Social tipping dynamics in the energy system

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Abstract. The fast growth in renewables energy technologies has led to ~~an~~ economic tipping ~~point~~ dynamics: ~~for~~ the early adoption of renewables has determined ~~through~~ economies of scale and economies of learning which in turn have driven further cost reductions and ~~growth~~increased adoption. Despite this progress~~However~~, ~~we do not observe a corresponding reduction in fossil fuel demand. The tipping point~~~~this has not led to~~ a complete system-wide energy transition has not occurred yet due to ~~, indicating~~ the continued presence of complex social and technical barriers. This paper connects evidence on ~~reviews~~ how the ~~cost~~economic tipping ~~point~~dynamics in renewables can ~~initiate~~~~precipitate~~ trigger ~~other~~ social tipping dynamics which potentially might accelerate ~~hold potential to bring us closer to a rapid and~~ a system-wide~~in the~~ energy transition. It does so by reviewing a variety of literature across several disciplines addressing socio-technical dimensions of energy transitions and bringing these together using basic Systems Dynamics terminology. These dynamics might be useful leverage points for policymakers and other actors interested in pursuing energy transition policies. ~~Finally~~Additionally, ~~and~~ the paper ~~it presents~~~~reflects on~~discusses energy communities as a promising and fast-growing niche environment that can exploit and foster such tipping dynamics.

1 Introduction

A transition from a fossil-fuel-based energy system to an energy system based on ~~renewables~~renewable energy sources is key to meeting climate targets. This energy transition involves interdependent changes to technologies and infrastructures, to the behaviour of firms and individuals, and institutions and governance. That is, energy transitions are socio-technical transitions (Geels et al., 2017). Historical case studies, for example, of the transition from wood to coal, argue that energy transitions typically take decades and have severe disruptive ~~socio-economic~~ effects, affecting the livelihood of many people (Freeman & Louçã, 2002). Both the fear of these negative ~~societal~~ consequences and the lock-in of the current fossil-fuel-based system are given as explanations for the slow pace of current-day sustainability transitions (Hughes, 1993; Negro et al., 2012).

This view of energy transitions as inevitably slow processes has recently been challenged. First, we now have some examples of relatively fast energy transitions, e.g., to natural gas in The Netherlands or to combined heat and power in Denmark (Sovacool, 2016). Second, the diffusion of renewable energy technologies like wind and solar has been much faster than anticipated by energy transition scenarios (Creutzig et al., 2017; de Coninck et al., 2018.; Trutnevyte et al., 2019; Wilson et al., 2013).

Social tipping dynamics, in analogy to the tipping dynamics of ecological systems, have received increased attention as a possible mechanism that accelerates and potentially explains the transition to more sustainable socio-technical systems (Otto et al., 2020). Social tipping dynamics for sustainability occur in social-environmental systems with alternative stable states,

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where a change process unfolds rapidly (or nonlinearly), driven by feedback mechanisms and with some degree of irreversibility or stickiness (Milkoreit, 2022)~~when a small change or intervention in the socio-economic system has a large effect on emission reductions (Milkoreit et al., 2018)~~.

In System Dynamics (SD) terminology, ~~F~~feedbacks are generally understood as circular causal processes where the effect of change in one part of a system leads to further change in that part. When an increase in X leads to further increases in X through this circular chain of causality, this is known as a positive or reinforcing feedback (or when a decrease leads to further decrease). Negative or balancing feedbacks occur when an increase in X leads to a decrease in X (or vice versa), and are therefore associated with stability. (REFs NEEDED HERE)

Furthermore, and following with SD terminology, ~~tipping cascades can occur~~ when feedback-powered tipping dynamics spread from one system to another ~~coupled systems~~one, or upwards to drive system change at a higher scale tipping cascades can occur (Sharpe & Lenton, 2021~~0~~). Therefore, while feedback loops are not as fundamental as other leverage points for ~~sustainability~~sustainability, which focus on system goals and paradigms (e.g. through large collective projects using social power) (Meadows, 2008), the relatively minor efforts triggering tipping dynamics nonetheless hold the potential to trigger deeper system change through cascading interactions.

For the energy system, the challenge is thus to connect the current tipping dynamics in low-level intervention points (i.e., subsidies, taxes) to higher-level intervention points to realize tipping cascades that fundamentally change the system.

Tipping dynamics are observed within various subsystems of energy systems (Geels & Ayoub 2023). These dynamics can occur when radical and incremental technological innovations move the system towards cleaner and more efficient energy production and consumption. But tipping dynamics can also occur within the realm of actors and institutions, where changes in policies, regulations, market dynamics, or in the choices and behaviours of firms and individuals can have large effects on the trajectory of the energy system (Otto et al. 2020). Such dynamics can act as catalysts for rapid changes and start cascading effects within the energy landscape.

~~Some distinguishing features of positive social tipping dynamics from, for example, ecological tipping dynamics, is that social tipping is frequently framed as normatively desirable and intentionally activated or triggered (Milkoreit, 2022).~~ Several social factors can initiate social tipping dynamics, including tipping in costs and prices, norms and behaviour and policy (Roberts et al. 2018, Otto et al. 2020). And these become "positive" social tipping dynamics and, compared for instance to ecological tipping dynamics, positive social tipping is frequently framed as normatively desirable and intentionally activated or triggered (Lenton et al 2022, Milkoreit, 2022). The solar energy sector in Germany presents a prominent example of positive social tipping: when strong public, policy and industry ~~support~~ support aligned simultaneously with a strong decrease in support for nuclear energy, this led to unexpected and fast price performance improvements and demand increases in solar technology, boosting the sector globally.

The~~is~~ importance of social and behavioural factors, like policy support, societal acceptance or changing norms, is extensively reported in descriptive case studies that are the foundation of the field of sustainability transitions research (Köhler et al., 2019). Social and behavioural change is, however, constrained by the existing socio-technical system and people's daily lives and behaviour, or social practices (Matthews & Wynes 2022). Social practices approaches shine a light on the culturally embedded routines which reproduce (but also potentially transform) socio-technical energy systems from the bottom up. Crucially, they also point to the differentiation of these practices across social groups (e.g., women versus men, upper class versus working class) (Husu, 2022). A key policy challenge is how to make the new and desired behaviour 'stick'.

Some demand-side behaviour changes are quite swift. An example is the substantial energy demand reduction in Europe in the winter of 2022/2023, resulting from concerns about high energy prices and the war in Ukraine (IEA, 2023). Similarly, but at a global system level, in 2020, the world witnessed a reduction in global fossil fuel emissions as a result of COVID-19 lockdowns across the globe. However, emissions rebounded in 2021, reaching levels comparable to those observed in 2019 (LeQuere et al. 2021, Friedlingstein et al. 2022). These observations reinforce that social tipping dynamics are tipping dynamics rather than tipping points (Milkoreit et al. 2018, Geels & Ayoub 2023), not just because they take some time to evolve, but also because different reinforcing processes are needed to provide momentum (Hughes 1987) and to ensure that

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the change sticks or becomes embedded or irreversible on the relevant time scales. Tabara et al. (2022) indicate that sectoral tipping is probably more relevant for transitions, while “full systems” tipping characterises structural transformations. However, even transition scholars refer to multi-system dynamics and cascades across systems (Papachristos et al. 2013, Rosenbloom et al. 2020, Kanger et al. 2021)..

~~Tipping dynamics are observed within various subsystems of energy systems (Geels & Ayoub 2023). These dynamics can occur when radical and incremental technological innovations move the system towards cleaner and more efficient energy production and consumption. But tipping dynamics can also occur within the realm of actors and institutions, where changes in policies, regulations, market dynamics, or in the choices and behaviours or of firms and individuals can have great large effects on the trajectory of the energy system (Otto et al. 2020). Such dynamics can act as catalysts for rapid changes and start cascading effects within the energy landscape, often driven by feedback loops and reinforcing mechanisms.~~

~~The study of the potential for tipping dynamics within the energy system is crucial for designing effective strategies and interventions that promote the sustainable decarbonizationenergy transition of our societies (Smith et al. 2020).~~

In the energy system, the cost reduction in renewable energy technologies is a driver for tipping dynamics. As solar and wind energy sources become prevalent in the energy system, their costs decrease, enabling wider adoption (Söderholm & Klaassen 2007, Way et al 2022). This, in turn, leads to economies of scale, further reducing costs and creating positive feedback loops that drive even more installations (Isoard & □Soria 2001). In economic terms, ~~the~~ tipping ~~point is reached dynamics are created~~occurs when the cost of renewable energy becomes competitive with or even lower than that of conventional energy sources~~, leading to a cascade effect in which the transition to renewable energy technologies eventually takes off~~.

