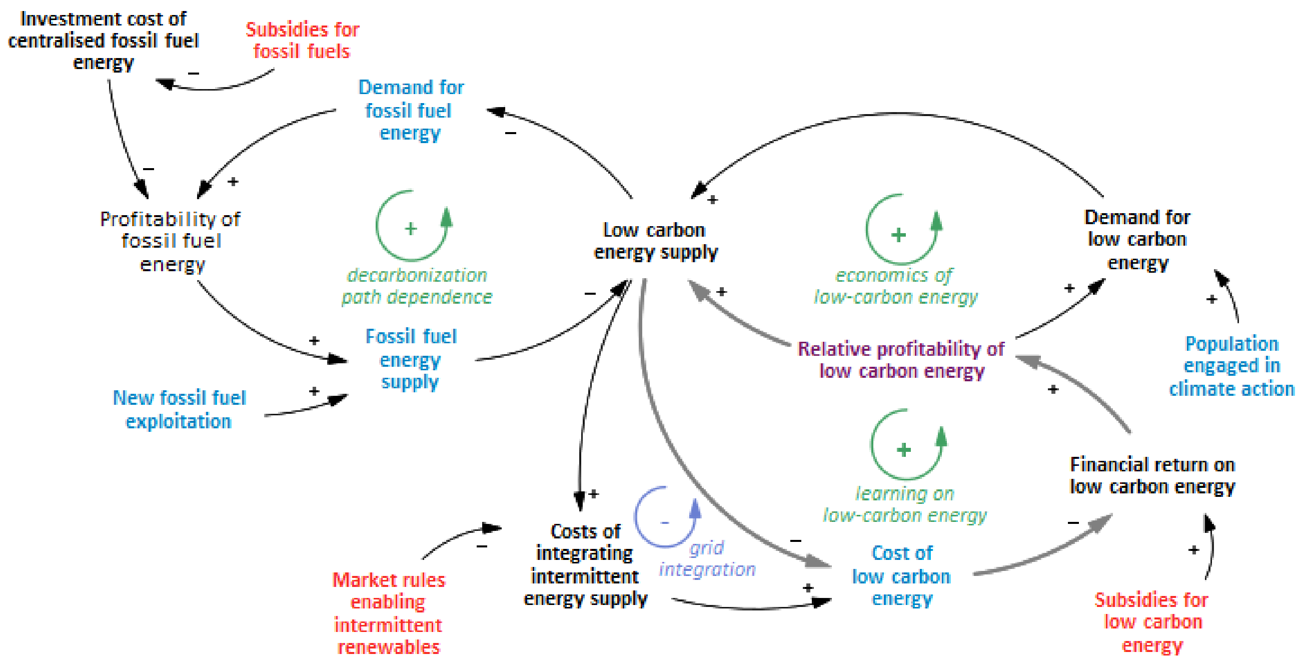


Figure 8: Feedback loops governing decarbonization of energy supply

These coupled feedback loops characterising market growth and economic competitiveness of low-carbon energy echo those explained above for decentralized energy. As noted, in some cases low-carbon and decentralized overlap (e.g., rooftop solar PV) but in other cases they do not (e.g., offshore wind). While conceptually similar, the feedback loops in each case have different implications and connections. For example, decentralized energy is strongly associated with the urbanisation subsystem, while low-carbon energy is strongly associated with the finance subsystem.

The full energy subsystem shown in Figure 9 combines these two sets of feedback loops for decentralization and for decarbonization. These feedbacks connect through rising 'demand for energy', which affects demand for both decentralized and low-carbon energy, and through the 'investment cost of centralised fossil-fuelled energy' which affects the profitability of the incumbent energy form.

Current evidence from energy markets, particularly the rapid cost declines and deployment of renewable power generation, suggests that the economic loops are close to or have already past critical thresholds, but are being dampened by issues of grid integration (of intermittent generation), utility lock-in, and fossil subsidies, as shown in the negative feedback mechanisms in Figure 9.

Tipping interventions relate to materialization of new low-carbon infrastructure ('decentralized energy supply'), to financial incentives ('subsidies for fossil fuels', 'subsidies for low-carbon energy'), and to regulations ('market rules enabling intermittent renewables'). These tipping interventions emphasize how public policy that sets appropriate rules and incentives to direct market activity can stimulate a wider range of actors driving both decentralization and decarbonization in energy systems.

Control parameters relate to the 'relative profitability of low-carbon energy' and the 'relative profitability of decentralized energy'. Once low-carbon energy consistently outcompetes incumbent fossil energy under a range of geographic and market conditions, positive feedbacks further strengthen their market position and a new system state is reached in which low-carbon energy is the default. The same logic applies equally to decentralized energy. Solar PV (decentralized and low-carbon) and offshore wind (low-carbon) are already cost-competitive in some jurisdictions and resource contexts. Both these control parameters are therefore appropriate choices of monitoring variable across regimes and contexts.

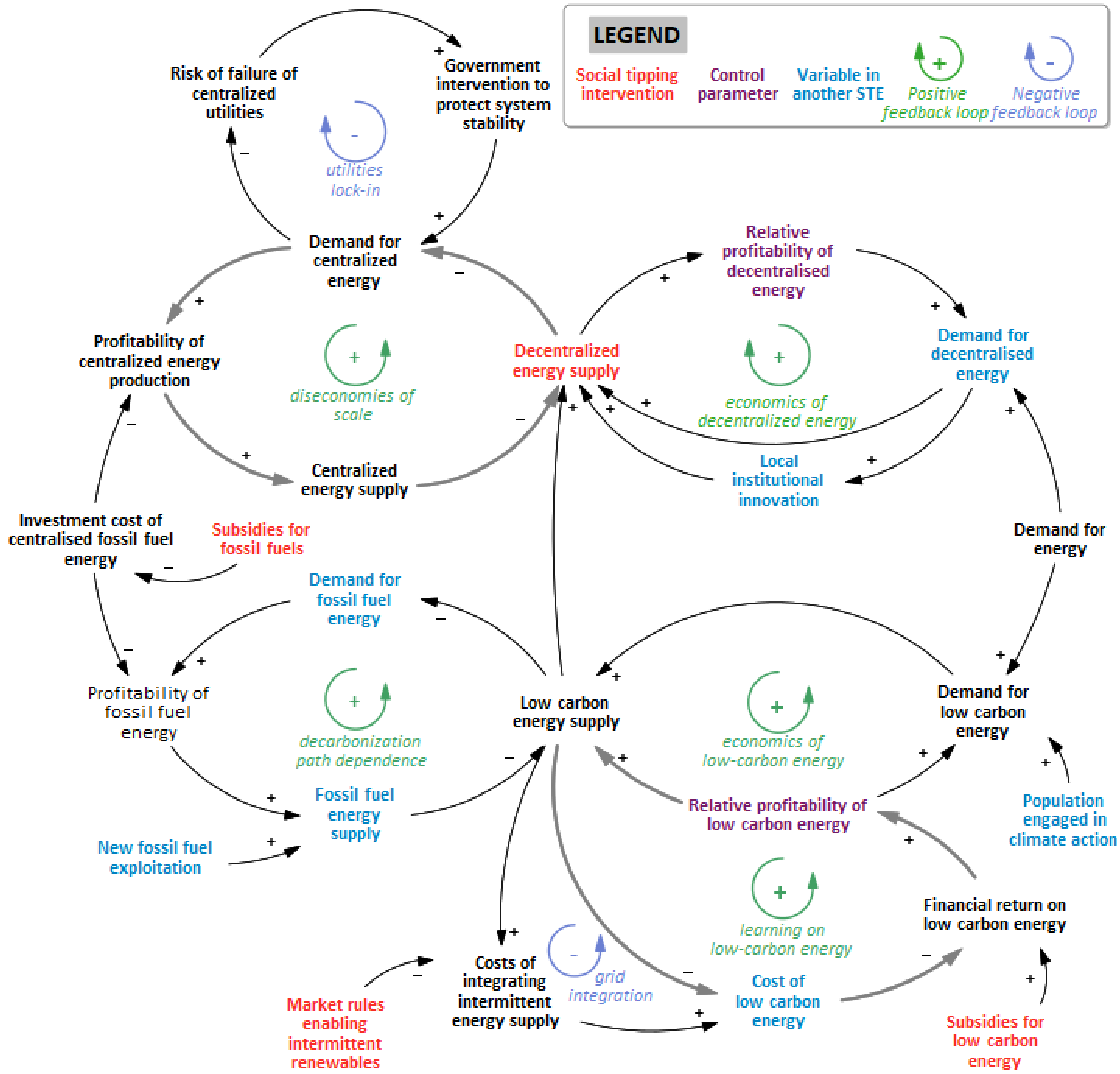


Figure 9: Social tipping processes in the energy production subsystem

The energy subsystem links to social tipping processes in the finance, norms, and urban infrastructure subsystems. Specific variables that act as bridges include:

- 'Local institutional innovation' (links to urban infrastructure)
- 'Demand for decentralized energy' (links from urban infrastructure)
- 'Demand for fossil fuel energy' (links to finance)
- 'Cost of low-carbon energy' (links to urban infrastructure and education)
- 'New fossil fuel exploitation' (links from finance)
- 'Fossil fuel energy supply' (links to norms and values)
- 'Population engaged in climate action' (links from education and information feedbacks)

While the energy subsystem represents competing but interrelated market and industry dynamics in fossil, low-carbon, and decentralised energy, these links show how change can be further accelerated or dampened by tipping processes in financial markets, cities, and societal norms.

Finance

Feedback mechanisms in the finance subsystem distinguish three sets of inter-related processes: fossil fuel investments governed by risk-return expectations, policy impacts including the exposure of fossil investments to regulatory risk, and carbon risk assessments shaped by central bank activism and market regulations. We explain each in turn, before presenting the full finance subsystem.

Figure 10 shows two principal feedback loops governing risk-return perceptions in fossil fuel investments. **Fossil-fuel path dependence** is a positive feedback loop that captures how capital allocated to fossil fuel assets leads to the exploitation of new reserves with financial returns supporting continued positive expectations for fossil fuel asset values. This dynamic is lagged due to the construction and implementation timelines between capital investment and new rigs, mining equipment, drilling operations, refineries, liquefaction plants and so on being ready to extract, process, and sell revenue-generating energy commodities.

In contrast, the positive feedback loop labelled **financial risk expectations** is extremely rapid as investors' perceptions of risk can affect expectations of asset value over ultra-short timescales (<1 second) in highly automated markets with large trading volumes of derivatives. A rise in expected asset values can improve perceived risk-return profiles leading to more capital allocation in the **fossil-fuel path dependence** loop. Conversely, a fall in expected asset values can rapidly undermine beliefs about future fossil production which in turn amplifies risk perception, and so on.

An additional positive feedback loop can exacerbate these potentially runaway dynamics. **Market demand for disclosure** captures how strengthened corporate disclosure of stranded assets amplifies the market's perception of risks and so further undermines the expected value of fossil fuel assets. The positive link from disclosures to perceived risk is not confirmed by recent empirical evidence so is marked by a dashed arrow. Here, 'fossil fuel divestment strategies' are an exogenous influence pushing up perceived risk of fossil fuel assets and pushing down capital allocation as a result. These influences are labelled in red to denote that divestment is possible social tipping intervention.

Conversely, **counter-betting** is a negative feedback loop that sees important market actors seeing opportunities in the rapid decline of fossil fuel assets' future value and so investing as the market falls. This can brake capital flight out of the fossil sector if it is sufficient to challenge mainstream beliefs.

