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Social tipping dynamics in the energy system

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Abstract. The fast growth in renewables has led to an economic tipping point for the adoption of renewables. However, we do not observe a corresponding reduction in fossil fuel demand. The tipping point has not led to a system-wide energy transition. This paper reviews how the cost tipping point in renewables can initiate other social tipping dynamics in the energy transition and it presents 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 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 the transition to more sustainable socio-technical systems (Otto et al., 2020). Social tipping dynamics occur when a small change or intervention in the socio-economic system has a large effect on emission reductions (Milkoreit et al., 2018). The solar energy sector in Germany presents a prominent example: when strong public, policy and industry 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. This 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).

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 firms and individuals can have great 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 energy 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. This, in turn, leads to economies of scale, further reducing costs and creating positive feedback loops that drive even more installations. In economic terms, the tipping point is reached 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. Examples 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.

As a result, the fast growth in renewables has not led to a corresponding decrease in demand for fossil fuels. As the energy transition requires a system-level transformation of the energy system, 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.

This paper examines these feedbacks and focuses on the question: How can the fast growth in renewables start system-wide tipping cascades that accelerate the energy transition? To this end, we first discuss the current understanding of energy transition in Section 2 and potential feedbacks in Section 3. Section 4 then discusses how the fast growth in renewable electricity supply may initiate further tipping processes. Section 5 then explores energy communities as an area where modularity is creating reinforcing feedbacks and where balancing feedbacks are weak or absent. Finally, section 6 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 vs. men, upper class vs. 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. Fast growth in renewable electricity supply drives social tipping in the energy system

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, making them cheaper than fossil generation.

For wind and solar energy generation, the main reinforcing feedback 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). Moreover, markets are still expanding as performance improvements 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. The increasing attention for floating solar illustrates this (Gonzalez-Sanchez et al. 2021, Jin et al. 2023), as well as the integration of wind technologies into the generation process of "green" hydrogen.

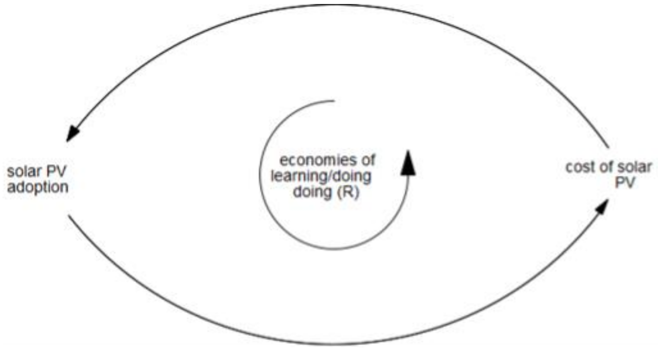

Figure 1: The simplified/stylized main feedback loop in solar energy

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).

Another positive feedback loop stems from policy interactions, whereby policy creates legitimacy and new interests, leading to increased lobbying and support for policy (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). 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).

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).

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

In end-use sectors, decarbonisation of the energy system can be further accelerated by tipping dynamics in wind and solar since electrification of the energy 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 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. 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. 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 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. But, barriers are 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).

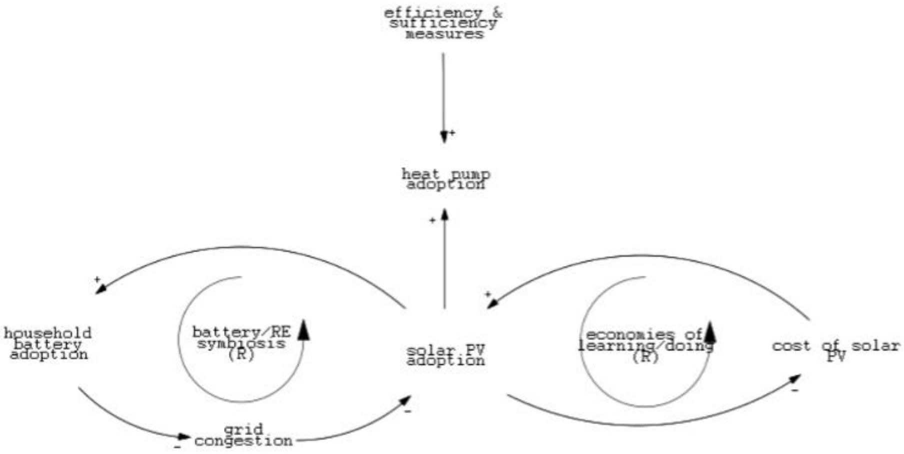

Figure 2: Feedback loop in electrification of heating & cooling

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 improve refers to 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.