These reinforcing feedbacks are weakened by balancing feedbacks that dampen the growth of renewables. These balancing feedbacks can originate from vested interests in the fossil-fuel-based system, but also from barriers encountered by renewables.

First, sources of balancing feedbacks, lock-in, and path dependence of fossil fuel-based energy systems are energy infrastructures, technologies and institutions (Hughes 1987, Dangerman & Schellnhuber 2013, Kohler et al. 2019). These can directly hinder the decarbonisation of the energy system through existing standards and resistance from incumbents and vested interests. Further, renewable energy generation sometimes faces curtailment and the mismatch of renewable supply with energy demand slows down replacement of fossil fuels. Indirectly, the availability of cheap energy has stimulated demand for energy-intensive goods and services. Similarly, the high return on fossil fuel investments and the assessment of renewables as risky make it difficult to move capital from fossil to renewables (Pauw et al. 2022). As an example, in the early 2000s UK government provided initial capital grants to boost offshore wind demonstration projects, resulting in a game changer into the overall offshore sector. This has in turn built confidence among financial investors, easing access to resources for project developers (i.e., lower interest rates) (Kern et al 2014; Geels and Ayoub 2023).

Second, ~~Examples~~ examples of barriers encountered by renewables are challenges related to intermittency and the need for a flexible and well-managed grid infrastructure to ensure a reliable and stable energy supply. The increasing need to electrify various end-user sectors (IRENA 2023) adds further complexity to the grid management challenge. For instance, the electrification of transportation is experiencing rapid growth, boosted by policy initiatives for the adoption of e-mobility. Similarly, there is a strong policy focus on electrifying heating and cooling systems in residential areas and districts. Moreover, the electrification of demand is not always viable, and the energy transition may negatively impact individuals with restricted financial resources (Sovacool et al. 2019). In addition, many processes that reinforce fossil-fuel-based energy systems, ranging from subsidies to vested interests and existing infrastructures are still in place. Energy infrastructures are typically built for a lifespan of around 40 years, and changing these infrastructures takes place on the timescale of months to years. Once built, they contribute to stabilising the system state and are a source of path dependence and lock-in.

Social dynamics can also create balancing feedbacks when they mobilise opposition and a lack of societal support for larger-scale solar and wind parks (Devine-Wright 2007, Klok et al. 2023, Windemer 2023). Therefore, cost-competitiveness is not a sufficient indicator to predict support for technologies for which the main public concerns are about spatial impacts, health and safety, and questions of fairness. This shows that economic tipping dynamics alone are not sufficient to realise rapid decarbonisation. As mentioned above, these are important balancing feedbacks which must be considered in any complete analysis of energy systems tipping (see, e.g, Eker & Wilson, 2022).

As a result, the fast growth in renewables has not led to a corresponding decrease in demand for fossil fuels. T~~As t~~he energy transition requires a system-level transformation of the energy system~~,~~ which depends on both phasing out fossil fuels, and accelerating renewable energy provision. In this paper we highlight the promise of positive tipping points in renewables development, while recognising that this is inevitably an incomplete picture without fully considering the fossil phase out side of the story. The purpose of this paper is not to provide a holistic analysis (examples of such attempts can be found in Eker & Wilson (2022), for example), but rather to highlight some promising avenues for positive energy system tipping. ~~four different feedback loops and their interactions need to be aligned: strengthening reinforcing feedback loops for renewables, reducing balancing feedback loops for renewables, reducing reinforcing feedback loops for fossil, strengthening balancing feedback loops for fossil.~~ To simplify explanation of such tipping dynamics in the energy system, some section of the paper makes use of SD modelling technique, also to better visualise reinforcing (R) and balancing (B) feedback processes.

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This paper therefore examines these positive ~~feedbacks~~feedbacks since t~~T~~he study of the potential for tipping dynamics within the energy system is crucial for designing effective strategies and interventions that promote the sustainable decarbonization of our societies (Smith et al. 2020).

~~and~~This paper addresses the following ~~focuses on the~~ question: How can the fast growth in renewables start system-wide tipping cascades that accelerate the energy transition? To this end, next ~~we first discuss the current understanding of energy transition in Section 2 and potential feedbacks in Section 3.~~ Section 2~~4~~ ~~then~~ discusses how the fast growth in renewable electricity supply may initiate further tipping processes. Here specific attention is given to the electrification of households, to avoid-shift-improve (ASI) measures for demand reduction and to how sustainable lifestyles, and the social and political system can generate tipping dynamics in the energy system. Section ~~5~~3 then explores energy communities as an area where ~~modularity is creating reinforcing feedbacks and where balancing feedbacks are weak or absent~~positive tipping dynamics hold great potential. Finally, section ~~6~~4 concludes.

~~2. Energy transitions, social tipping cascades, and leverage points~~

~~Social tipping dynamics in low carbon transitions occur when a small change in the socio-economic system has a significant effect on emission reductions (Milkoreit et al. 2018). Several social factors can initiate social tipping dynamics, including tipping in costs and prices, in norms and behaviour and in policy (Roberts et al. 2018, Otto et al. 2020). When tipping dynamics in one part of the system initiate similar feedbacks in other parts of the system, this may lead to tipping cascades and fundamental system changes, or sustainability transitions.~~

~~Social and behavioural change is, however, constrained by the existing socio-technical system and people's daily lives and behaviour, or social practices (Matthews & Wynes 2022). Social practices approaches shine a light on the culturally embedded routines which reproduce (but also potentially transform) socio-technical energy systems from the bottom up. Crucially, they also point to the differentiation of these practices across social groups (e.g., women versus. men, upper class versuss. working class) (Husu, 2022). A key policy challenge is how to make the new and desired behaviour 'stick'. Some demand-side behaviour changes are quite swift. An example is the substantial energy demand reduction in Europe in the winter of 2022/2023, resulting from concerns about high energy prices and the war in Ukraine (IEA, 2023). Similarly, but at a global system level, in 2020, the world witnessed a reduction in global fossil fuel emissions as a result of COVID-19 lockdowns across the globe. However, emissions rebounded in 2021, reaching levels comparable to those observed in 2019 (LeQuere et al. 2021, Friedlingstein et al. 2022). These observations reinforce that social tipping dynamics are tipping dynamics rather than tipping points (Milkoreit et al. 2018, Geels & Ayoub 2023), not just because they take some time to evolve, but also because different reinforcing processes are needed to provide momentum (Hughes) and to ensure that the change sticks or becomes~~

~~embedded or irreversible on the relevant time scales. Tabara et al. (2022) indicate that sectoral tipping is probably more relevant for transitions, while "full systems" tipping characterises structural transformations. However, even transition scholars refer to multi-system dynamics and cascades across systems (Papachristos et al. 2013, Rosenbloom et al. 2020, Kanger et al. 2021). This aligns with views from system dynamics, where leverage points focusing on single feedback loops have a smaller effect on the transformation of the system than leverage points that focus on the goals and paradigm of the system (Meadows, 2008).~~

~~For the energy system, the challenge is thus to connect the current tipping dynamics in low-level intervention points (subsidies, taxes), connect to higher-level intervention points to realize tipping cascades that fundamentally change the system.~~

~~3.~~ 2 Fast growth in renewable electricity supply drives social tipping in the energy system

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Most evidence on tipping dynamics in energy systems concerns the price performance of new technologies (Otto et al. 2020). Renewables are now among the cheapest energy generation options ~~(Haegel et al. 2019, IRENA 2022a,b)~~. Cost reductions in renewable generation technologies like wind energy and solar photovoltaics (PV) have been massive and much faster than predicted. The price of electricity from solar energy declined by 89% from 2009 to 2019 and the price of wind energy declined by 70% in this period. In some contexts, cost-parity ~~has been reached in energy generation for wind and solar~~ in energy generation for wind and solar has been reached or even exceeded, making them cheaper than fossil generation (Haegel et al. 2019, IRENA 2022a,b).