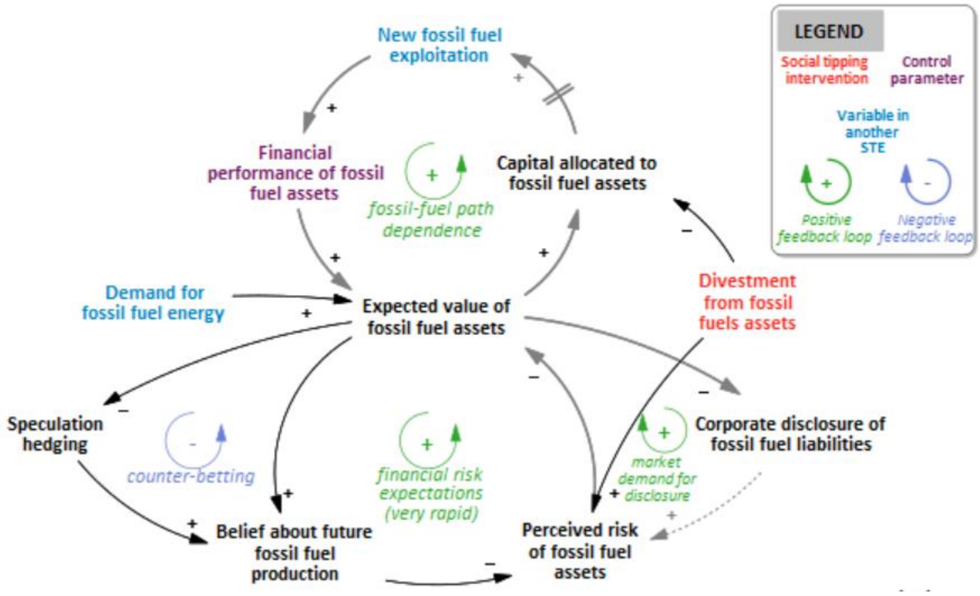


Figure 10: Feedback loops governing fossil fuel investments

Figure 11 captures the interactions between climate policy, regulatory risk, and investment strategies. The main feedback loop shown towards the top left is positive, and captures **policy impact on investor beliefs**. More stringent global and national emission reduction commitments reduce the perceived economic viability of existing and new fossil fuel assets. However, this is dependent on **policy credibility** shown as a linked positive feedback loop that captures the stringency, credibility, and momentum in the Paris Agreement process, as perceived by the investor community. Momentum and credibility of climate policies can be operationalized with respect the number of countries who enhance their Nationally Determined Contributions (NDCs) (ClimateWatch 2022a) or the number of countries that have net zero pledges in their law, policy documents or political pledges (ClimateWatch 2022b).

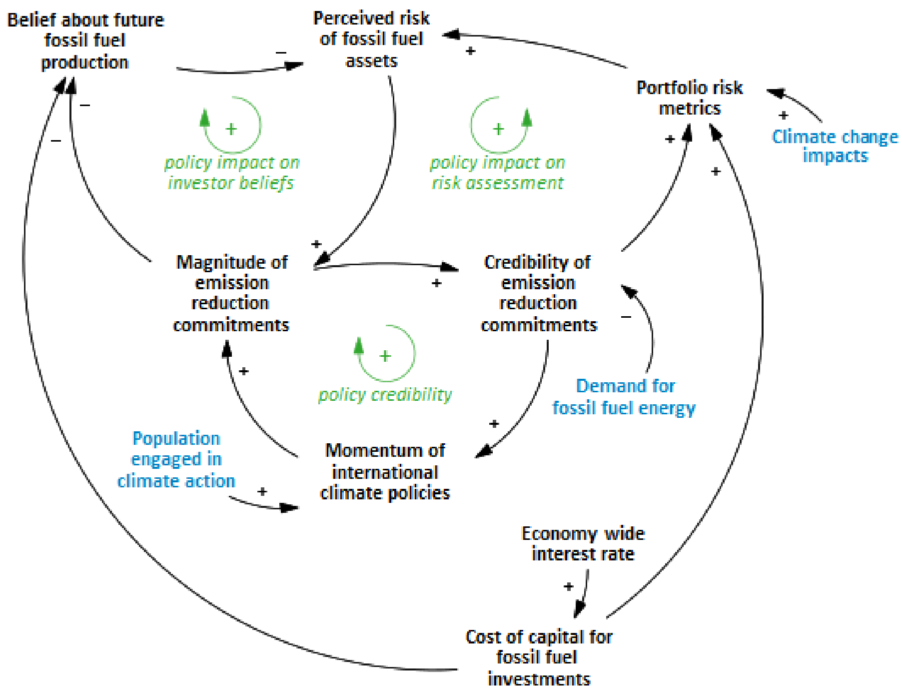


Figure 11: Feedback loops governing policy impacts on fossil fuel investments

Another loop that makes a reinforcing effect on the perceived risk of fossil fuel assets is the **policy impact on risk assessments** which implies that more credible and stringent climate policy strengthens reporting on portfolio risk metrics , and increases perceived risk of fossil fuel assets. The cost of capital for new fossil fuel investments, set by central banks, is another factor that undermines market beliefs about future fossil fuel production and so enables progress on emission reductions. As cost of capital increases, the risk of fossil fuel assets (portfolio risk metrics) increases, too.

These three positive feedback loops together represent how clear and demonstrable progress implementing Paris Agreement goals in enforced national policy frameworks can drive self-reinforcing dynamics of capital reallocation out of a fossil fuel sector with increasing risks of assets being stranded.

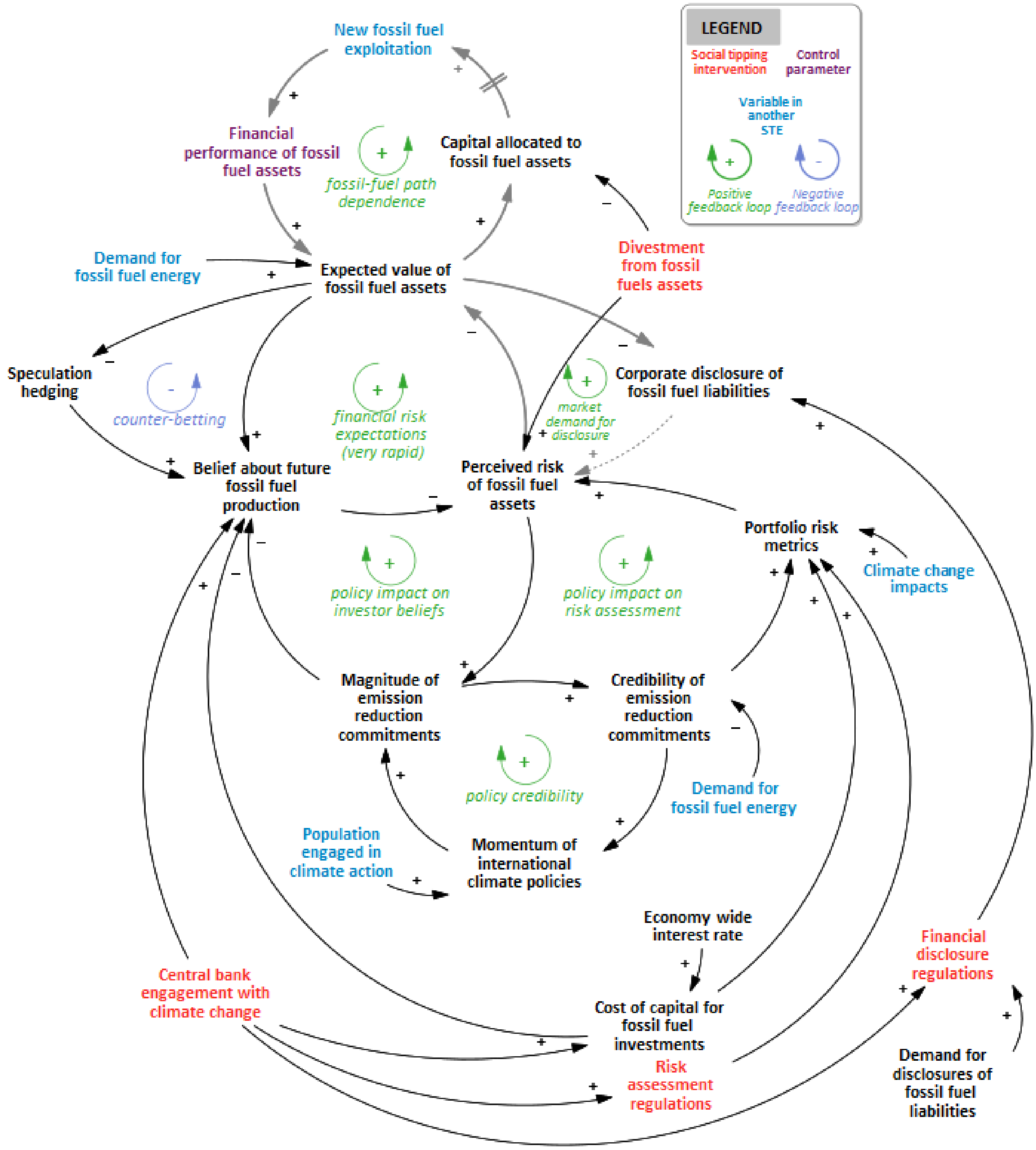


Figure 12: Social tipping processes in the finance subsystem (investments, policy impacts and risk assessments)

Figure 12 integrates these two sets of feedback loops with the key linkages running through the variables on 'belief about fossil fuel production' and 'perceived risk of fossil fuel assets'. These two variables are influenced by a range of financial, policy, and market factors. Figure 12 also introduces a final set of processes relating to financial market regulations and the role of central banks. These are shown around the outside of the lower part of the figure. 'Central bank engagement with climate change' is an important intervention in the financial subsystem that can increase the cost of capital for fossil fuel investments directly (e.g., by communicating risk) or that can lead indirectly to stronger regulatory requirements for climate value at risk (VaR) assessments and/or financial disclosures on carbon liabilities. Central banks also create awareness about the climate risks through their scenario analysis and affect the belief about future fossil fuel production.

The financial subsystem identifies four tipping interventions of which two are regulatory ('risk assessment regulations' and 'financial disclosure regulations') for standardising and strengthening market awareness of carbon liabilities. Financial market regulators and related international coalitions are the key actors, with 'central bank engagement with climate change' also capturing the catalytic role which activist central bankers can play. 'Divestment from fossil fuel assets' is also an important intervention point with major institutional investors already tacitly or explicitly reducing their exposure to fossil fuel risk.

The single control parameter identified in the financial subsystem relates to 'financial performance of fossil fuel assets'. If reduced demand for fossil fuel energy under a strong and stable international policy regime undermines the basic financial viability of existing fossil fuel assets, then a potentially rapid tipping of financial markets away from fossil fuels could ensue.

The finance subsystem links to social tipping processes in multiple other subsystems. Specific variables that act as bridges include:

- 'New fossil fuel exploitation' links to the energy subsystem (where it increases the 'fossil fuel energy supply')

- 'Demand for fossil fuel energy' links from the energy subsystem (and both increases the 'expected value of fossil fuel assets' while also undermining the 'credibility of emission reduction commitments')

- 'Climate change impacts' links from the norms and values subsystem (and reinforces the need for 'risk assessments using climate VaR calculations')

- 'Population engaged in climate action' links from the norms and values subsystem (and strengthens 'momentum of international climate policies')

These connections formalise the interdependencies between financial market activity, investor risk perceptions, and capital investments on the one hand, and wider policy and social mobilisation around climate change as well as the continued practical use of fossil fuel energy to power daily life.

Education and Information Feedbacks

Education and information provision on consumer products are identified as two other key subsystems that can lead to social tipping dynamics. We explore the feedback mechanisms in these two subsystems together, as they both trigger climate action through knowledge. Figure 13 shows the feedback loops we identified in relation to education and climate action specifically. *Climate action* is a general term in this study that encompasses various forms of actions such as individual behaviour change and participation in social movements. Therefore, one of the key variables, *population engaged in climate action* refers to people who either adopt low-carbon technologies and behaviours or participate in social movements.

Curriculum adaptation is the main feedback loop that describes the role and adaptation of the education system. As climate change is covered more in school curricula, this leads to a wider public knowledge about the causes and impacts of climate change through students, and to a wider engagement in climate action through the spread of pro-environmental values an norms. A wider engagement in climate action creates more thought leaders within the youth movement or in the broader public, and their advocacy leads to more coverage of climate change in school curricula, for instance in more schools and in more courses.

Knowledge spread through social movements describes a similar reinforcing mechanism where public knowledge is directly broadened by thought leaders besides school curricula. This loop refers, for instance, to youth movements where climate knowledge spreads through thought leaders in the student communities. The more people engage in climate action, their visibility leads to more people recognizing pro-environmental values and norms, hence creating the positive loop of **descriptive norm change**.

