Energy Systems

4.3.1 Energy systems

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Summary

The tipping dynamics in wind and solar power create potential for cascading effects to energy demand sectors, including household energy demand. These most likely start with shift actions and 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 and the key leverage points present a knowledge gap. Moreover, these behavioural feedback loops require strong additional policy support to 'make them stick'.

Key messages

- For many countries the power sector has recently passed a tipping point in which the declining price of renewable electricity supply is reinforcing exponential growth, with over 80 per cent of new electricity generation in 2022 being solar and wind.
- Fast growth and declining price in renewable electricity supply is driving social tipping in the electricity system, as shown in the uptake of EVs, PV or heat pump systems and interactions between them.
- Reducing energy demand by identifying options to avoid energy-intensive activities, shifting to less energy-intensive activities and improving energy service efficiency can accelerate decarbonisation of the energy system.

Recommendations

- Further foster clean energy technology development and diffusion worldwide, especially in emerging markets.
- Enable positive tipping points in the adoption of novel technologies (shift and improve) and behaviours (avoid) with strong regulations that incentivise demand reductions.
- Set minimum efficiency levels for buildings and appliances.
- Encourage much-needed research on evidence of spillovers from one to more environmentally friendly behaviours and how to enable such spillovers.
- Implement strong additional policy support for behavioural feedback loops to 'make them stick'.

4.3.1.1 Introduction

The goal of energy systems is to provide energy services to end users. The main energy uses are for heat and electricity in industry and buildings and for transport (4.3.2). The industrial, residential and transport sectors together account for 70 per cent of the total global electricity consumption in 2019, and these sectors also are responsible for approximately 60 per cent of the worldwide carbon dioxide (CO_2) emissions (IEA, 2021a, IEA, 2023a). The decarbonisation of the energy system is a key driver of overall decarbonisation efforts. Energy systems are socio-technical systems; they consist of the technologies that generate energy and convert and deliver this energy to end users, but also of the actors and institutions that perform and govern these tasks. Within energy systems, the subsystems that can undergo tipping dynamics can be found in technologies, but also in social systems when actors and institutions change demand patterns (Geels, 2023).

Most consideration of tipping dynamics in energy systems concerns the price performance of different technologies (Otto et al., 2020; Sharpe and Lenton, 2021; Meldrum et al., 2023). Cost-parity has been reached and exceeded in many regions in a 'new-for-new' comparison of energy generation from wind and solar, versus incumbent fossil fuel generation, with the majority of new installed capacity in 2022 being renewable (IEA, 2022a; IRENA, 2023). In OECD countries, the resulting fast growth in wind and solar generation capacity has led to a reduction in fossil fuel demand in the electricity production, but not globally, as other nations increased fossil fuel demand (IEA, 2021b; OurWorldInData, 2022). Renewable energy generation sometimes faces curtailment and the mismatch of renewable supply with energy demand slows down replacement of fossil fuels, which benefit from their incumbent position. This shows that economic tipping points alone are not sufficient to realise rapid decarbonisation. Below, we explore how the tipping dynamics in wind and solar technology may initiate further positive tipping in the energy system, and we touch upon what this means for coal-intensive regions (Box 4.3.2) and we investigate advances relevant for industry (Box 4.3.2).

4.3.1.2 Fast growth in renewable electricity supply drives social tipping in the energy system

Cost reductions in renewable generation technologies like wind energy and solar photovoltaics (PV) have been much faster than predicted. Renewables are now among the cheapest electricity generation options (Haegel et al., 2019; IRENA, 2022a; IRENA, 2022b).

For wind and solar energy generation, the main reinforcing feedbacks that created these tipping dynamics are cost reduction and performance improvements through investment in research and development, learning-by-doing and economies of scale, leading to more deployment and, in turn, to more learning and price reduction.

(Sharpe and Lenton 2022; Kavlak et al., 2018, Nemet and Greene, 2022). The German feed-in tariff for renewables discussed in 4.2.1 was historically an enabling condition for a positive tipping point in the solar PV sector (Otto et al., 2020; Clark et al., 2021). 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. The exponential growth of offshore wind power in the North Sea (Drummond et al., 2021; Geels and Ayoub, 2023) and the increasing attention for floating solar (Karimirad et al., 2021; Pouran et al., 2022) illustrates this. Renewable energy generation coupled with battery storage is expected to reach cost parity compared to power generation from natural gas in the near future, if it has not done so already (Meldrum et al., 2023), as battery costs are driven down by the growing electric vehicle industry, further enhancing the competitiveness of renewables with fossil fuels.