For wind and solar energy generation, the main reinforcing feedback (denoted by R in Figure 1) that created these tipping dynamics is cost reduction and performance improvement ~~(Figure 1)~~ through economies of learning and economies of scale, leading to more deployment and, in turn, to more learning (Sharpe & Lenton 2021, Kavlak et al. 2018, Nemet & Greene 2022).

The diffusion of solar PV is also analysed as a social process where considerations of observability and trialability and processes like word-of-mouth play a role next to costs and performance (Rogers 2003, Bollinger & Gillingham 2012, Palm 2017, Rode & Weber 2016). Adoption of rooftop solar PV, for instance, is typically clustered in space, where people are more likely to adopt when people nearby also have adopted (Graziano & Gillingham 2015, van der Kam et al. 2018). Therefore, more adoption leads to increased observability and trialability (i.e., learning), which in turn leads to more adoption.

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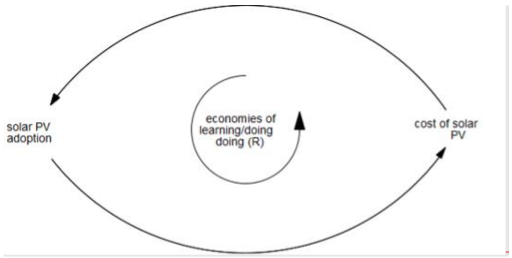
Moreover, markets ~~are still expanding as performance improvemen~~ts make the technology attractive to a wider range of users. As a result of these technological improvements and cost reductions, renewable generation is increasingly possible in locations where wind or sun conditions are less favourable or where installation is more difficult and costly, as demonstrated by the~~. The~~ increasing attention for floating solar (Gonzalez-Sanchez et al. 2021, Jin et al. 2023)~~), as well as the integration of wind technologies into the generation process of economically viable "green" hydrogen.~~



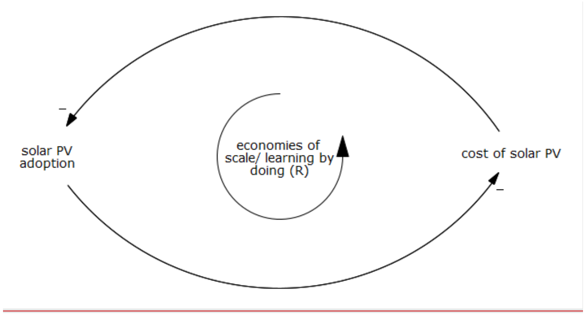


Figure 1: ~~The simplified/stylized main feedback loop in solar energy.~~ This causal loop diagram ~~figure~~ illustrates the stylized feedback loop occurring in solar energy: as more solar PV is adopted, costs are reduced to due economies of scale and learning effects, in turn driving up further solar PV adoption~~cost reduction has a positive effect on adoption and vice versa, fuelled by economies of scale and learning effect~~

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~~The cost-performance feedback loop is the main, but not the only feedback driving the tipping dynamics for wind and solar. For instance, the diffusion of rooftop solar PV is typically clustered in space, where people are more likely to adopt when people nearby also have adopted (Graziano & Gillingham 2015, van der Kam et al. 2018). This suggests that the diffusion of these technologies is partly a social process where considerations of observability and trialability and processes like word-of-mouth play a role next to costs and performance (Rogers 2003, Bollinger & Gillingham 2012, Palm 2017, Rode & Weber 2016). In this feedback more adoption leads to increased observability and trialability, which in turn leads to more adoption.~~

~~Another positive feedback loop stems from policy interactions, whereby policy not only stimulates deployment but also creates legitimacy and new interests, leading to increased lobbying and support for policy to support the new industries and further deployment (Hess 2016, Meckling et al. 2017, Meckling 2019, Roberts et al. 2018, Rosenbloom et al. 2019, Sewerin et al. 2020, Fesenfeld et al. 2022). For instance, the German feed-in tariff for renewables is frequently mentioned as an enabling condition for this feedback (Otto et al. 2020, Nijsse et al., 2023). Further, strong pro-environment policies may incentivise firms towards more and R&D and innovation, thereby expanding industrial sectors for low-carbon technologies. In this way, public opinion may also increase support and acceptance for new low-carbon technologies, increasing pressure on policymakers in setting-up goals and strategies for a more sustainable society (Geels and Ayoub, 2023). The political sphere can also be seen as a tipping element itself, as it not only can trigger social tipping but can also tip itself into a new state, generating a tipping cascade (Stadelmann-Steffen et al. 2021, Eder & Stadelmann-Steffen 2023).other~~

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~~The resulting fast growth in wind and solar generation capacity has however not led to corresponding reductions in fossil fuel demand. Sources of dampening feedbacks, lock-in, and path dependence of fossil fuel-based energy systems are energy infrastructures, technologies and institutions (Hughes 1987, Dangerman & Schellnhuber 2013, Kohler et al. 2019). These can directly hinder the decarbonisation of the energy system through existing standards and resistance from incumbents and vested interests. Further, renewable energy generation sometimes faces curtailment and the mismatch of renewable supply with energy demand slows down replacement of fossil fuels. Indirectly, the availability of cheap energy has stimulated demand for energy-intensive goods and services. Similarly, the high return on fossil fuel investments and the assessment of renewables as risky make it difficult to move capital from fossil to renewables (Pauw et al. 2022).). As an example, in the early 2000s UK government provided initial capital grants to boost offshore wind demonstration projects, resulting in a game changer into the overall offshore sector. This has in turn built confidence among financial investors, easing access to resources for project developers (i.e., lower interest rates) (Kern et al 2014; Geels and Ayoub 2023).~~

~~Social dynamics can also create dampening feedbacks when they mobilise opposition and a lack of societal support for larger-scale solar and wind parks (Devine-Wright 2007, Klok et al. 2023, Windemer 2023). Therefore, cost-competitiveness is not a~~

~~sufficient indicator to predict support for technologies for which the main public concerns are about spatial impacts, health and safety, and questions of fairness. This shows that economic tipping points alone are not sufficient to realise rapid decarbonisation.~~

4. ~~Tipping dynamics that build on the fast growth in wind and solar technologies and services~~

~~4.~~ 2.1. Household ~~electricification~~electrification

~~5.~~

In end-use sectors, the tipping dynamics in wind and solar may initiate further decarbonisation of the energy system ~~can be further accelerated by tipping dynamics in wind and solar~~ through electrification of ~~since electrification of the~~ energy demand~~supply may generate positive feedbacks or cascades~~. The transportation sector is a relevant example of these advancements. The increasing prevalence of electric cars, along with other electricity-powered alternatives such as e-bikes, e-scooters, and other mopeds, indicates the key role of batteries ~~into~~ in ~~the~~ novel modular demand and the significant contribution to sector-wide decarbonisation. The electrification of the energy system also impacts the role of electric transport devices. In addition to facilitating emission-free mobility, these devices can support the grid infrastructure during periods of ample electricity generation from renewable sources by functioning as modular storage systems.

Another important aspect of the rapid expansion of wind and solar power generation capacity is the impact on the electrification of the residential sector, which includes heating and cooling systems (Figure 2). The fast cost reductions as observed in wind and solar are more likely to occur in smaller and modular technologies (Wilson et al. 2020). In the residential sector, there are several other small and modular technologies that may reach cost-parity in the short term, like household batteries and heat pumps (Meldrum et al. 2023).

Household batteries are specifically attractive in places where feed-in tariffs for solar energy into the grid are much lower than the retail price for energy from the grid. ~~.~~

The large-scale adoption of household batteries may ~~further~~ influence the decarbonisation of the energy system in two ways.

First, it reduces curtailment of household solar PV generation, better matching renewable energy supply with demand. Second, it reduces grid congestion during peaks in solar generation (reinforcing feedback on the left in Figure 2). Currently, in several countries, this grid congestion is a barrier to further grid integration of renewables. Few countries have strong incentives in place to stimulate demand to synchronise with the availability of renewable energy supply.