Media escalation is a reinforcing mechanism that can lead to more thought leaders and advocacy for climate action through an increase in population-level risk perception, and the visibility of these thought leaders escalates media coverage. Media coverage of climate change affects the public knowledge also directly and further reinforces the education and climate action loops. As climate risk perception increases in the public, either through thought leaders, media coverage or directly by climate change impacts, it leads to more people experiencing eco-anxiety, which reduces their self-efficacy, hence engagement in climate action. This forms the loop of **inaction** that can dampen the potential tipping dynamics created by curriculum adaptation, knowledge spread, media escalation and norm changes.

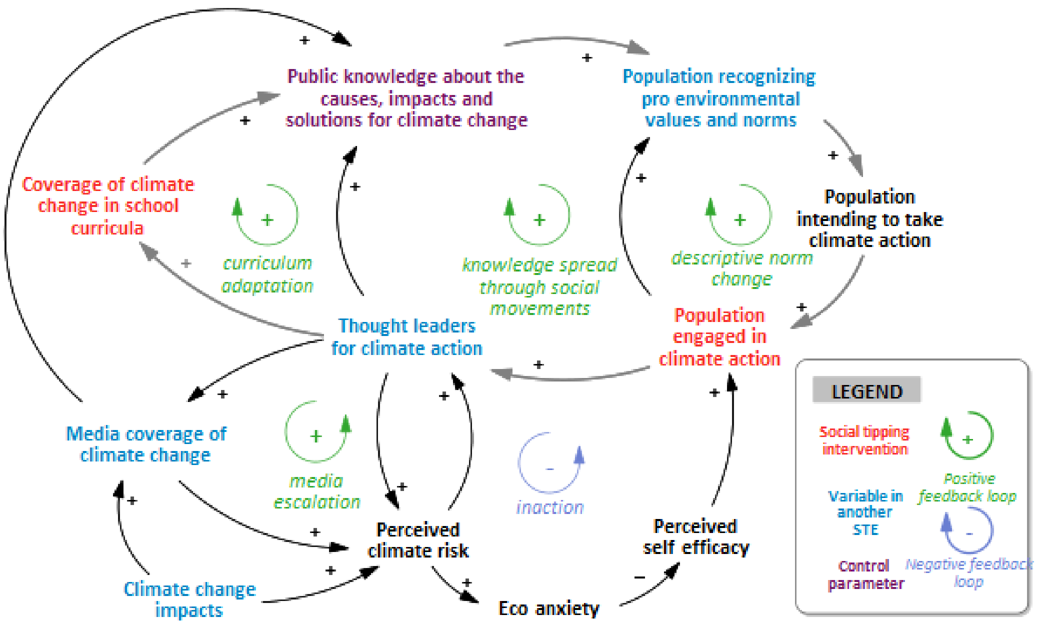


Figure 13: Feedback loops of education and climate action

Formal education, i.e. educational attainment level, increases individuals' adaptive capacity and their perceived self-efficacy, hence leads to more engagement in climate action. This link is not included in the diagram since it is beyond the feedback mechanisms discussed above that can underlie tipping dynamics. Coverage of climate change in school curricula strongly depends on teaching capacity, which is not included in the diagram for the same reason.

Public knowledge and climate action triggered by climate change education are part of several other reinforcing feedback mechanisms that can accelerate the creation of an enabling context and subsequently the engagement in climate action. These feedback loops shown in Figure 14 are as follows:

Injunctive norm change describe how engagement in climate action is reinforced as individuals perceive it approved by the society. This differs from the spread of new values and behaviours through visibility, as in the case of descriptive norm change. In other words, as pro-environmental norms and values become more widespread, the social cost of engaging in climate action declines, and this creates a better enabling context for climate action.

Innovation (for consumer products) is another feedback loop that reinforces the enabling context and climate action. More widespread pro-environmental values and norms create incentives for entrepreneurial activity, which then leads to more low-carbon products and services in the market, and enables consumers to engage in climate action.

Product labelling is a similar mechanism where disclosure of carbon emissions on consumer products imply an enabling context and support climate action. Providing a key information feedback to consumers, demand for such disclosures are triggered by public knowledge about climate change. Public knowledge also narrows the gap between the actual and perceived cost of low-carbon consumption, for instance low-carbon urban technology. As the public perception better aligns with declining costs of low-carbon consumption, perceived affordability will imply a better enabling context for action. This mechanism is named **learning about consumer solutions**.

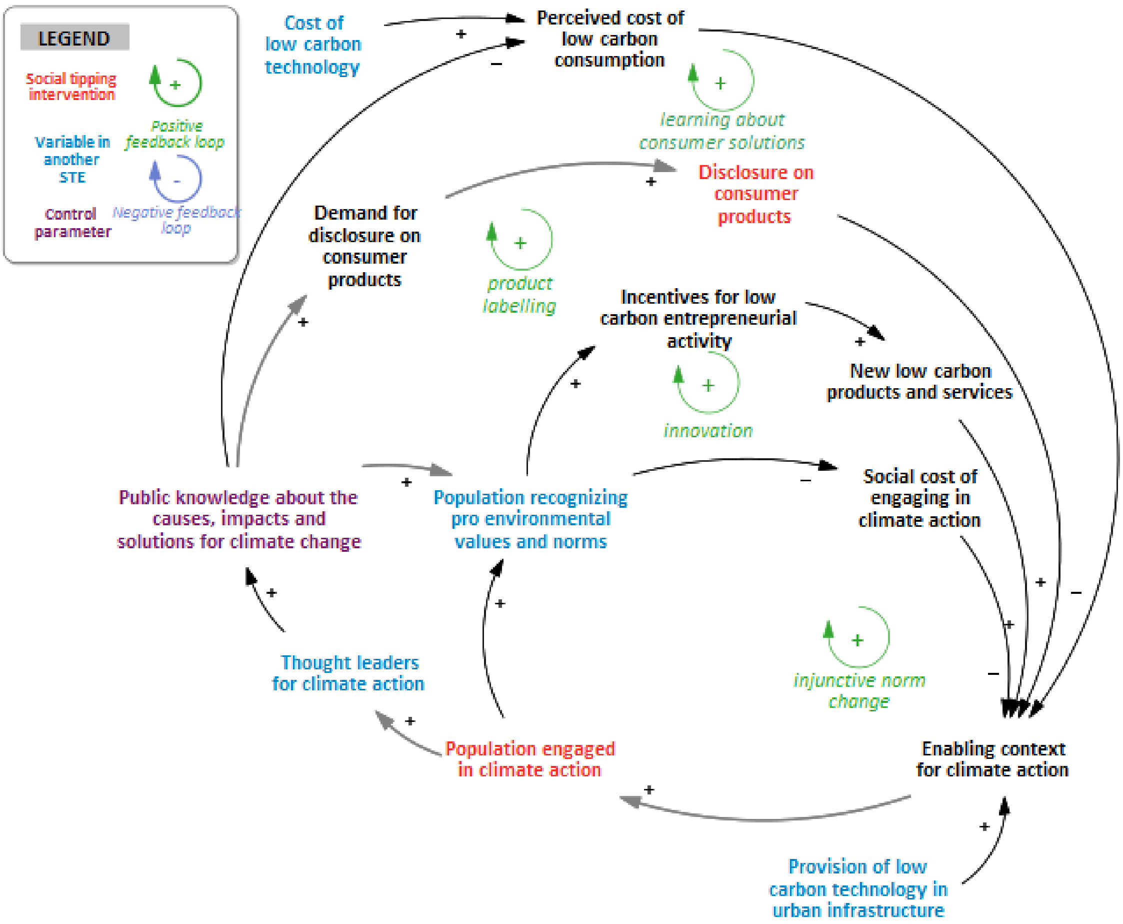


Figure 14: Feedback loops creating an enabling context for climate action

Figure 15 shows the merging of these feedback mechanisms in the education and information feedbacks subsystem. The abundance of positive feedback loops highlights the importance and potential of this subsystem in stimulating rapid climate action. Such tipping dynamics, though, can be hindered or even reversed, if these positive loops operate in an undesired direction, for instance if a decreasing teaching capacity leads to a lower coverage of climate change in school curricula.

'Engagement in climate action' (population engaged in climate action) and 'coverage of climate change in school curricula' are the two key interventions, which represent "climate education and engagement" identified by Otto et al. (2020) as the social tipping intervention in the education system. 'Disclosure on emission products' is another intervention that can trigger tipping dynamics. 'Public knowledge about the causes, impacts and solutions of climate change' is the control parameter in this subsystem, which is on the intersection of several feedback mechanisms and hence can trigger tipping dynamics.

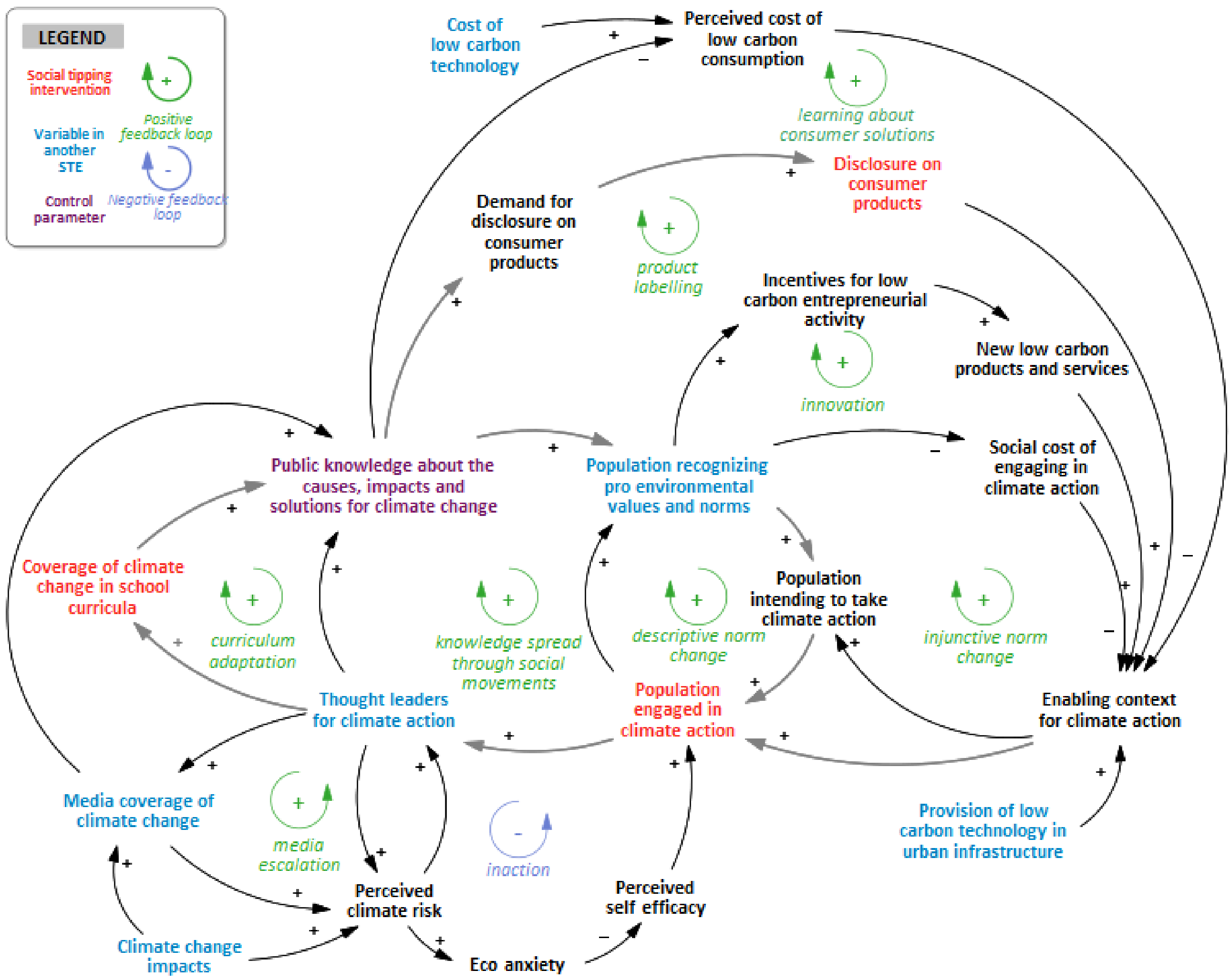


Figure 15: Social tipping processes in the education and information systems

The education and information feedbacks subsystem is tightly linked especially to the norms and values subsystem via the following connecting factors:

- 'Climate change impacts' (links from norms and values)
- 'Media coverage of climate change' (links to and from norms and values)
- 'Thought leaders for climate action' (links to and from norms and values)

- ‘Cost of low-carbon technology’ (links from urban infrastructure)
- ‘Population recognizing pro-environmental values and norms’ (links from urban infrastructure)
- ‘Provision of low-carbon technology in urban infrastructure’ (links from urban infrastructure)

Urban Infrastructure

Due to rapid urbanization especially in the developing countries, decarbonization of the urban infrastructure is identified as one of the key social tipping elements. We identified three main feedback loops shown in Figure 16 that can govern the decarbonization dynamics of urban infrastructure. We use *urban infrastructure* as a general term that refers not only to the residential and commercial building stock but also to the transport, energy and other service infrastructure in urban areas. Similarly, *low-carbon technology* is a general term that covers various low-carbon technologies, from green energy to sustainable materials, energy efficiency and carbon sequestration.