More generally, the different 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).

Avoid options reduce unnecessary energy consumption. Changes in the energy behaviour 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 induced demand reductions lead to a higher budget and more energy demand (Newell et al. 2021, van den Bergh 2011, Sorrell et al. 2020). Further, 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).

Digitalisation 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.

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 to 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).

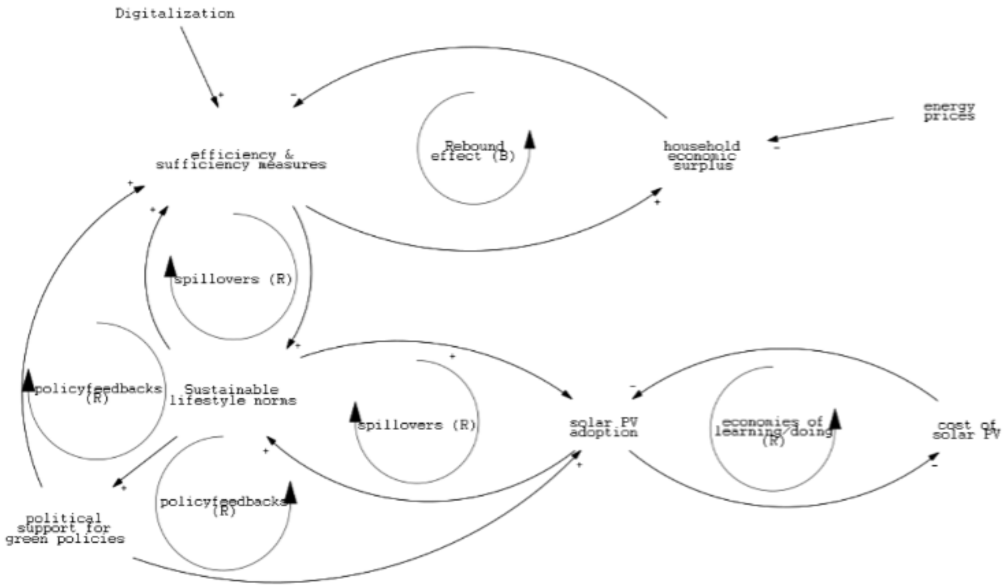

Figure 3: Feedback processes in reducing energy demand

Social 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. 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, 2017). For the energy transition, similar dynamics can potentially be found with the renewables industry. Furthermore, 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, 2002, 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.

5. 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 to tipping cascades. Or in system dynamics terms, the dynamics remain restricted to low level leverage points (Meadows, 2008). This section explores energy communities as an environment where the reinforcing feedbacks are strengthened and the balancing feedbacks are reduced.

Many energy communities take the form of renewable energy cooperatives 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, 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 main objective for example to reduce dependence on the centralised energy infrastructure while also taking advantage of the

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possibility to produce, consume and sell back to the grid the energy produced (Yildiz et al. 2015, Bauwens et al. 2016, Bauwens 2022) 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).
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, energy communities can strengthen the reinforcing feedbacks discussed above, while balancing feedbacks are weak or absent. Their cooperative and legal structures often require that any profits are re-invested in the community, further stimulating investment in clean energy technologies. 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.

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).

Financial constraints is one of the main factors increasing the willingness to participate in an energy community (Heuninckx et al. 2022). For instance, some households may evaluate the initial investment to buy a home storage system as not affordable, or a given technology may supply energy while above the needs of a household. Sharing practices 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). 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).

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. 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.

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

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