The electrification of heating is a ~~second~~ technology area that benefits from the fast decarbonisation of the electricity supply. Heat demand is often met by natural gas boilers. Based on IEA (2022) analysis, natural gas accounts for 42% of global heating energy demand, with a 40% share of the heating mix in the European Union and over 60% in the United States. ~~When low-carbon, sustainable, heat sources are available, this may be a preferred option. However, when this is not the case, electrification of heating demand through heat pumps is one option which can lead to a large reduction in energy demand~~ When low-carbon heat sources like waste heat are available, this is a preferred option. When this is not the case, electrification of heating demand through heat pumps can lead to a large reduction in energy demand. Nevertheless, the shift to low-carbon heat sources requires changes in technologies and infrastructure in houses and neighbourhoods.

Here, important enablers are increased insulation (also to reduce overall heat demand) and increased renewable electricity supply. For instance, the adoption of solar PV coupled with efficiency and sufficiency measure may both yield to increased adoption of heat pumps, as shown at the top in Figure 2. ~~But~~However, barriers to electrification of heating exists, such as ~~are~~

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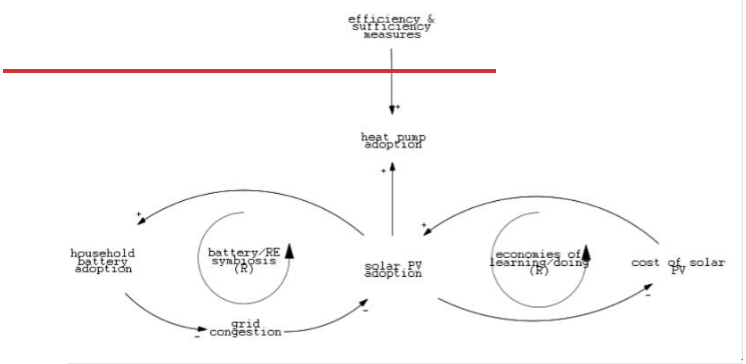
the lack of technologies for heat storage and the cumbersome installation process. A more radical and politically challenging behavioural change would be to provide incentives to live in smaller homes or to have higher occupancy per dwelling, for example in planning decisions.

~~The declining cost of solar has also led to the development of solar home systems of energy poor areas in the global south. While the potential for such systems to contribute to well-being is large, the literature provides evidence of a misfit with local needs (Groenewoudt et al. 2020).~~



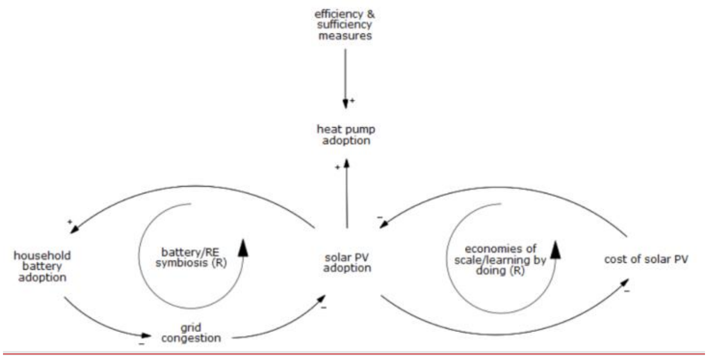


Figure 2: Feedback loop in electrification of heating & cooling. The reinforcing feedback between cost reduction and increased adoption of solar PV may trigger another reinforcing feedback of adoption of household battery and reduction in grid congestion, resulting into futher solar PV adoption. Furthermore, solar PV adoption supportsof demand for heat pumps, boosted by adequate efficiency and sufficiency measures

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2.2. Avoid-Shift-Improve measures and Energy demand reduction~~ and sustainable lifestyles~~

In addition to these technology-~~-~~driven processes, demand reduction is key. However, demand reduction options are often constrained by the existing socio-technical system. It is, for example, difficult for individuals to change their mobility practices, when demand of employers regarding workplace presence do not change.

The Avoid-Shift-Improve (ASI) framework (Creutzig et al. 2022) is often used to identify those demand reduction options. Avoid options reduce unnecessary energy consumption, possibly by redesigning service provisioning systems. Shift refers to the switch to already existing competitive, efficient and cleaner technologies and service provisioning systems. ~~And ~~I~~i~~mprove refers to efficiency improvements~~ in efficiency~~ in existing technologies. While improve options are not sufficient to tip the energy system to a decarbonised state, they are an important enabler for options that can. ~~Any increase in efficiency reduces the need for avoid and shift activities.~~ Figure 3 adds ASI measures as an additional element in previous figure on feedback loop in electrification of heating & cooling.

~~More generally, t~~The different ASI measures ~~options ~~often co-occur. While avoid options have the largest mitigation potential, they often need to be flanked with shift and improve options to be attractive. For example, when people switch from natural gas heating to heat pumps, good insulation (improve) is a condition. Typically avoid and shift options require larger changes in social practices and in the broader socio-technical system. Options where both behavioural and technological change is required, or that require a substantial change in social and user practices, are typically more difficult to realise and thus difficult as a starting point for tipping dynamics (Geels et al. 2018).

The demand for energy should be brought in line with what can be sustainably produced. On the one hand, energy access and service provision will need to grow for many less-developed countries, and for poor people everywhere to ensure decent living standards and well-being (IPCC 2022a). On the other hand, reduction in energy use is widely regarded as a key pillar of decarbonisation in wealthy countries. Indeed, reducing energy demand is key in 1.5 degree pathways (Koide et al. 2021). Household energy demand grows with income, and individuals with high socioeconomic status are responsible for a large share of emissions (IPCC 2022b). Thus, they are capable of reducing GHG emissions by becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies (Creutzig et al. 2022). Reducing income inequality and aiming for sufficiency-level incomes may thus affect both well-being and energy use (Du et al. 2022).

Higher prices lead to reduced energy demand, providing evidence for measures like a carbon tax. Natural gas consumption in the EU and in the period August 2022 to January 2023 decreased by 19% compared to the average gas consumption for the same months in the previous 5 years. However, this also came with increased levels of energy poverty, particularly affecting low-income households in badly insulated homes (IEA 2023). Interestingly the high prices also triggered and opened the opportunity for sufficiency-based energy price interventions.

Because of the relationship between income and energy use, a rebound effect may occur (see top right balancing feedback in Figure 3) when technologically or socially induced demand reductions lead to a higher budget and more energy demand (Newell et al. 2021, van den Bergh 2011, Sorrell et al. 2020).

Digitalisation (at the top-left in Figure 3) can play a key role in avoiding unnecessary energy demand (Wilson et al. 2020). At the individual and household level, lifestyle changes regarding energy demand, including turning down the thermostat and reducing the demand for hot tap water (shorter showers), are effective strategies (Roy et al. 2012, Creutzig et al. 2016, Ivanova et al. 2020). These strategies are most effective when combined with policy support and shift and improve measures. More specifically, digital technologies are key to better match renewable supply with demand to avoid curtailments and grid congestion (load shifting and balancing) but have not yet reached widespread diffusion.