Diffusion among consumers is a reinforcing feedback loop that describes the positive effect of demonstrations of carbon neutrality on raising consumer interest, leading to a higher demand for low-carbon technology, and further demonstration projects. The rise in consumer preferences for low-carbon technology leads to a higher demand also for decentralized energy and wider adoption of pro-environmental norms and values.

Learning on low-carbon technology is another feedback loop that describe the reinforcing effect of demonstration projects. The more pilot projects are implemented to explore and demonstrate carbon neutrality, the lower the information and transaction costs between actors involved, leading to a lower total cost of low-carbon technology and increasing the demand for it.

Demand triggered by demonstration projects leads to a reinforcing loop of **diffusion among suppliers**, too. As the demand for low-carbon urban technology increases, the providers acquire more capacity to supply this technology, and implement more demonstration projects. The capacity building of providers is also triggered by standards and regulations, which also enhance the provision of low-carbon technology through tighter monitoring of implementation.

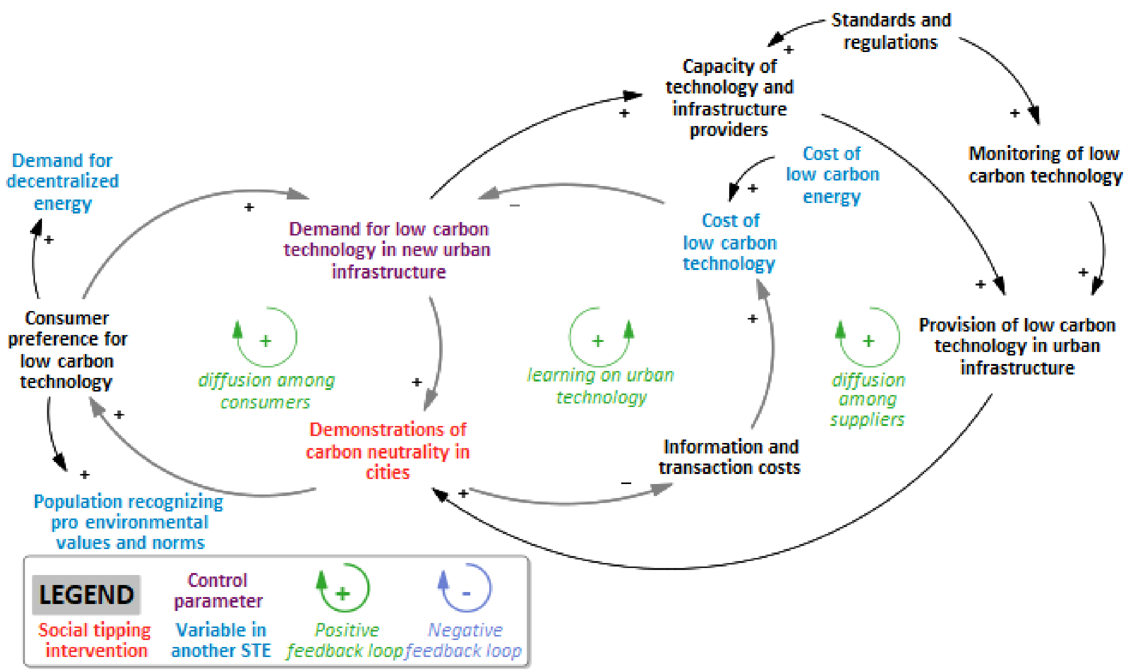


Figure 16: Feedback loops of the diffusion of low-carbon technologies in urban infrastructure

The abovementioned loops can help to accelerate urban decarbonization, and urbanization itself is governed by three main loop shown in Figure 17.

Urbanization is the feedback loops that creates a rapid population increase in urban areas with the attractiveness of infrastructure and service availability. The more available the services, the more appealing urban living is, hence a higher population and demand for urban infrastructure. This reinforcing mechanism, though, can be balanced by two feedback loops of de-urbanization.

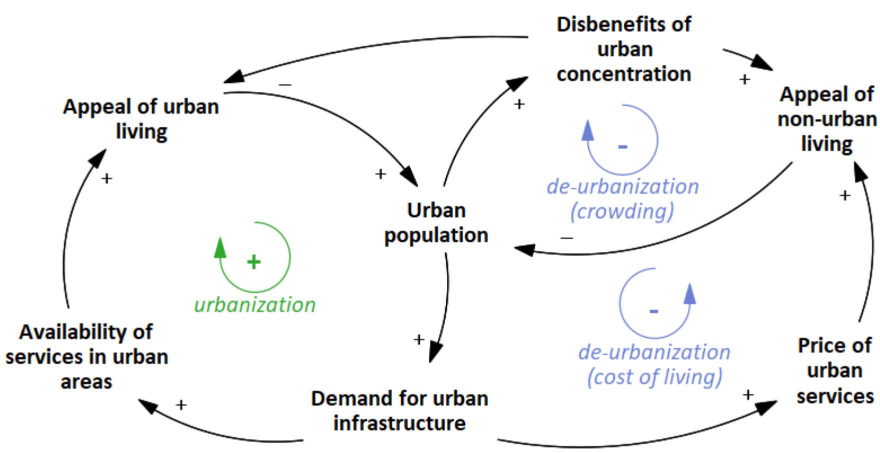


Figure 17: Feedback loops of urbanization

De-urbanization due to cost of living describes the mechanism where an increased demand for urban infrastructure increases prices, and makes non-urban living more appealing and leads to a decline in urban population. **De-urbanization due to crowding** is a similar feedback loop where the appeal of non-urban living is increased by disbenefits of urban concentration, as observed in some populous cities such as New York and San Francisco during the COVID pandemic.

The merged diagram in Figure 18 illustrates how urbanization can trigger or dampen decarbonization in the urban environment. If the **urbanization** loop is dominant over de-urbanization and works in a positive direction, the demand for urban infrastructure can indeed increase rapidly, leading to a subsequent increase in the demand for low-carbon technology. The urgency created by this rapid increase in demand for urban infrastructure, though, might jeopardize capacity building by the technology providers. In that case, **diffusion among suppliers** counter-acts on the reinforcing dynamics of learning and consumer diffusion loops and dampens the possible tipping dynamics of urban decarbonization.

'Demonstrations of carbon neutrality' is the key social tipping intervention in the urban infrastructure subsystems since it can trigger the three reinforcing loops and accelerate diffusion of low-carbon technology. 'Demand for low-carbon technology' is the control parameter, on which tipping dynamics can be observed.

The urban infrastructure subsystem involves the following interactions with the other subsystems:

- 'Cost of low-carbon energy' (links from energy production)
- 'Demand for decentralized energy' (links to energy production)
- 'Population recognizing pro-environmental values and norms' (links to education and information feedbacks)
- 'Cost of low-carbon technology' (links to education and information feedbacks)

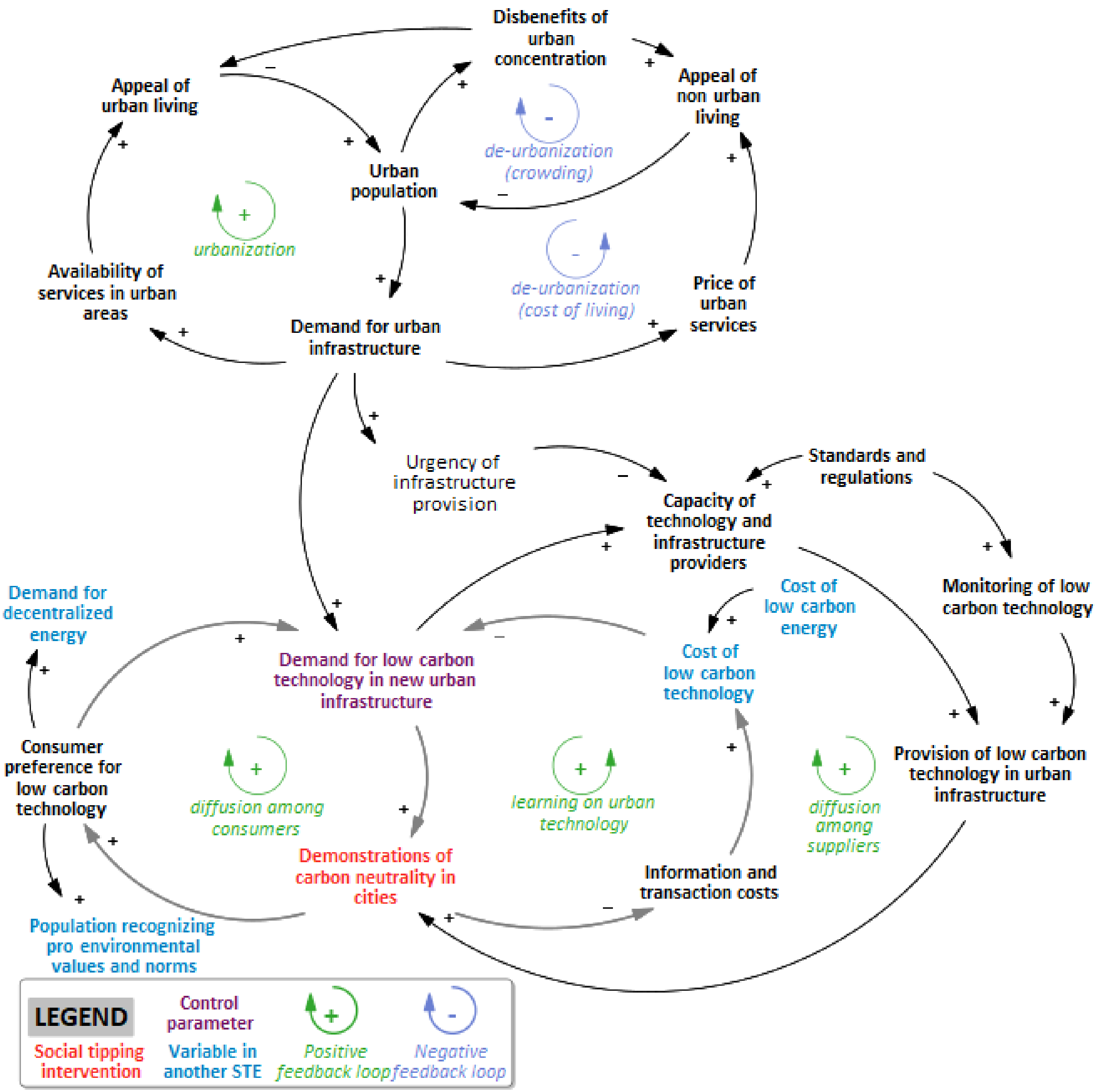


Figure 18: Social tipping processes in the urban infrastructure subsystem

Feedback Mechanisms between Social Tipping Elements

The five social tipping elements or subsystems discussed above have numerous interactions marked in the diagrams by 'blue variables'. These interactions create wider feedback loops that can accelerate or counteract tipping dynamics for decarbonization.