The cost-performance feedback loop is the main, but not the only, feedback driving the tipping dynamics for wind and solar. For instance, there is evidence for social contagion in the diffusion of rooftop solar PV, which is typically clustered in space where people are more likely to adopt when people nearby also have adopted (Graziano and Gillingham, 2015; van der Kam et al., 2018). This suggests that their diffusion is partly a social process influenced by, for example, **observability**, **trialability**, and **word-of-mouth** (Rogers, 2003) and **social comparison** (Bergquist et al., 2023).

Another reinforcing feedback loop stems from policy interactions, whereby policy creates legitimacy and new interests, leading to increased lobbying and support for policy (Roberts et al., 2018; Meckling, 2019; Rosenbloom et al., 2019; Sewerin et al., 2020). Further, strong pro-environment policies may incentivise firms towards more RandD 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 creating goals and strategies for a more sustainable society (Geels and Ayoub, 2023).

Sources of dampening feedbacks, lock-in and path-dependence of fossil fuel-based energy systems include energy infrastructures, technologies and institutions (Köhler et al., 2019). These can directly hinder the decarbonisation of the energy system through existing standards and resistance from incumbents and vested interests. 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 require policy attention to stimulate the move of capital from fossil to renewables (Pauw et al, 2022, 4.4.4). As an example, in the early 2000s, the 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 lead to reinforcing feedbacks but may also create dampening feedbacks when they mobilise opposition and a lack of societal support for larger-scale solar and onshore wind farms (Devine-Wright, 2007; Klok et al., 2023; Windemer, 2023). Cost-competitiveness is not a sufficient indicator to predict support for technologies for which the main public concerns are about spatial/visual impacts, health and safety, and questions of fairness.

Policy for positive social tipping can seek to strengthen reinforcing feedbacks and reduce dampening feedbacks. The policy-relevant timescales of the energy system vary from months to decades. 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. In contrast, some demand-side behaviour changes are quite swift. An example is the substantial energy demand reduction in Europe in the winter 2022/2023, resulting from concerns about high energy prices and the war in Ukraine. A key policy challenge is how to make the new behaviour 'stick'.