~~Avoid options reduce unnecessary energy consumption. The demand for energy should be brought in line with what can be sustainably produced. On the one hand, energy access and service provision will need to grow for many less-developed countries, and for poor people everywhere to ensure decent living standards and well-being (IPCC 2022a). On the other hand, reduction in energy use is widely regarded as a key pillar of decarbonisation in wealthy countries. Indeed, reducing energy demand is key in 1.5 degree pathways (Koide et al. 2021). Household energy demand grows with income, and~~

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~~individuals with high socioeconomic status are responsible for a large share of emissions (IPCC 2022b). Thus, they are capable of reducing GHG emissions by becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies (Creutzig et al. 2022). Reducing income inequality and aiming for sufficiency-level incomes may thus affect both well-being and energy use (Du et al. 2022).~~

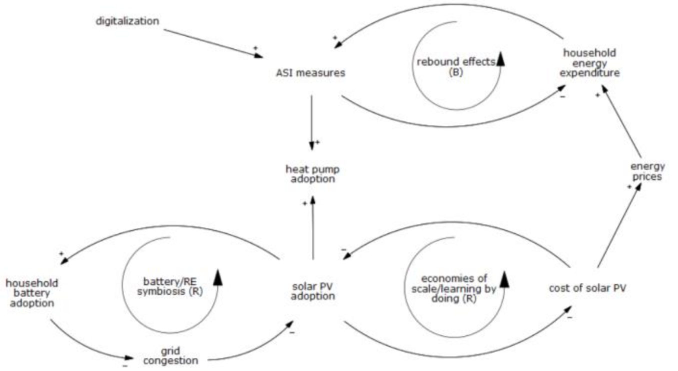

Figure 3: Feedback processes in reducing energy demand

2.3. Sustainable lifestyles, and social and political tipping dynamics in the energy system

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Changes in the energy behaviour and lifestyle of individuals can make a large contribution but are only feasible when supported by changes in the broader socio-technical system (Nisa et al. 2019, Niamir et al. 2020). This means that social tipping of energy consumption by individuals, households or organisations is conditioned by a range of factors such as social and cultural norms, ownership and control of resources, technology accessibility, infrastructure design and services availability, social network structures, and organisational resources (Steg et al. 2018). ~~Because of the relationship between income and energy use, a rebound effect may occur when technologically or socially induced demand reductions lead to a higher budget and more energy demand (Newell et al. 2021, van den Bergh 2011, Sorrell et al. 2020).~~ Avoid options reduce unnecessary energy consumption. ~~Further~~But, when avoiding energy use is undesirable from a well-being perspective, then shifting the way this activity is done (or finding an alternative means to the same goal) is key.

~~For these reasons, the demand for energy should be brought in line with what can be sustainably produced. On the one hand, energy access and service provision will need to grow for many less-developed countries, and for poor people everywhere to ensure decent living standards and well-being (IPCC 2022a). On the other hand, reduction in energy use is widely regarded as a key pillar of decarbonisation in wealthy countries. Indeed, reducing energy demand is key in 1.5 degree pathways (Koide et al. 2021). Household energy demand grows with income, and individuals with high socioeconomic status are responsible for a large share of emissions (IPCC 2022b). Thus, they are capable of reducing GHG emissions by becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies (Creutzig et al. 2022). Reducing income inequality and aiming for sufficiency-level incomes may thus affect both well-being and energy use (Du et al. 2022).~~

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~~Higher prices lead to reduced energy demand, providing evidence for measures like a carbon tax. Natural gas consumption in the EU and in the period August 2022 to January 2023 decreased by 19% compared to the average gas consumption for the same months in the previous 5 years. However, this also came with increased levels of energy poverty, particularly affecting low-income households in badly insulated homes (IEA 2023). Interestingly the high prices also triggered and opened the opportunity for sufficiency-based energy price interventions.~~

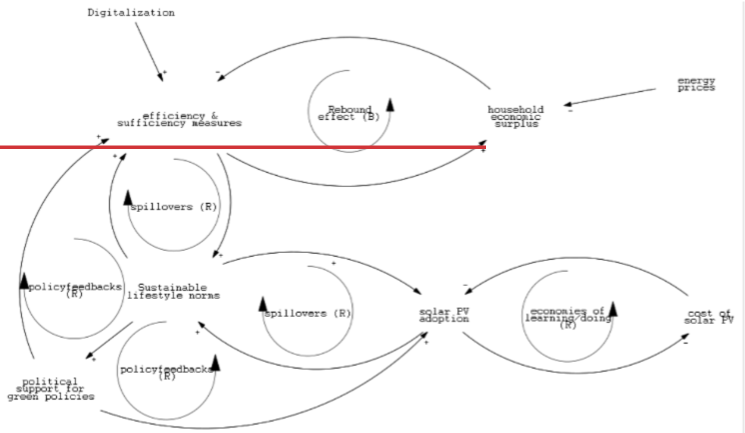
When the demand reductions stem from changes in norms or behaviours with a sustainability motive, the risks of rebound effects are lower. However, different attitudes make some demand-side alternatives difficult to scale up in the population (Geels 2023). ~~Not all find enabling conditions leading t~~Often lacking are enabling conditions for~~o~~ just and smooth change, as for instance city infrastructure or the built environment may prevent people from avoiding using private cars instead of alternatives like walking, cycling, or taking public transport.

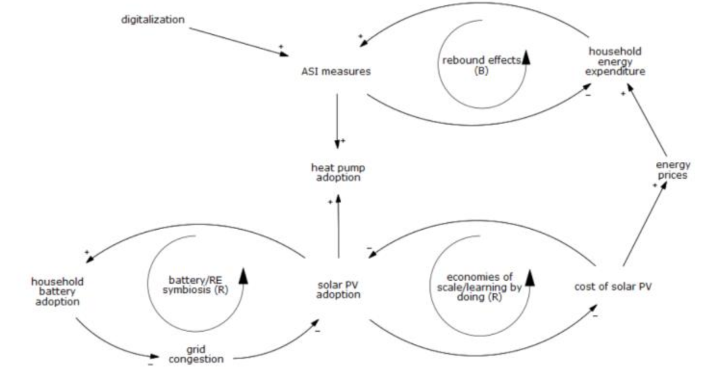
~~Interestingly, pro-environmental behaviours may induce other pro-environmental behaviours, so changes in behaviour in mobility, or food may spill over to energy behaviours (Steg & Vlek 2009, Steg 2023). The adoption of household PV for environmental reasons may thus induce other pro-environmental behaviours. When the new behaviour becomes common and the norm starts to shift, this also increases the political feasibility of strict regulation. There is, for example, public support for measures like incentives towards renewable technology and a ban on least energy-efficient household appliances.~~

~~Empirical studies show that informing people about the energy conservation behaviours of their neighbours combined with the public labelling of energy conservation behaviour as desirable, can lead to significant reductions in energy consumption behaviour (Gockeritz et al. 2010, Allcott 2011, Horne & Kennedy 2017, Bonan et al. 2020). A key takeaway from these studies is that a relatively weak form of sanctioning (i.e., showing approval and disapproval of particular behaviour by using thumps up/down or positive and negative smileys), already has a modest positive effect on energy savings. Peer effects in social network structures can provide inhibiting or supporting conditions for the diffusion of energy conservation practices, depending on the structure of the network and the type of activity (Wolske et al. 2020).~~

~~The positive feedback loop mechanism of opinion exchange can thus increase awareness and promote more sustainable lifestyles. However, it can also have a negative effect when contrarians get the majority in a given social group, leading to the amplification and reinforcement of anti-environmental beliefs. For this reason, avoiding opinion polarisation is crucial in climate-related issues to foster cohesion for effective government action (Badullovich 2023, Mayer & Smith 2023). Citizens' environmental consciousness and the formation of their opinions directly affects actions that impact the local and global environment (Chung et al. 2019, van den Bergh et al. 2019).~~

~~The presence of a group with strong anti-environmental beliefs can discourage pro-environmental engagement and support for climate change initiatives. Opinion polarisation makes it challenging to reach consensus and decreases public support for environmental initiatives, posing a challenge for policymakers (Maertens et al. 2020). To mitigate negative feedback loop and harness the positive cascade effect of opinion dynamic, some governments have implemented policies to incentivize pro-environmental behaviours, while awareness campaigns and education aim to correct misinformation and provide accurate information (Charlier & Kirakozian 2020, Baiardi 2022). When opinions drive clique formation, they can lead to concrete pro-environment actions, such as social movements and support for climate change initiatives (Winkelmann et al. 2022).~~





~~Figure 3: Feedback processes in reducing energy demand~~

~~Social and political tipping dynamics in the energy system~~

~~The cost-performance feedback loop is the main, but not the only feedback driving the tipping dynamics for wind and solar. For instance, the diffusion of rooftop solar PV is typically clustered in space, where people are more likely to adopt when people nearby also have adopted (Graziano & Gillingham 2015, van der Kam et al. 2018). This suggests that the diffusion of these technologies is partly a social process where considerations of observability and trialability and processes like word-of-mouth play a role next to costs and performance (Rogers 2003, Bollinger & Gillingham 2012, Palm 2017, Rode & Weber 2016). In this feedback more adoption leads to increased observability and trialability, which in turn leads to more adoption.~~