Here we highlight these interactions by focusing on feedback loops across subsystems that affect 'Fossil fuel energy supply' as a proxy for global GHG emissions which is our outcome indicator of interest. To ensure clarity and interpretability, we show only the main cross-subsystem interactions and not the full set of relationships in each subsystem. These are shown, along with control parameters and interventions, in the previous subsystem diagrams.

Throughout the visualizations in this section, we colour the variables according to the subsystem they appeared in (see diagrams in previous section). This categorization is based solely on the subsystem in which each variable was mainly discussed in the workshop. In reality many variables are relevant for multiple subsystems, particularly cross-cutting or broad impact variables like climate policy, societal action, or climate impacts. So, for example, the variable 'climate change impacts' is associated with the *Norms and Values* subsystem as this was where it was primarily discussed, even though it is also relevant to other subsystems.

STE Interactions between Energy Production – Urban Infrastructure – Education and Information Feedbacks

Figure 19 depicts two main positive feedback loops that affect 'Fossil fuel energy supply' resulting from interactions between energy production and urban infrastructure through policy and society.

Decarbonization in urban areas through social movements outlines the broader effects of providing low-carbon technology in urban environments. Low-carbon urban technology leads to a higher population fraction engaged in climate action, either through a more enabling context or through mainstreaming pro-environmental values and norms. This wider engagement in climate action leads to more policy support that restricts fossil fuels, and lower fossil fuel energy supply. When the inhibiting effect of cheap fossil fuel energy diminishes, the costs of low-carbon energy, and subsequently the costs of low-carbon urban technology declines, leading to further decarbonization of urban infrastructure.

Decentralization and decarbonization in urban areas refers to the positive relationship between consumer preferences triggered by low-carbon technology provision in urban environments and the demand for decentralized energy. Local institutional innovation created by decentralized energy initiatives leads to a higher capacity to provide low-carbon urban technology and returns a wider consumer group preferring low-carbon options. This reinforcing loop can accelerate decarbonization by reducing the supply of fossil fuel energy if it operates in the growth mode and increases the demand for decentralized energy.

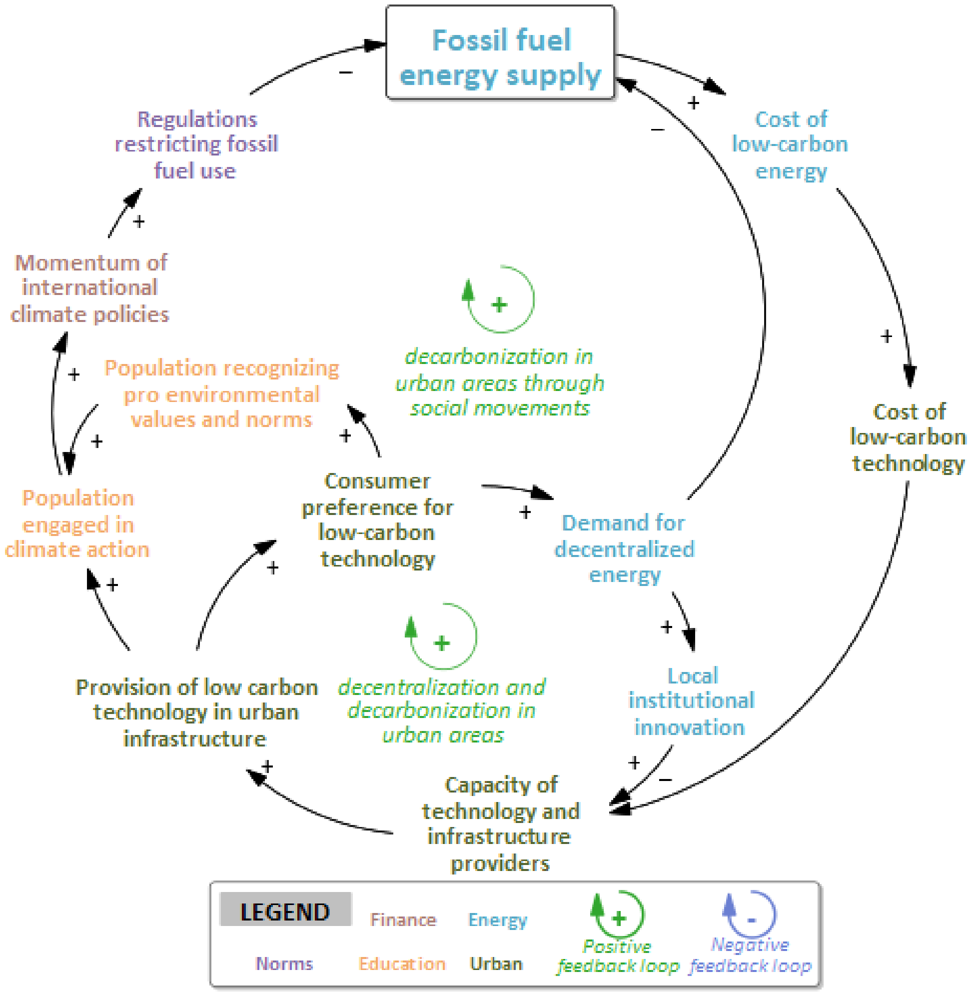


Figure 19: Feedback loops emerging from interactions between energy production, urban infrastructure and education

STE Interactions between Energy Production – Finance

The energy and finance subsystems are tightly coupled with respect to the 'Fossil fuel energy supply', giving rise to the interconnected feedback loops shown in Figure 20. These also capture the important mediating role of national and international policies.

Fossil fuel financing through market presence refers to the basic reinforcing loop between investments in fossil fuel exploitation and demand for fossil fuel energy. The higher the supply of fossil fuel energy, the higher the demand for it and the higher the expected value of fossil fuel assets, leading to more investments, and more supply. While contributing to the fossil fuel lock-in if it operates in the growth mode, any decreasing stimuli, for instance on the expected value of assets, can push this reinforcing loop to the exponential decline mode and lead to rapid decarbonization.

Fossil fuel financing through policy credibility further reinforces the investments in fossil fuels and subsequent market presence, because the higher the demand for fossil fuel energy, the lower the credibility of emission reduction pledges by the governments, and the higher the expected value of fossil fuel assets.

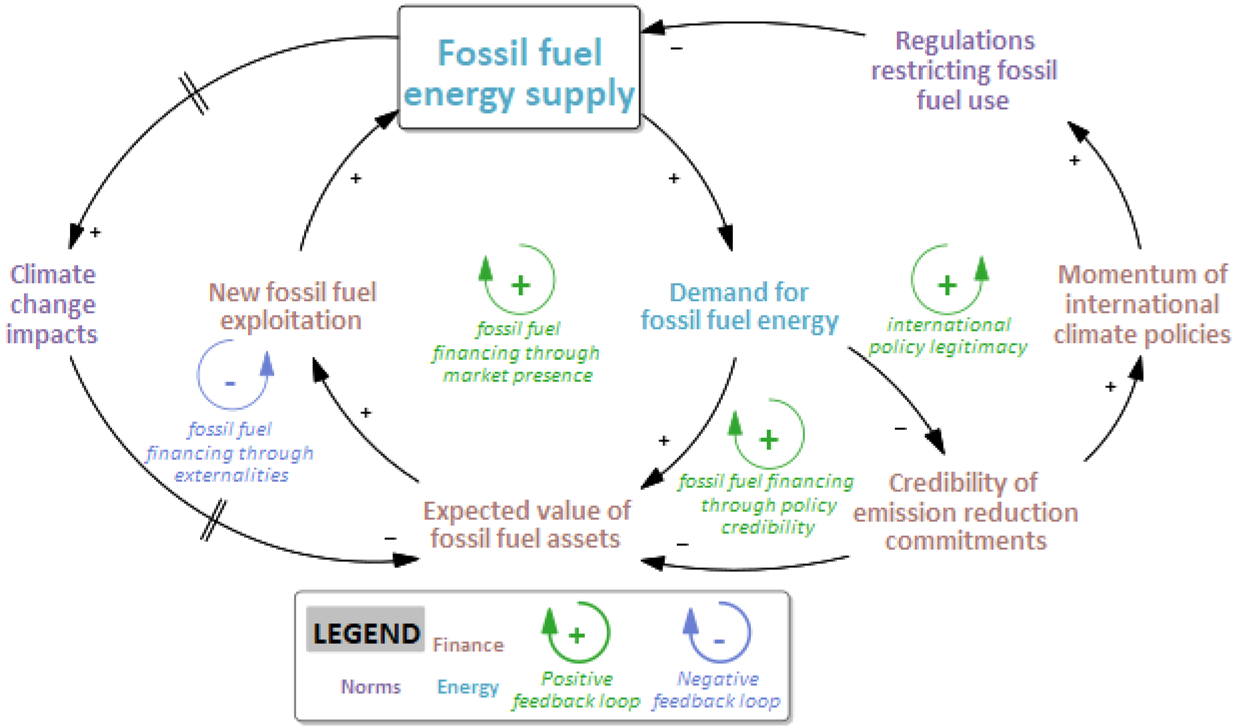


Figure 20: Feedback loops emerging from energy production and finance interactions

If the supply of fossil fuel energy declines, the resulting lower demand and high credibility of emission pledges can lead to a spill-over of international climate policies. Subsequently, more regulations restricting fossil fuels leads to an even lower supply, creating another reinforcing loop, **international policy legitimacy**.

Another factor that negatively affects the investments in fossil fuels is the climate change impacts. As a low expected value of fossil fuel assets leads to a lower supply fossil fuel energy, climate change impacts will decline in the long-term. This loop of **fossil fuel financing through externalities** balances either the decline or the growth of fossil fuel supply even though it is slow.

STE Interactions between Energy Production – Norms and Values - Education and Information – Urban Infrastructure – Finance

'Fossil fuel energy supply' can be reduced by public engagement in climate action either directly through an increasing demand for low-carbon energy, or indirectly through policies and their financial implications. The cascading effects of public engagement in climate action lead to two key feedback loops that interconnect the five social tipping elements (subsystems) we discussed, as Figure 21 shows.

Enabling social pressure on policy and finance describes a reinforcing feedback loop based on the negative effect of engagement in climate action on fossil fuel energy supply either through demand, regulations or finance. If a wider public engagement in climate action leads to a lower fossil fuel energy supply, this decreases the cost of low-carbon technology, and further increases the population engaged in climate action since low costs create an enabling context.

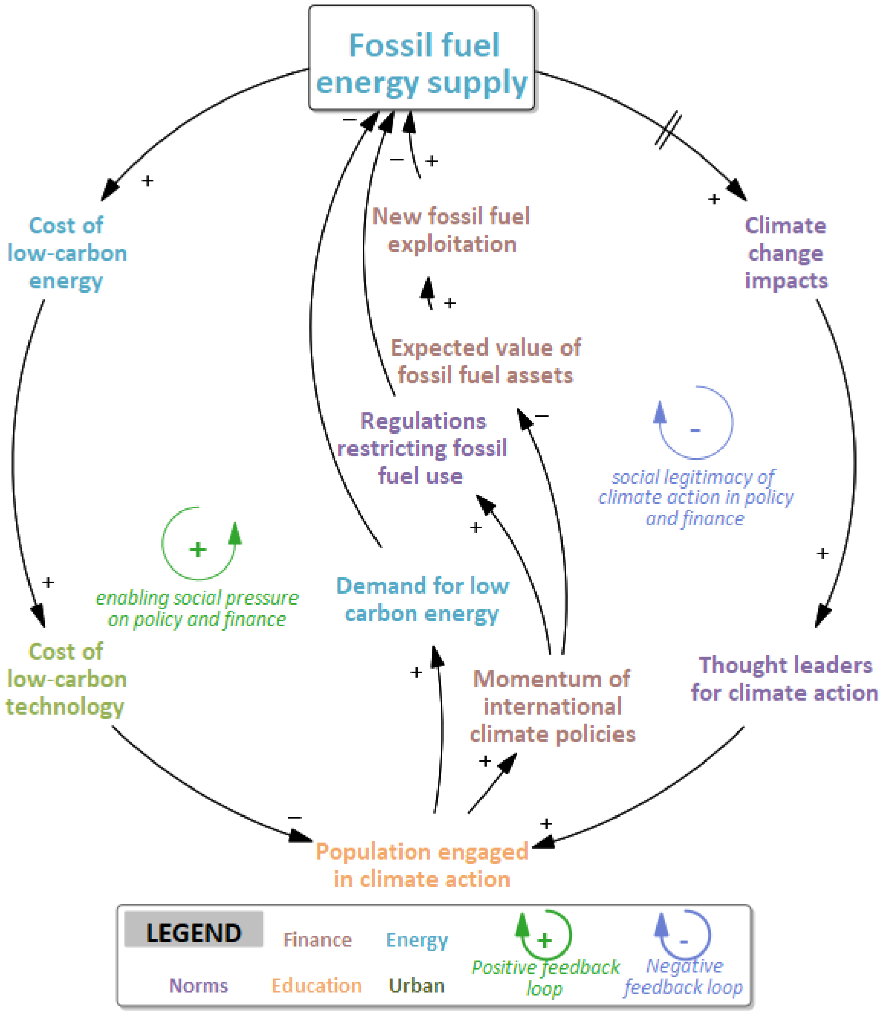


Figure 21: Feedback loops emerging from the interaction of energy production, urban infrastructure, finance, norms and education subsystems

Social legitimacy of climate action in policy and finance refers to a balancing loop where a higher population fraction engaged in climate action leads to lower fossil fuel energy supply, hence lower climate change impacts in the long-term. Yet, this might imply a tapering media coverage and advocacy by thought leaders, leading to a lower engagement in climate action.