4.3.1.3 Positive tipping dynamics that build on the fast growth in wind and solar technologies and services

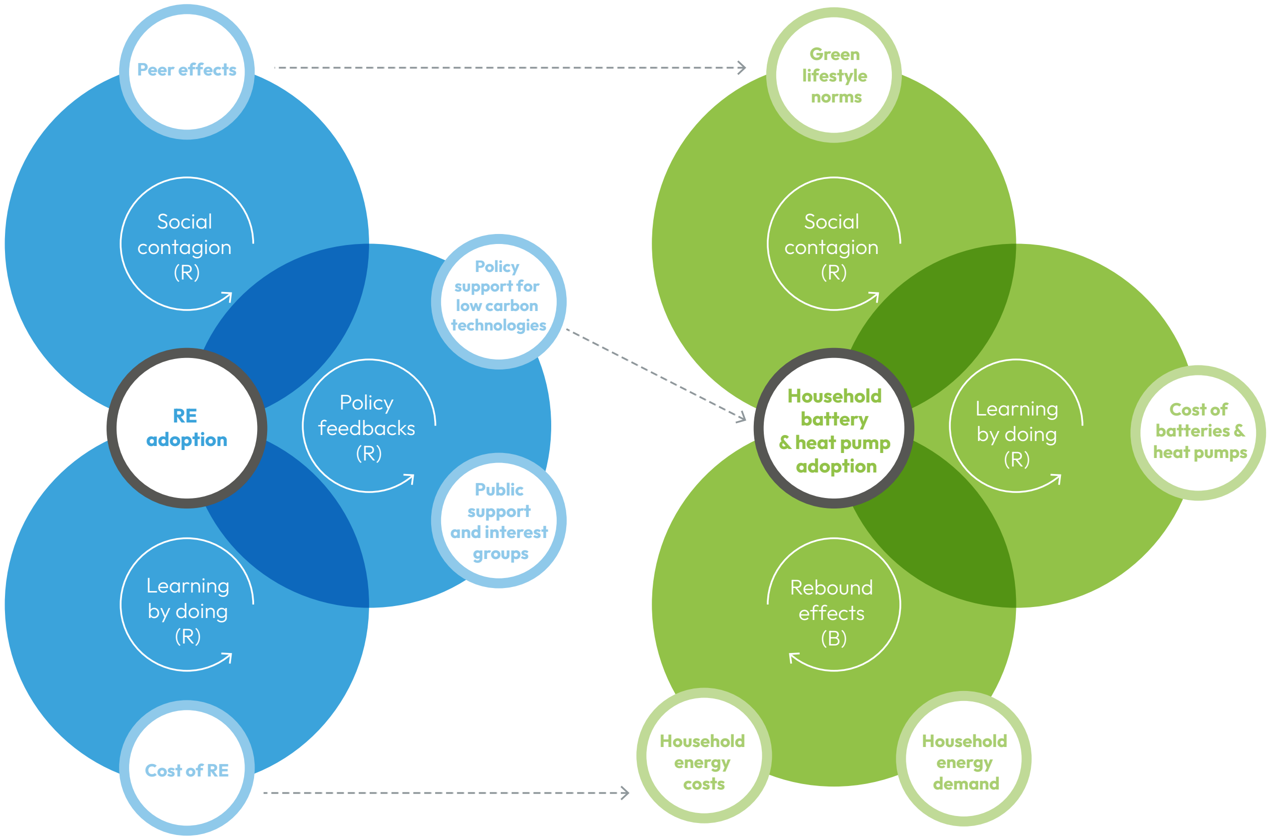

Figure 4.3.2: Cascading effects from renewable energy supply to household energy demand. The feedbacks that led to the strong growth in distributed renewable energy supply, can also strengthen the feedbacks that help reduce household energy demand when policy support is in place. R = reinforcing feedback, B = balancing/dampening feedback.

Two further significant developments are needed to transform the energy system. Firstly, while for many regions renewable energy potential exceeds demand, a fast energy transition faces constraints regarding the availability and sustainable sourcing of materials and personnel (Wang et al., 2023). Most scenarios therefore envision a reduction of demand where the demand for energy should be brought in line with what can be sustainably produced in the short term. Indeed, reducing energy demand is key in 1.5°C pathways (Koide et al., 2021). Reduction in energy use is thus widely regarded as a key pillar of decarbonisation in wealthy countries. At the same time, 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 wellbeing (IPCC, 2022a). Although we observe a decoupling of energy demand and income in some places, in general household energy demand grows with income. Pro-environmental attitudes and behaviour have also been correlated with income, further complicating the challenge of how to reduce income inequality and material and energy consumption to sustainable sufficiency levels (Du et al., 2022). Moreover, individuals with high socio-economic status (top 10 per cent) are responsible for a large share of emissions (IPCC, 2022b; IEA, 2021b). These individuals could have a large positive impact when they reduce GHG emissions, becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies (Creutzig, et al., 2022). Such approaches are also discussed in the context of energy justice and equitable energy demand reduction (Büchs et al., 2023).

Second, when no low-cost zero-emission energy sources, like waste heat, are available, the energy system should electrify. In addition, but beyond the scope of this section, attractive technological alternatives like green hydrogen should be developed for hard-to-electrify demand (4.3.2).

To identify possible tipping dynamics and tipping elements in energy systems, we follow the avoid, shift, improve (ASI) logic (Creutzig et al., 2022, 4.3.1). While improve options are not sufficient to tip the energy system to a decarbonised state, they are an important enabler for options that can. Moreover, they may have important health co-benefits and reduce the material needs of the energy system. 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.