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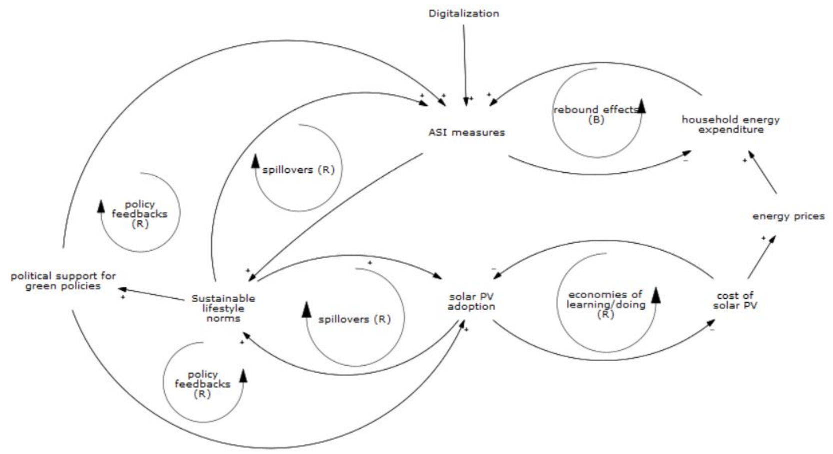

Figure 4. Social and political dynamics in energy system tipping

Empirical studies show that informing people about the energy conservation behaviours of their neighbours combined with the public labelling of energy conservation behaviour as desirable, can lead to significant reductions in energy consumption behaviour (Gockeritz et al. 2010, Allcott 2011, Horne & Kennedy 2017, Bonan et al. 2020). ~~A key takeaway from t~~These studies ~~is~~show that a relatively weak form of sanctioning (i.e., showing approval and disapproval of particular behaviour by using thumps up/down or positive and negative smileys), already has a modest positive effect on energy savings. Peer effects in social network structures can provide inhibiting or supporting conditions for the diffusion of energy conservation practices, depending on the structure of the network and the type of activity (Wolske et al. 2020).

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The presence of a group with strong anti-environmental beliefs can discourage pro-environmental engagement and support for climate change initiatives. Opinion polarisation makes it challenging to reach consensus and decreases public support for environmental initiatives, posing a challenge for policymakers (Maertens et al. 2020). To mitigate negative feedback loop and harness the positive cascade effect of opinion dynamic, some governments have implemented policies to incentivize pro-environmental behaviours, while awareness campaigns and education aim to correct misinformation and provide accurate information (Charlier & Kirakozian 2020, Baiardi 2022). When opinions drive clique formation, they can lead to concrete pro-environment actions, such as social movements and support for climate change initiatives (Winkelmann et al. 2022).

Social acceptance and changes in norms and behaviours, may have large influence on both direct consumer demand and policy support (Edelenbosch et al., 2018; Nemet, 2006). Civil society engages with energy transitions in many ways: from adopting energy efficient technology, to joining energy cooperatives; from environmental activism to resistance against wind parks (Chilvers et al., 2021~~; Smith, 2012~~). These interactions are driven by (changes in) perceptions, attitudes, motivations, emotions, beliefs, values, and norms (Clayton et al., 2015), sometimes triggered by external events like the oil crisis or nuclear accidents. Some of these factors also may influence the willingness to adopt a certain technology (as in Edelenbosch et al., 2018), adoption or societal acceptance is not only driven by price.

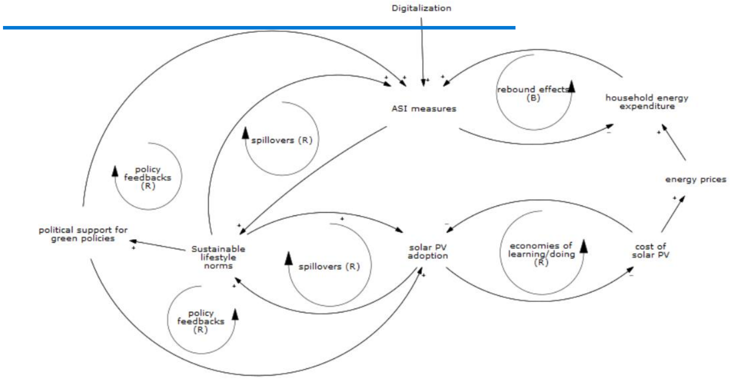
There is extensive literature on the social acceptance of renewable energy infrastructure (Batel, 2020; Ellis & Ferraro, 2017; Wolsink, 2018). One of the most prominent conceptualisations of social acceptance is Wüstenhagen et al.'s (2007) social acceptance triangle, comprising community, market and socio-political acceptance. This draws attention to the fact that community acceptance or local opposition to projects can influence general public or political acceptance, and societal demand for renewable energy. From this perspective, demand is not simply the economic behaviour of individuals or households but is a product of societal relations. One potential balancing feedback for renewables deployment is project delays caused by local opposition, which leads to pressure to streamline planning and reduce participation options, which in turn creates more opposition. This dynamic is seen in many EU countries today.

Finally, policy feedbacks are well recognised in political science literature, whereby policy not only stimulates deployment but also creates legitimacy and new interests, leading to increased lobbying and support for policy to support the new industries and further deployment (Hess 2016, Meckling et al. 2017, Meckling 2019, Roberts et al. 2018, Rosenbloom et al. 2019, Sewerin et al. 2020, Fesenfeld et al. 2022).~~.~~ ~~–~~ For example, Kelsey (2021) identifies 'green spirals' which resembled tipping dynamics for the reduced use of CFCs for ozone protection. Policies engendered new industrial interests who in turn support new policies. Kelsey also identified that these spirals can transcend domestic politics and scale up to the international level. This is similar to the notion of tipping cascades.

Key considerations for policymakers hoping to create tipping dynamics in this way is the sequencing of policies~~-~~ (Meckling et al,~~,~~ 2017). For the energy transition, similar dynamics can potentially be found with the renewables industry. For instance, the German feed-in tariff for renewables is frequently mentioned as an enabling condition for this feedback (Otto et al. 2020, Nijsse et al., 2023). Further, strong pro-environment policies may incentivise firms towards more and R&D and innovation, thereby expanding industrial sectors for low-carbon technologies. In this way, public opinion may also increase support and acceptance for new low-carbon technologies, increasing pressure on policymakers in setting-up goals and strategies for a more sustainable society (Geels and Ayoub, 2023).

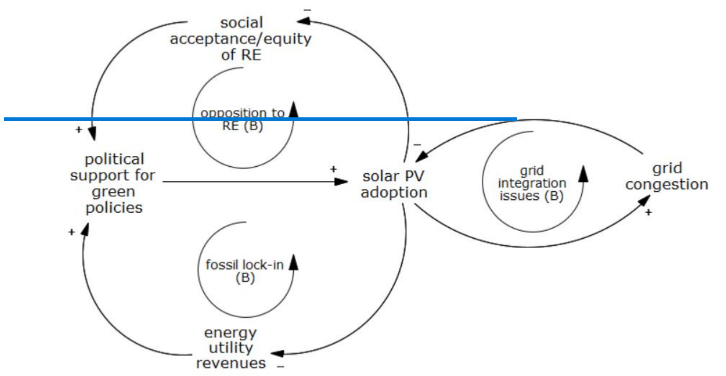
The political sphere can not only trigger social tipping but can also tip itself into a new state, generating a tipping cascade (Stadelmann-Steffen et al. 2021, Eder & Stadelmann-Steffen 2023). Indeed, the same applies to any group, organisation or institution that is part of the socio-technical system. For example, civil society could also be a key element in energy system tipping dynamics.~~Furthermore, i~~ Increasing attention is being paid to prosumerism which can be understood as a broad movement towards a decentralized democratic energy model (Campos & Marín-González, 2020). These and other civil society movements interact with the state, which in turn creates opportunities or barriers to different lines of action for citizens or households, engendering balancing or reinforcing policy feedbacks~~ (cite)~~.