Most feedback loops we identified in this study, either within or between the subsystems, are reinforcing loops, which can generate tipping mechanisms, exponential growth and rapid decarbonization in the social systems. However, these reinforcing loops can also operate in a negative direction and cancel out the desired effects of each other. Therefore, to reap the benefits of existing reinforcing mechanisms for social tipping dynamics, they must be ensured to function in the desired direction.

Many balancing feedback loops we identified in this study, such as **social legitimacy of climate action in policy and finance**, relate to diminishing climate action if the climate change impacts can be avoided in the long-term. The possibility of such mechanisms tapering decarbonization stresses the importance of sustained action to ensure long-term stability in the climate system.

Intervening in and Monitoring Social Tipping Processes

Harnessing the social tipping processes for rapid emission reductions requires intervening in these processes with effective levers and at effective points in time. While quantitative models can provide an ex-ante analysis of these interventions, their actual ex-post effectiveness is best analysed by monitoring the key indicators in the social tipping elements.

Interventions

Identifying interventions that can trigger cascading effects within and between subsystems is the main purpose of social tipping analysis in policy-relevant domains like climate change mitigation. The interventions we discussed in this study for each subsystem are derived from (Otto et al. 2020) as summarized in Table 1. Some of the interventions are clearly policy levers (e.g., subsidies for fossil fuels, financial disclosure regulations) whereas others are more complex processes with many different mechanisms and actors for intervening (e.g., decentralised energy supply, engagement in climate action). During the workshop, discussion on interventions was time-constrained so refining and ensuring consistency between the set of interventions identified is an important area for further work.

Many of the interventions shown in Table 1 are broadly comparable with others from the literature. For example, an expert policy advisory group to the UK's Committee on Climate Change recently recommended 40 'sensitive intervention points' that exploit socio-economic tipping points for accelerating progress towards net-zero (Hepburn et al. 2020). These included:

- Deepening public engagement by lowering 'thresholds' to behavioural change, such as energy efficiency or dietary alternatives, while also educating the public, involving people in decision-making, and providing trusted information at key decision points (similar to interventions in our *education and information feedbacks* subsystem)
- Accelerating technological progress using "pathfinder" cities and regions to test integrated approaches to achieving net zero across low-carbon electricity, heat and transport (similar to interventions in our *urban infrastructure* subsystem)
- Redirecting capital flows through net-zero aligned, transparent accounting and auditing' (similar to interventions in our *finance* subsystem)

However, the literature also extends into intervention areas not discussed in our workshop. As examples, the same 'sensitive intervention points' study (Hepburn et al. 2020) also identified:

- Delivering on social justice in the net-zero transition via a clear long-term vision for specific regions and marginalised groups, coupled with incentives for the private sector to invest in deprived areas
- Reorganising government to lead on net-zero from the centre, by requiring any company meeting with ministers to have a plan to reach net zero emissions;
- Leveraging global dynamics by introducing a border carbon adjustment, and consider forming bilateral and multilateral preferential trading arrangements for environmental goods and services;
- Increasing business ambition by celebrating and engaging with businesses that shape industries;

- Harnessing the law through a government legal team drive legal and regulatory shifts including a requirement on all regulators to regard the Paris Agreement, Sixth Carbon Budget and 2050 Net Zero target in their duties.

In both our and others' work identifying social tipping interventions, it is important to try and clearly distinguish general strategies, measures, actions, and policies for mitigating climate change from the specific class of interventions of interest in a social tipping context - i.e., those can activate positive feedback mechanisms to trigger cascading dynamics across scales and subsystems.

Interventions must also be linked to clear empirical evidence of their actual or potential effectiveness in triggering positive feedback mechanisms. Unintended consequences of interventions also needs considering, if this goes beyond a slowing or reversal of social tipping processes. As an example discussed during the workshop, 'rapid divestment from fossil fuel assets' identified as an intervention in the finance subsystem can lead to financial instability and adverse distributional consequences that can undermine system functioning.

Monitoring

As noted earlier, social tipping processes have a complex set of drivers, mechanisms, and outcomes so early-warning indicators with well-defined critical thresholds for tipping are not readily available (Winkelmann et al. 2022). Evaluation of tipping processes can likely only be made in hindsight through process tracing of specific triggering events and amplifying mechanisms.

However, various indicators have been proposed to track progress on key variables associated with social tipping processes. In particular, cost parity between clean and fossil energy is a key indicator of potentially rapid system change if clean energy starts to consistently outcompete fossil fuel incumbents across contexts and geographies.

Climate Action Tracker (2019) identify potential transformation points in the energy system, with trackable indicators for each. These include:

- Cost parity between renewable electricity generation with storage, and new or existing fossil-fuel assets;
- Up-front cost parity between electric vehicles and conventional vehicles (or electric vehicles find large-scale niches such as cities);
- Up-front cost parity between building new net-zero energy homes and building inefficient homes;
- Cost-parity between direct air capture and storage of CO_2 and mitigation options in hard-to-abate sectors (e.g., aviation);
- Availability of competitive zero-carbon high-intensity heat for industrial processes;
- E-bikes become the norm for intra-urban mobility.

More recently, researchers at the New Climate Institute have proposed a 'transformation seismograph' for tracking enablers or indicators of tipping processes in power and transport systems (Höhne et al. 2021). Indicators on the seismograph cover inputs, outputs, intervention points, control parameters, and other variables in a specific subsystem or social tipping element. By tracking change over time across multiple indicators, the seismograph can show if the likelihood of tipping processes is increasing.

Social tipping processes can best be monitored by tracking the 'control parameters' or forcing variables that can trigger tipping dynamics. Control parameters we have identified based on Otto et al. (2020) are the elements of key feedback loops, often at their intersection, which can encapsulate the joint effect of these feedback mechanisms on the system behaviour over time. Therefore, monitoring control variables can be useful in detecting whether tipping is approaching or started, so that interventions can be adjusted accordingly. If control parameters are not operationalizable, measurable or for which quantitative data is not available, other variables in the social tipping elements can be used to monitor the tipping processes.

In Table 1, we list the social tipping interventions and control parameters as identified by Otto et al. (2020) and as refined in this study, and we specify the monitoring variables that correspond to each of the five social tipping elements.

In the *norms and values* and *energy production* subsystems, the control parameters can function as monitoring variables. Relative profitability of low-carbon and decentralized energy can be obtained from available data on the market prices and costs of low-carbon and decentralized energy technologies, as well as those of fossil fuel energy. Population against fossil fuel exploitation, as an indicator of value changes, can be monitored with global surveys such as the World Values Survey, and it can be complemented with high-frequency data from social media platforms (Eker et al. 2021).

Table 1: Interventions, control parameters and monitoring variables in each social tipping element

	Intervention		**Control parameter**		**Monitoring variable**
	Otto et al. (2020)	*This study*	*Otto et al. (2020)*	*This study*	*Selected examples**
Norms and Values	Recognition of the immoral character of fossil fuels	Thought leaders for climate action	The perception of fossil fuels as immoral	Population against fossil fuel exploitation	Population against fossil fuel exploitation
Energy Production	Subsidy programs Decentralized energy production	Subsidies for fossil fuels Subsidies for low-carbon energy Decentralized energy supply Market rules enabling intermittent renewables	The relative price of fossil-fuel-free energy	Relative profitability of low-carbon energy Relative profitability of decentralized energy	Relative profitability of low-carbon energy Relative profitability of decentralized energy
Finance	Divestment movement	Risk assessment regulations Financial disclosure regulations Central bank engagement with climate change Divestment from fossil fuel assets	Profitability of fossil fuel exploitation	Financial return on fossil fuel assets	*Number of systemically important companies calculating climate VaR in risk assessments* *Price return on fossil fuel investments* *Central banks in the NGFS* *Central banks doing climate stress tests*
Education and Information Feedbacks	Climate education and engagement Emission information disclosure	Engagement in climate action Coverage of climate change in school curricula Disclosure on consumer products	Climate change and impacts awareness The number of products and services disclosing their carbon emissions	Public knowledge about the causes, impacts and solutions of climate change Disclosure on consumer products	*Percentage of individuals willing to pay more than a certain value for climate action*
Urban Infrastructure	Carbon neutral cities	Demonstrations of carbon neutrality	The demand for fossil-fuel-free technology	Demand for low-carbon technology	*Use of low-carbon technology*

* Variables in italics are monitoring variables identified in this study, different from control parameters (see text for details). NGFS = Network for Greening the Financial System.

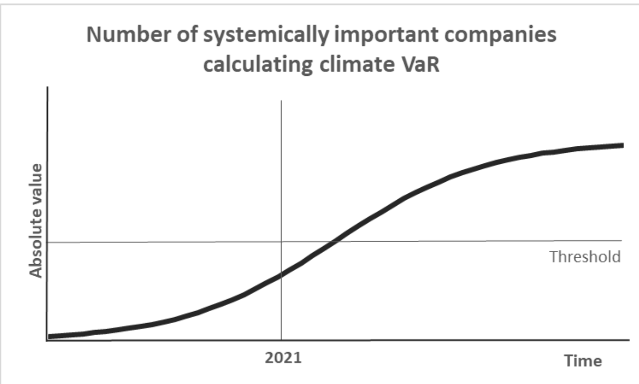
Selected examples of monitoring variables and their trajectories

The new monitoring variables we identified in this study relate to the *finance*, *education and information feedbacks*, and *urban infrastructure* subsystems. We discuss these variables and their possible trajectories below.