Avoid options reduce unnecessary energy consumption. Changes in the energy behaviour of individuals can make a large contribution, specifically when supported by changes in the broader socio-technical system ranging from subsidies to norms for energy-efficient housing to educational and information campaigns (Nisa et al., 2019; Niamir et al., 2020). More specifically, 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 (Richmond and Kaufmann, 2006), 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). While there is some empirical evidence for such a rebound effect (Berner et al., 2022; Brockway et al., 2021; Stern, 2020) – making decoupling of energy demand more difficult – decoupling has been observed in several Organisation for Economic Co-operation and Development (OECD) countries in recent years.

Digitalisation and AI can play a key role in avoiding unnecessary energy demand (Wilson et al., 2020; Giotitsas et al., 2022., see 4.4.4). 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 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 prevent curtailments and grid congestion (load shifting and balancing) but have not yet reached widespread diffusion.

Higher prices (and temperatures) lead to reduced energy demand for heating. Natural gas consumption in the EU and in the period August-November 2022 decreased by 20 per cent compared to the average gas consumption for the same months in the previous five years (Eurostat, 2022). However, this also came with increased levels of energy poverty, particularly affecting low-income households in badly insulated homes (IEA, 2023b). Interestingly the high prices also triggered and opened the opportunity for sufficiency-based energy price interventions in the form of price ceilings for gas and electricity in response to the energy crises in the winter of 2022-2023.

When the demand reductions stem from changes in norms or behaviours with a sustainability motive, the risks of rebound effects are lower. Interestingly, **pro-environmental behaviours also induce other pro-environmental behaviours**, so changes in behaviour in mobility or food may spill over to energy behaviours (Steg and Vlek, 2009; Steg, 2023). The adoption of household PV for environmental reasons may thus induce other pro-environmental behaviours. As an example, evidence for Austria shows that the adoption of PV and electric vehicles are correlated (Cohen et al., 2019). 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 (Poortinga et al., 2020).However, there is also evidence that these spillover effects are insufficient for the substantial lifestyle changes that are needed (Thøgersen and Crompton 2009; Truelove et al., 2016).

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 (Göckertiz, 2010; Allcot, 2011; Horne and Kennedy, 2017; Bonan, 2020). A key takeaway from these studies is that a relatively weak form of sanctioning (e.g., approval and disapproval of particular behaviour by using thumbs 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).

If avoiding energy use is undesirable from a wellbeing perspective, then shifting the way this activity is done (or finding an alternative means to the same goal) is key. For electricity use, the decarbonisation of the energy system, driven by the cost reductions in wind and solar, is a large driver. Such reductions are more likely in smaller and more modular technologies (Wilson et al., 2020). Other small and modular technologies that may reach cost parity in the short term are 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 tariffs for energy from the grid (4.5.2).

The large-scale adoption of household batteries may influence the decarbonisation of the energy system in two ways: first, it reduces curtailment of household PV generation, better matching renewable energy supply with demand. Second, it reduces grid congestion during peaks in solar generation. Currently, in several countries, this congestion is a barrier to further grid integration of renewables. To stimulate demand to synchronise with the availability of renewable energy supply, utilities are offering dynamic tariffs that discriminate between time of use and sometimes also location of use (Nicolson et al., 2018; Freier and Loessl, 2022). These developments then further improve the attractiveness of household batteries.

The electrification of heating is a second technology that benefits from the fast decarbonisation of the electricity supply. For heat demand, which is often met by natural gas boilers (based on IEA, 2022b analysis, natural gas accounts for 42 per cent of global heating energy demand, with a 40 per cent share of the heating mix in the European Union and over 60 per cent in the US), the shift to low-carbon heat sources requires changes in technologies and infrastructure in houses, commercial buildings and neighbourhoods. 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.

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, the cumbersome installation process, and the high upfront installation costs. Supported by regulation and policy incentives, the demand for heat pumps is increasing fast in several countries (IEA, 2022c), providing further opportunities for cost and performance improvements through learning by doing. 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 cascading effect described above can contribute to energy demand reduction in rich countries. The declining cost of solar has also led to the development of solar home systems for energy-poor areas in the Global South, where off-grid solar technologies are estimated to be the least costly and most viable way to electrify the majority of those who lack access to electricity (IEA1, IEA2). Reliable access to electricity can unlock a cascade of benefits including access to cooking, cooling or heating, refrigeration for storing foods and medicines, lighting, power for agriculture, irrigation and other economic activities, and access to communications, banking and information. It plays a critical role in healthcare, sanitation and resilient livelihoods (PIDG report). A key barrier for enabling widespread deployment of solar power in the Global South is the high cost of capital in these economies – however, threshold and network effects in financial systems exist which could unlock investment (4.4.3.4). While in many of these countries the potential for solar energy, and for such systems to contribute to wellbeing, is large, the way they are packaged can fail to fit with local needs (Groenewoudt et al., 2020). Learning-by-doing is likely to play a key role in accelerating deployment, alongside continued support by international policy and investment to realise the potential benefits of solar at scale and develop local energy markets.