While research on policy feedbacks frequently targets its findings towards policymakers, this knowledge can also be used by civil society or interest coalitions to try to initiate such feedback processes. Indeed, some research from social movements theory identifies movement-policy feedbacks or ‘opportunity/threat’ spirals in which “~~‘~~demands lead to concessions that encourage further demands, and so on”~~’~~ (Biggs, 2003~~2~~, p. 228; McAdam et al., 2001). Winkelmann et al. (2022) discuss the relationship between the Fridays for Future movement and European states in ways which could align with this idea. Focussing specifically on energy, such feedbacks could help to explain the recent boom of the energy cooperative movement in countries like the Netherlands, for example.



~~Figure 4. Social and political dynamics in energy system tipping~~

~~Sources of balancing feedbacks, lock-in, and path dependence of fossil fuel-based energy systems are energy infrastructures, technologies and institutions (Hughes 1987, Dangerman & Schellnhuber 2013, Kohler et al. 2019). These can directly hinder the decarbonisation of the energy system through existing standards and resistance from incumbents and vested interests. Further, renewable energy generation sometimes faces curtailment and the mismatch of renewable supply with energy demand slows down replacement of fossil fuels. Indirectly, the availability of cheap energy has stimulated demand for energy-intensive goods and services. Similarly, the high return on fossil fuel investments and the assessment of renewables as risky make it difficult to move capital from fossil to renewables (Pauw et al. 2022). As an example, in the early 2000s UK government provided initial capital grants to boost offshore wind demonstration projects, resulting in a game changer into the overall offshore sector. This has in turn built confidence among financial investors, easing access to resources for project developers (i.e., lower interest rates) (Kern et al 2014; Geels and Ayoub 2023).~~



~~Fig. 5. Balancing feedbacks~~

~~5.~~ 3. Tipping dynamics in Energy Communities

While there is thus potential for ~~isolated~~ tipping dynamics in technology adoption, the balancing feedbacks regarding system integration and social practices hamper the ~~scale up~~scale-up to tipping cascades. Or in system dynamics terms, the dynamics remain restricted to ~~low level~~low-level leverage points or feedback loops (Meadows, 2008). This section explores energy communities as a social innovation which targets higher level leverage points such as system rules and goals at both micro/meso (e.g. community) and macro levels (e.g. policy supports~~ via lobbying etc.~~). ~~n environment where the reinforcing feedbacks are strengthened, and the balancing feedbacks are reduced.~~ They do so by changing the institutional environment in which individuals or other actors operate, which can lead to a strengthening or weakening of balancing and reinforcing feedbacks described above. They can also lead to the creation or removal of~~r~~ certain feedbacks under new system conditions.

Many energy communities take the form of renewable energy cooperatives. A renewable energy cooperative is as a bottom-up, legally registered collective of citizens that aims to create social, environmental and/or economic benefits for its members through energy-related activities (Doci et al., 2015; van Summeren et al., 2020; Hicks & Ison, 2018). Many cooperatives are local enterprises with diversified activity portfolios (Reis et al., 2021). They~~ that~~ create value for their members via energy-related projects, ranging from awareness raising to cooperative energy production (Oteman et al., 2014). In the EU, the Clean Energy Package, adopted in 2019, aims for a central role for these cooperatives in decarbonising the energy system. More specifically, it advocates energy cooperatives as a way to enable citizens to participate in and benefit from the transition. Renewable energy cooperatives have increased in scale, scope and number throughout European member states ~~(~~(Blasch et al., 2021; ~~Rescoop~~ REScoop.eu, 2020). ~~Many cooperatives are local enterprises with diversified activity portfolios (Reis et al., 2021).~~

~~A renewable energy cooperative is as a bottom-up, legally registered collective of citizens that aims to create social, environmental and/or economic benefits for its members through energy-related activities (Doci et al., 2015; van Summeren et al., 2020; Hicks & Ison, 2018).~~ Energy communities ~~are social structures and~~ often have social and sustainability goals as a main objective, for example to reduce dependence on the centralised energy infrastructure, while also taking advantage of the possibility to produce, consume and sell the energy produced back to the grid ~~the energy produced~~ (Yildiz et al. 2015, Bauwens et al. 2016, Bauwens et al. 2022). Other objectives include ~~or the objective~~ to reduce energy poverty and to accelerate decarbonisation of the energy system via the spread of renewable energy solutions (Shapira et al. 2021).

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Typical characteristics of energy communities are voluntary and open membership (van den Berghe and Wieczorek, 2022), the 'one member – one vote' principle (Wierling et al., 2023), a high degree of community ownership and governance, and fair value distribution (Mourik et al., 2020). Activities of renewable energy cooperatives include collective energy generation and selling, collective purchasing of renewable energy, ~~–~~consulting and awareness raising (Gui & MacGill, 2018) and development & ownership of energy projects (Wierling et al., 2023). In addition, some cooperatives also offer (peer-to-peer) trading of energy balancing and flexibility services (van Summeren et al., 2020; Verkade & Höffken, 2019).

~~Interestingly~~~~As mentioned above, e~~Energy communities can strengthen, weaken, add or remove the~~ reinforcing~~ feedbacks discussed ~~above~~in previous sections~~, while balancing feedbacks are weak or absent~~. As mentioned in the introduction and visualised in Figure 5 below, some key balancing feedbacks for renewable energy adoption include pushback from incumbent fossil-based utilities, grid integration issues, and social acceptance problems.

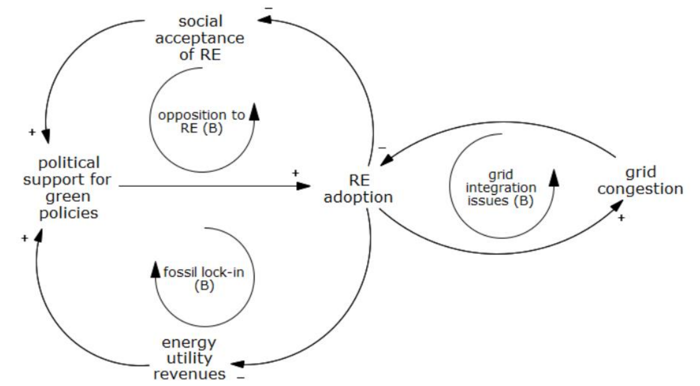

Fig. 5. Balancing feedbacks for RE adoption.

~~Their cooperative and legal structures often require that any profits a~~Energy communities' cooperative and legal structures often require that any profits are re re-invested in the community, further stimulating investment in clean energy technologies. ~~In fact, decentralised production is believed to have the potential to initiate positive feedback loops within the energy system, accelerating the shift towards cleaner technologies (Eker & Wilson, 2022).~~ The electrification of residential districts can then also create a positive feedback loop into the adoption of home storage systems and other sustainable choices. Especially communities that strive for energy autonomy or independence from the grid reduce grid congestion, even if they do not actively offer flexibility to the grid (see reinforcing feedback loop on the right in Figure 5). Secondly, energy communities are found to be more accepted and supported by local citizens (Hogan et al., 2022; Jobert et al., 2007; Musall et al., 2011; Rogers et al., 2008; Strachan et al., 2015; Warren and McFadyen, 2010), which can in turn influence broader socio-political acceptance. While energy communities might face equal pushback from incumbent utilities, this increased community and socio-political acceptance might also buffer against this.

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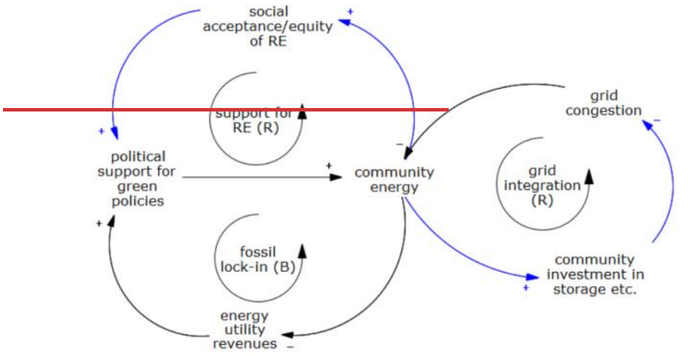

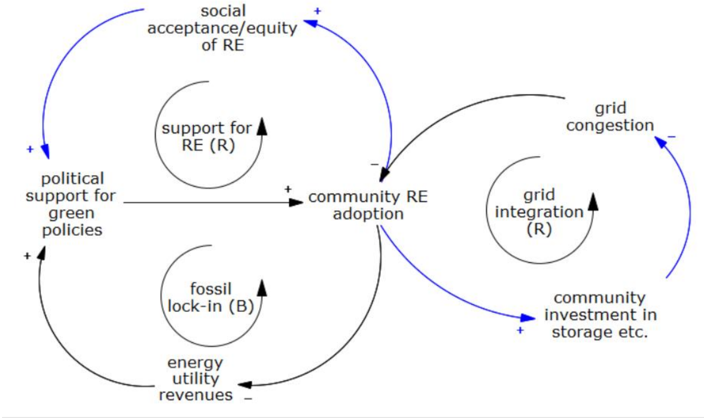

Fig. 6~~5~~. Energy communities can turn balancing feedbacks into reinforcing feedbacks for RE adoption. Blue arrows indicate new mechanisms arising from the institutional context of renewable energy.