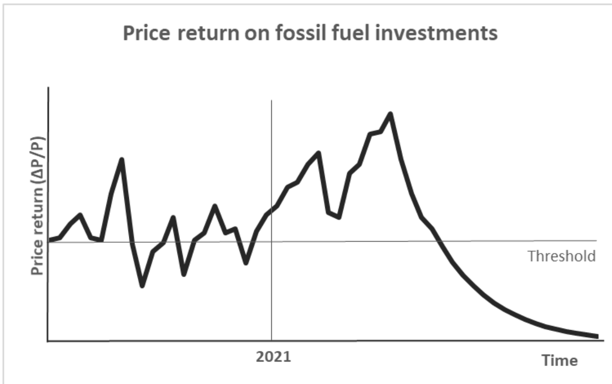
Finance

Number of systemically important companies calculating climate VaR in risk assessments refers to the variable 'risk assessments using climate VaR calculations' (Figure 12). It is an indicator of climate risk perception, hence the perceived risk of fossil fuel assets. Systemically important companies can be defined as those which have more than $ 100 billion in assets. We estimate this variable to have increased increasingly in the past years, as the trajectory in Figure 22a shows, and the critical threshold is yet to be achieved in the next few years.s

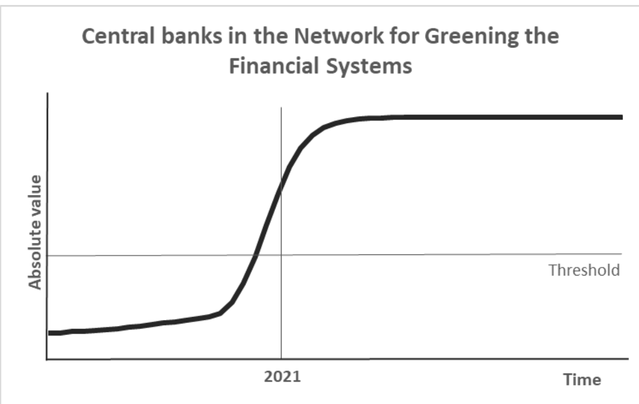
Price return on fossil fuel investments is the fractional return on investment ($\Delta P/P$) in fossil fuel companies that are in the S&P 500 index, as a proxy for the variable 'financial return on fossil fuel assets' in the causal loop diagram of the finance subsystem (Figure 12). This is a highly volatile variable fluctuating on an hourly or daily basis. In a tipping trajectory, the decline phase of one of the fluctuations is expected to be continuous, approximating to zero gradually as Figure 22b illustrates.



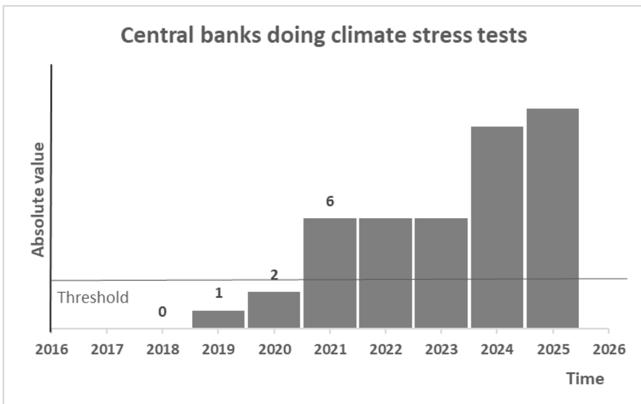
(a)



(b)



(c)



(d)

Figure 22: Monitoring variables in the finance subsystem and their illustrative tipping trajectories

Central banks in the Network for Greening the Financial Systems (NGFS) is an indicator of the intervention 'Central bank engagement with climate change' in the finance subsystem. As Figure 22c shows, it has increased rapidly in recent years, currently at 67, and it is expected to increase slowly and saturate in the coming years. Since central bank engagement is an exogenous intervention, monitoring this variable can be helpful in tracking whether and to what extent the feedback loops in the finance system are triggered.

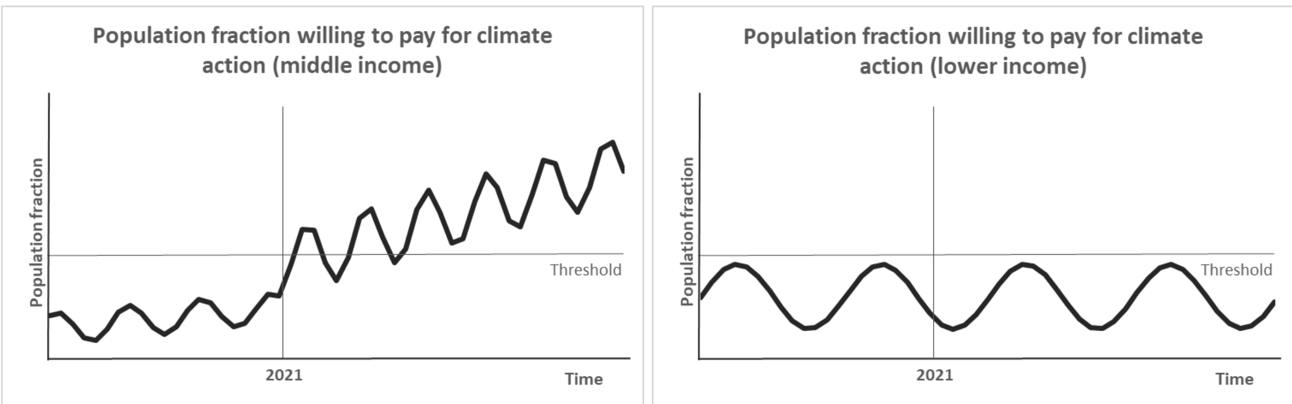
Central banks doing climate stress tests is another indicator of 'Central bank engagement with climate change' and 'risk assessment regulations'. In 2019, only one central bank has reported such tests (Central Bank of the Netherlands). Bank of France has done the first stress test in 2020, and four more central banks (Austrian, Swiss, Italian and European) joined in 2021. This cumulative number of central banks doing climate stress tests is expected to increase incrementally as shown in Figure 22d, and if this increment is large, for instance if five more countries join, it can create a favourable momentum for tipping dynamics.

Education and information feedbacks

In the *education and information feedbacks* subsystem, we identified **willingness to pay for climate action** as a variable that can be used to monitor 'engagement in climate action'. The data for this variable, which is already collected and used in some contextual studies, can be obtained from large scale surveys.

Willingness to pay can be operationalized in a metric such as **population fraction that is willing to pay above a certain amount for climate action**. Willingness to pay is heavily dependent on economic situation. It was relatively low in 2010, for instance, during the economic crisis. Therefore, it is expected to fluctuate over time depending on economic growth. We distinguish between two income groups for this monitoring variable. For the middle income groups (Figure 23a), these fluctuations are expected to be more frequent, since their expenditure preferences are more sensitive to the economic situation, yet follow an increasing trend on average. Willingness to pay, as an indicator of engagement in climate action, is currently estimated to be well below a critical threshold that can lead to tipping dynamics.

In the lower income groups, willingness to pay for climate engagement is also expected to fluctuate (Figure 23b), yet with lower sensitivity to economic situation. Unlike the middle income groups, these fluctuations are not anticipated to follow an increasing trend on average without any significant intervention. However, an increasing trend in the minimum values of each phase can indicate tipping dynamics.



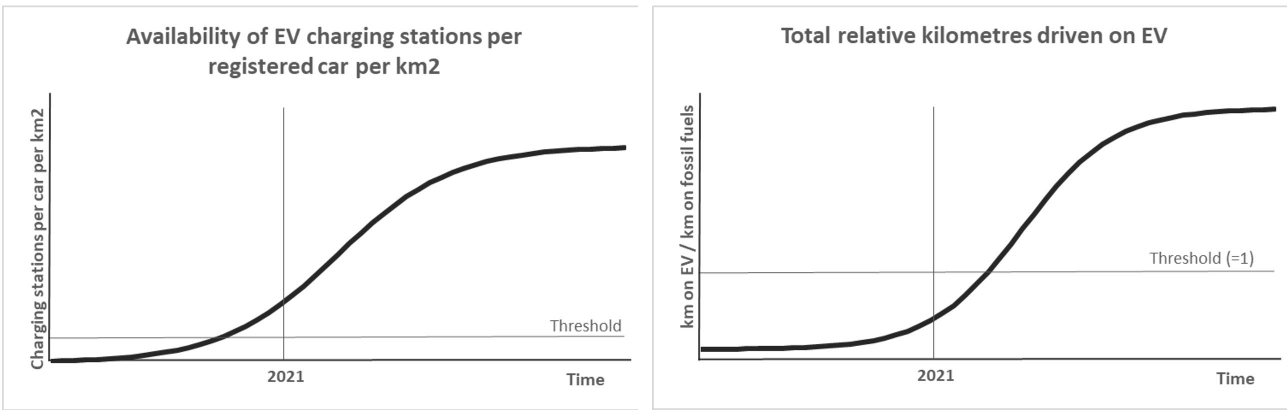
(a) **(b)**

Figure 23: Monitoring variables in the education and information feedbacks subsystem and their illustrative trajectories

Urban infrastructure

Since it is a measurable indicator of the demand for low-carbon technology, we chose **use of low-carbon technology** as the monitoring variable in this subsystem. However, this variable needs to be specified for every low-carbon technology distinctively, considering their broader use beyond niche settings and their market penetration with respect to carbon-intense technologies. Our focus was on the electric vehicles (EV) and we defined the following two variables that can help tracking the spread of EV adoption.

Availability of EV charging stations per registered car per km^2 refers to the provision of low-carbon technology in urban infrastructure. It is normalized with respect to the total number of registered cars in a certain area to take urban density and the relative scale of EV adoption into account. As Figure 24a shows, this variable is expected to follow a logistic growth trajectory in a tipping process, and the critical threshold that starts rapid growth might have been already crossed.



(a) **(b)**

Figure 24: Monitoring variables in the urban infrastructure subsystem and their illustrative tipping trajectories

Total relative kilometres driven on EV $\left(^{km's\ driven\ on\ EV}/_{km's\ driven\ on\ fossil\ fuels}\right)$ is another monitoring variable that can facilitate tracking the progress of low-carbon urban technology with respect to fossil fuels. Even though the current value of this metric is estimated to be very low as Figure 24b illustrates, once a critical threshold between 0.2 and 0.5 is exceeded, this variable is expected to follow an exponential growth, yet on a longer time horizon than the availability of charging stations.

Conclusions and Next Steps

This study delineated social tipping processes that are feedback mechanisms governing potential social tipping dynamics. Several positive feedback loops within and between energy, finance, urban infrastructure, norms and values, and education subsystems can facilitate tipping dynamics towards accelerated decline of the fossil fuel energy supply. These reinforcing loops relate to: supply and demand mechanisms as well as learning effects in the energy market; climate risk perceptions and policy impacts in the financial markets; norm changes, media escalation and information feedbacks in social systems. The negative feedback loops we identified mainly relate to technology lock-ins and increasing resistance to climate action in the long-term should climate impacts are avoided – but as this latter feedback is not of concern as it would imply significant progress had been achieved on climate stabilisation.

The complex coupling of the feedback mechanisms identified make it hard to estimate or simulate future dynamics. Even though positive feedback loops can lead to exponential change of many system elements in the desired direction, they can also function in the reversed direction and obstruct potential tipping dynamics. Aggregate simulation models quantified with empirical data can be used to explore the dynamic behaviour created by the coupling of these feedback loops.

Causal loop diagrams presented in this report are a first step towards building a such formalised system dynamics model for simulating interconnected social tipping processes. This would be a medium-term and highly inter-disciplinary research endeavour, beginning with an emphasis on a subset of relationships in one or more subsystems for which functional forms, parameter values, and response sensitivities are broadly established in the literature. Such a quantitative model would help identify the most loops with greatest influence on tipping dynamics over different timescales, and would also help analyse the interventions that are most beneficial in triggering the tipping dynamics.

The recent Moore et al. (2022) publication in *Nature* sets the benchmark in this exciting field. Moore et al. (2022) develop a quantitative model of seven interdependent subsystems characterised by a detailed set of 20+ feedback processes and parameters, ranging from network homophily governing the flow of information through social networks to status quo bias in political institutions that makes them less responsive to shifting public opinion. They use hindcasting runs against observations to constrain the model's parameter space, and then generate a large (100,000) ensemble of model runs to explore the outcome space. They find that low-emission trajectories consistent with Paris Agreement targets can emerge through positive tipping dynamics for which certain processes are key: social conformity, technological learning, political responsiveness to public opinion, and cognitive biases in personal experiences of climate impacts.

Another theme for further research is the elaboration of other potential social tipping elements. For instance, the food and land use system, being responsible for around a quarter of annual GHG emissions, can also contribute to a rapid decarbonization if demand patterns in the Global North and agricultural management practices in the Global South can rapidly change. Feedback mechanisms in this and other sectors should be investigated to determine their interactions with other social tipping elements and whether they can constitute a tipping process.

One final theme for further research is to move the framing of social tipping processes away from a reactive problem focus (how to reduce emissions) and towards a more dynamic opportunity focus (how to enable human flourishing). Participatory modelling of feedback loops during the workshop were also oriented more narrowly towards climate change mitigation rather than more broadly towards the UN Sustainable Development Goals (SDGs), or the human needs-fulfilment perspective of the Mission Innovation Net-Zero Compatibility Initiative (Pamlin 2021). As a result, some of the social tipping processes and interventions identified are incremental, individual, and market-oriented, particularly in the education and information feedbacks subsystem.