Box 4.3.1 Just energy transitions – tipping in coal- and carbon-intensive regions?

The socioeconomic transitions of coal- and carbon-intensive regions have raised concern for just transitions focusing on labour market opportunities. Essen and Duisburg in the German Ruhr Region, for example, have advanced in this transition process (>30 years) in different ways. Both cities experienced incremental changes in their demographic, economic and political trajectories. We can also identify a bifurcation in the cities' visions and their narrative development: Essen envisions a green, sustainable future, whereas Duisburg remains devoted to its industrial storyline. Neither of the cities have crossed a tipping point in the hard quantitative indicators (e.g. unemployment rate, GDP) yet the narrative change may indicate a significant and qualitative shift in the long term: if the cities embark on different trajectories now, this will likely result in stronger social and economic differences in the future. Maybe seen from a few decades into the future, the period around 2020 can be identified as a tipping period in one or both cities.

Successful examples exist where renewable energy stepped in when the fossil fuel industry declined. In Denmark, Esbjerg was a major port for the oil and gas industry. It was specifically targeted by the Danish Government to be a major beneficiary of the new offshore wind sector. Today, one in nine jobs (5,000 in total) in Esbjerg is related to wind power. The town received dedicated policy support for just transition which can be replicated elsewhere. Offshore wind has been revitalising communities in the North East of England that were left behind when coal mines closed in the 1980s. Offshore wind development now offers high-skill level jobs and opportunities for economic development and export-oriented local supply chains through investment in local facilities and communities. The UK is the largest off-shore wind power market in Europe. For just energy transitions benefiting communities, local value-creation will be key.

Box 4.3.2 Decarbonising the steel sector

The global steel industry is responsible for 7 per cent of greenhouse gas emissions (OurWorldinData, 2023) and needs to decarbonise quickly, by adopting low-carbon technologies instead of blast furnaces. Three scales are relevant here: the whole global steel industry, individual steel companies, and their specific production facilities. The ultimate goal is to see a tipping point at the global scale, which means a significant decrease in emissions across the industry. This will only happen when specific companies or facilities tip first. When some pioneering companies decide to switch to low-carbon technologies, it could set off a chain reaction. Currently, 11 full-scale green hydrogen DRI steel plants are planned to be operational by 2030, and once around 6 per cent of steel plants make this change, the prices of these technologies is expected to drop, making them more accessible to others, and emissions will start to decrease. Carbon pricing or equivalent subsidy can accelerate the point at which green steel becomes competitive with fossil fuel-based production (Meldrum et al., 2023). This process takes time, but it is crucial for the long-term goal.

How to trigger tipping points at the individual company level is the more urgent concern, in order to enable this wider tipping point. This happens when a company decides to commit to a net-zero pathway by using low-carbon technologies instead of fossil-based practices. The evidence for a potential tipping point is even stronger when the decision is backed by concrete plans for technology implementation and investment in new infrastructure.

One example is voestalpine, an Austrian steelmaker that decided to reduce emissions by replacing parts of its blast furnace process with green hydrogen-based direct reduction and electric arc furnaces (voestalpine, 2023a). This move shows the beginning of a positive feedback loop, pushing the company further along the path to net-zero emissions when new technologies become more common.

Political and economic factors also play a role. EU and national policies, such as the emission trading system, put pressure on companies to reduce emissions. When customers demand low-carbon steel products, it drives innovation and motivates steelmakers to provide more low-carbon options. These factors can trigger tipping, pushing the industry closer to the net-zero goal.

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Chapter Reference 4.3: Positive tipping points in energy, transport and food systems

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