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Embracing community values and norms can also function as an external incentive for behaviour change and can increase the adoption rate of sustainable practices (Smith. et al. 2020, Manfredo et al., 2017). The rise of community energy within western Europe is an example of embedding sustainable behaviour within the existing motivation mechanisms of individuals. Where within the former fossil-fuel-based centralised energy systems were aimed at pursuing energy security (i.e., achieving affordable, available, acceptable and accessible energy for all members of society Cherp & Jewell (2014)), the technological innovation of affordable small-scale technologies could suddenly fulfil the existing desires and demands for democracy, autarky, justice and social cohesion (Brown et al. 2020, van de Poel & Taebi 2022). Once new behaviour is adopted, the engagement in such energy community practices can lead to a positive feedback loop between sustainable behaviour (Sloot et al. 2018) and the prioritisation of ecosystem system conservation-related values (Radke et al. 2022)~~.~~.

Energy communities are forms of grassroots innovation originating from bottom-up processes (Doci et al. 2015, Vries et al. 2016). People decide to join a community either for self-interests but also because of social cohesion and sense of community (Albinsson & Perera 2012). In order to maintain long-term stability, strong motivation is often required by key project leaders. Shared social norms, values, trust, and collaboration among members also contribute to this attempt (Schoor & Scholtens 2015). This often creates challenges when communities grow in size (Barnes et al. 2022)~~-~~. By increasing in size, an energy community becomes too large to be smoothly organised and managed, leading also to business models that deviate from the original idea of polycentricity and equity (Blasch et al. 2021, Anfinson et al. 2023).

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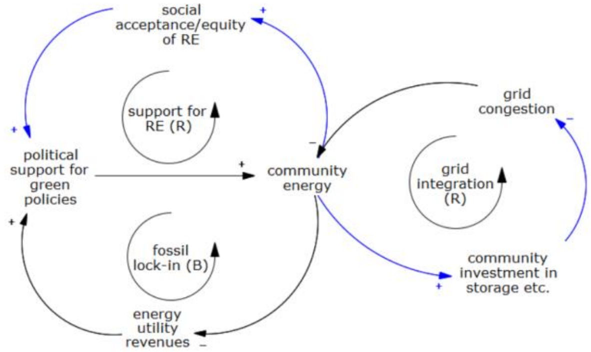
Together with socio-environmental motivations, the economic component ~~Financial constraints is~~ is among ~~one of~~ the main factors increasing the willingness to participate in an energy community (Heuninckx et al. 2022). For instance, buying independently a home storage system may be a very expensive investment for some households, becoming ~~may evaluate the initial investment to buy a home storage system as~~ not affordable. ~~.~~ In these situations, S~~s~~haring practices in energy communities may become crucial ~~in energy communities~~ as they enhance affordability and access to essential goods and services (Watson 2004). The demand for privately owned goods leads to inefficient consumption and excessive production (Baudrillard 2016, Frenken & Schor 2017), contradicting the United Nations' Sustainable Development Goal number 12, which emphasises doing more with fewer resources. Instead, participation into an energy community can help transitioning from individual to shared ownership and consumption of goods, thereby enabling sustainable consumption while also increasing empowerment, reciprocity and energy democracy (Pasimeni 2021, Dudka et al. 2023, Ivanova &Buchs 2023). Moreover, studies have demonstrated that shared ownership decreases the demand for individually owned goods, creating a positive feedback loop where changes in demand (but not reduction) prompt corresponding adjustments in the supply side (Pasimeni & Ciarli 2023). For instance, when participation in an energy community motivates people to share also (electric) vehicles this will result in using fewer cars, reducing production and the overall environmental impact (Nematchoua et al. 2021, Belmar et al. 2023).



~~Fig. 6. Energy communities can turn balancing feedbacks into reinforcing feedbacks for RE adoption.~~

To summarise, energy communities are in line with sustainable goals and targets, while also addressing economic considerations for households facing financial constraints. Moreover, as energy communities have the potential to expand into providing other sustainable goods and services, they align with the sufficiency logic (Thomas et al. 2019) and polycentric systems of governance (Ostrom 2010). These communities, especially those aiming for complete autonomy from centralised energy systems, operate differently from traditional market-based organisations. Communities operate outside the dynamics driven solely by price concerns and instead prioritise energy independence, social cohesion, and community well-being (Hasanov & Zuidema 2018). This approach may lead to more sustainable lifestyles and an overall reduction in fossil fuel consumption, although it remains uncertain whether energy communities will also result in a decrease in overall energy consumption.

~~6.~~ 4. Discussion and Conclusions

~~The tipping dynamics in wind and solar create the potential for a further scaling up through the energy systems. These most likely start with *shift* actions and the adoption of household scale batteries and heat pumps. Key enablers are strong regulations incentivising reductions in demand and setting minimum efficiency levels for buildings and appliances. While there is evidence of spillovers to more environmentally friendly behaviour, the extent of these spillovers and the key leverage points present a knowledge gap. Moreover, these behavioural feedback loops require strong additional policy support to 'make them stick'. Energy communities provide an attractive, fast-growing niche that fosters further upscaling of these tipping points. With a commitment to the further diffusion of renewable energy technologies, but a fundamentally different set of goals and operating principles compared to incumbent actors, they present a high-impact leverage point.~~

The tipping dynamics observed in the wind and solar power sectors have the potential to trigger cascading effects throughout energy demand sectors, including household energy consumption. This transformative process is likely to start with shift actions, such as the adoption of household scale batteries and heat pumps, thereby enhancing less energy-intensive lifestyles. These actions will modify energy demand and improve energy service efficiency, which are instrumental in accelerating the decarbonisation of our energy system.

Nevertheless, a strong regulatory framework is crucial to the speed of this transition as it can incentivise reductions in energy demand and set minimum efficiency standards for buildings and appliances. By doing so, regulation becomes key enabler of positive tipping points in the adoption of novel technologies and behaviours, facilitating the shift to more sustainable practices.

Although spillover effects are observed, as adoption of environmentally friendly behaviours seems to increase, a substantial knowledge gap exists. Specifically, it is important to understand the extent of these spillovers and the key leverage points. Research efforts must be dedicated to shedding light on the connections between individual actions and systemic change.

Moreover, behavioural feedback loops, once identified, require policy support to "make them stick". Strengthening the connection between individual choices and institutional reforms requires effort to bridge effectively these two levels of influence.

In this complex landscape, energy communities emerge as an attractive and rapidly growing niche. Communities are likely to boost widespread adoption of renewable energy technologies, and have fundamentally different goals and operating principles compared to incumbent actors locked-in the centralised energy system. Energy communities are therefore high-impact leverage points, capable of catalysing significant changes in the energy landscape.

By looking deeper into the dynamics of renewable energy adoption and behavioural shifts, it becomes clear that bridging the gap between ~~individual actions~~tipping dynamics and institutional reforms is pivotal to unlocking the full potential of sustainable energy systems. This can be addressed at several scales. For example, the relationship between community energy and behavioural tipping dynamics and spillovers is one potential area of future investigation. Furthermore, we can also ask how community energy as a social innovation can cascade upwards and tip higher level or coupled systems.

~~By embracing this synergy, enforcing strong regulations and minimum efficiency standards, and researching on spillovers and behavioural feedback loops, the transition toward a more sustainable and decarbonised energy future will be faster.~~

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Competing interests The contact author has declared that none of the authors has any competing interests

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