Put differently, social tipping processes can both help accelerate positive change within current systems and help catalyse the emergence of new systems geared around the needs, potentials, and flourishing of a growing global population (Pamlin 2021). Table 2 provides some examples on which to build.

Table 2: An opportunity and needs-fulfilment focus on social tipping processes based on (Pamlin 2021), in contrast to the findings from our workshop co-modelling.

	Tipping processes and interventions in Otto et al. (2020) and our workshop	*Alternative tipping processes supporting needs-based transformation*	*Alternative tipping processes supporting new solution providers*
Norms and Values	Population against fossil fuel exploitation Thought leaders for climate action	New narrative of long-term global sustainability for a growing population	Shift from incrementalism and neoclassical models to transformative system change
Energy Production	Subsidy programs Decentralized energy production Market rules for intermittent renewables	Needs-driven demand for sustainable materials Business models for dematerialisation and material reuse Downsizing energy-intensive industries and manufacturing	Integrated design of buildings and net-positive communities Architects, service providers, and smart technologies in new systems for delivering on human needs
Finance	Risk assessment regulations Financial disclosure regulations Central bank engagement with climate change Divestment from fossil fuel assets	System transformation from greening current tools and avoiding high-carbon assets to investing in 1.5°C compatible solutions	New stakeholders delivering key services including micro-lending, crowd-funding, and blockchain-driven innovation Solution providers identifying and pursuing granular 1.5°C compatible innovations
Education and Information Feedbacks	Climate education and engagement Coverage of climate change in school curricula Climate change and impacts awareness Disclosure on consumer products	Societal awakening around positive energy futures and needs fulfilment Educative shift away from emission-reduction problem framing 1.5°C compatible products and services widely available at point of use	Changemakers, educators, advocates, and sustainable business leaders change the conversation around climate change
Urban Infrastructure	Carbon neutral cities Consumer interest in low-carbon technology	Targets, frameworks, and incentive structures for cities to enable flourishing lives Mindset shift away from efficiency and productivity and towards human needs	Redefinition of leadership from net-zero to flourishing lives Mechanisms for exporting solutions from frontrunners

Appendix: Concept models

The diagrams below depict the concept models that were used to initiate co-modelling in the expert workshop. These concept models are derived from the literature on social tipping elements, mainly (Otto et al. 2020).

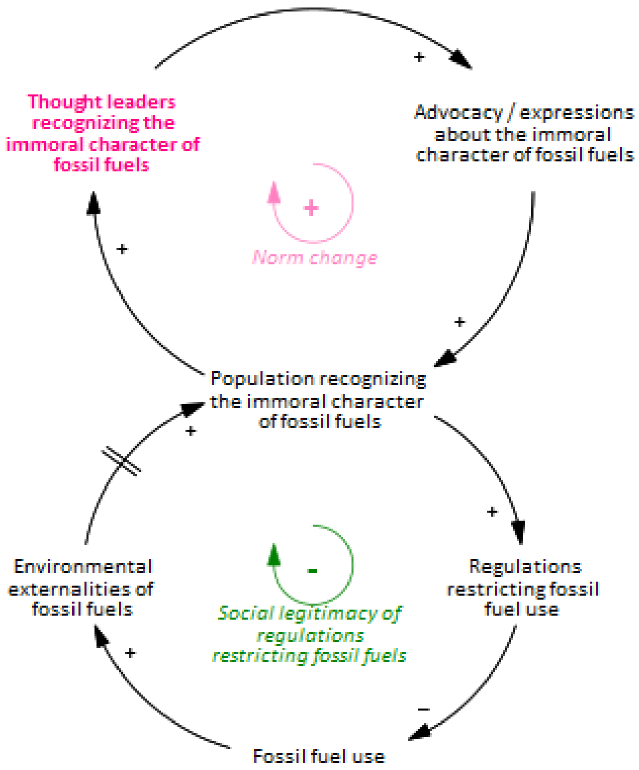


Figure A.1: Concept model of the norms and values subsystem

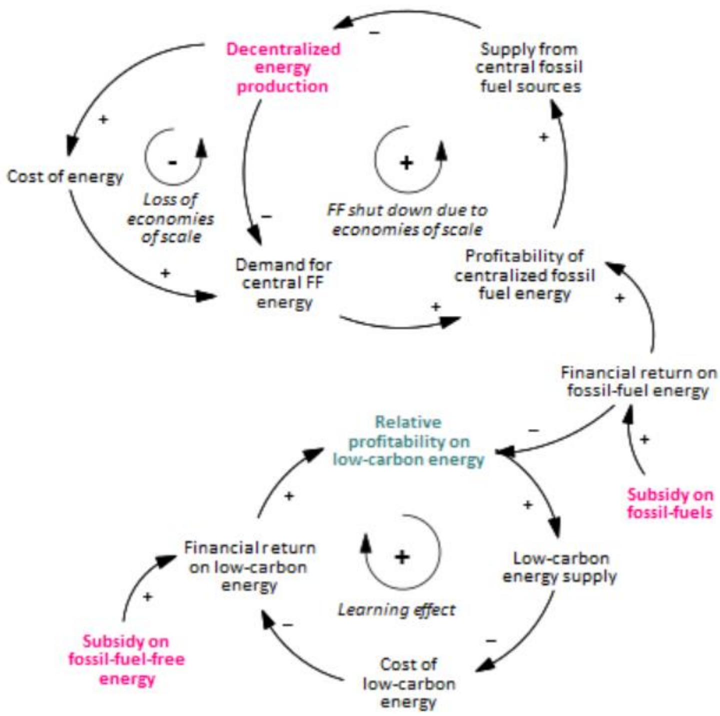


Figure A. 2: Concept model of the energy production subsystem

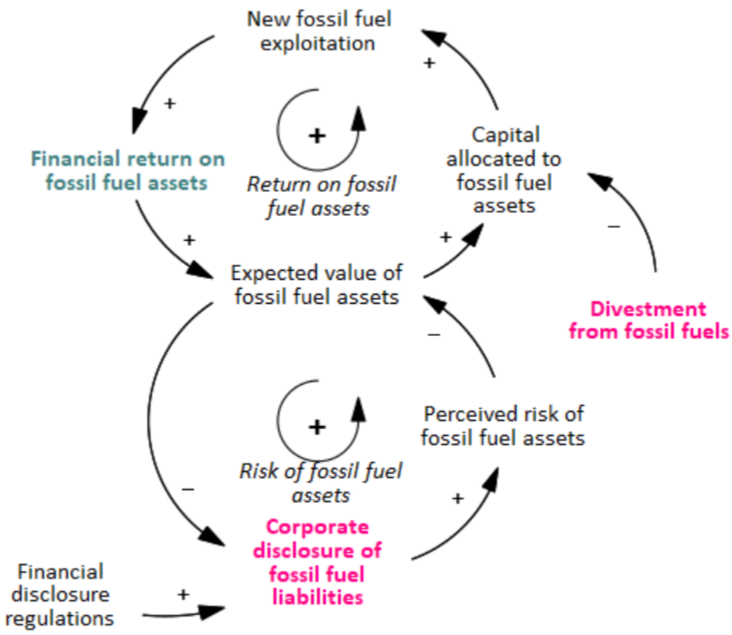


Figure A.3: Concept model of the finance subsystem

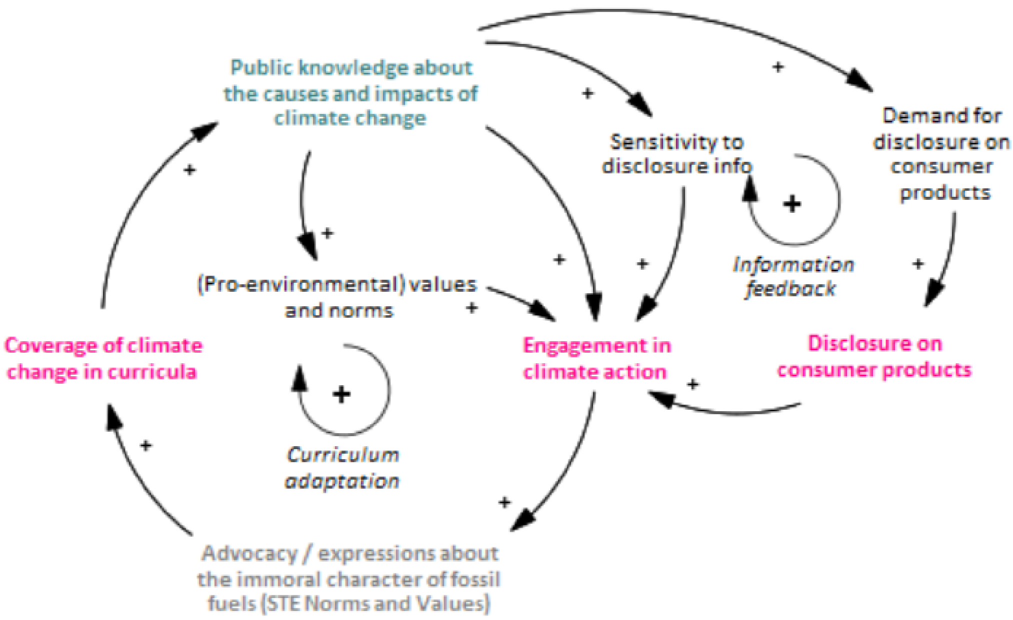


Figure A.4: Concept models of the education and information feedbacks subsystem

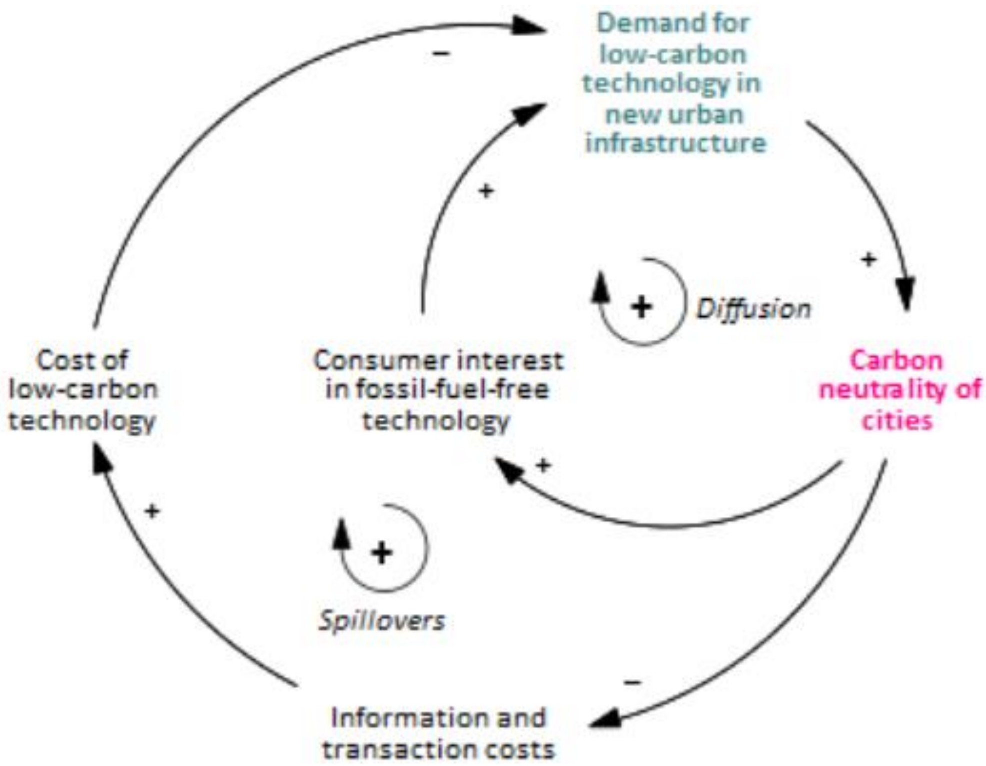


Figure A. 5: Concept model of the urban infrastructure subsystem

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