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The importance of tipping points for sustainable development*

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Abstract

Solving major sustainability problems such as climate change and the loss of biodiversity requires overcoming a fundamental dilemma: on the one hand, central decisions on the realignment of the economy and society should be quick and far-reaching, on the other hand, actual decision-makers are strongly oriented towards established structures, which entail great inertia and path dependencies. As a result, expectations and reality are often still far apart in sustainability policy. Tipping processes can play a decisive role in closing this gap and generally describe a non-linear and self-sustaining dynamic which can be triggered when a critical threshold (a tipping point) is crossed. The targeted promotion of crossing important thresholds can thus become a successful strategy for sustainability policy. In this paper, we highlight the importance and limitations of tipping dynamics in promoting sustainability. We develop an integrative formal approach to illustrate the characteristics of tipping dynamics in nature, technology, politics, society and the economy, and deepen the discussion using two case studies from economic history. Finally, we discuss implications for research, policy and institutions.

Keywords: Tipping point, sustainability, climate policies, non-linear development

JEL Classification: Q54, Q55, Q56, O35

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1 Sustainability of development

Sustainability aims to achieve a balance between the needs of current and future generations (Brundtland, 1987). In view of the major ecological challenges of today, long-term thinking and action requires a departure from past developments in important areas such as mobility, energy and infrastructure (IPCC, 2023). However, in most historical phases, economic and social development have been strongly path-dependent, which means that the existing structures shaped the subsequent development, for example through previous investments in R&D, the size of established markets, economies of scale or acquired habits ("lock-in" effects, see e.g. Aghion et al., 2016, Barnes et al., 2004 and Arthur, 1989).

One manifestation of this path dependency is that fossil-based technologies have been able to establish themselves on the market for decades despite their known ecological disadvantages, so that today's production systems are highly dependent on fossil fuels as inputs — a situation known as "carbon lock-in" (see e.g. Seto et al., 2016; Unruh, 2002 and Unruh, 2000). In doing so, fossil energies benefit from technological and institutional economies of scale, which have so far severely hampered the spread of low-emission technologies (Klitkou et al., 2015; Foxon, 2002). Fossil fuels are still the main source of energy for power generation around the world. They are needed for the production of steel, cement, chemicals and other goods and will continue to dominate international transportation for the foreseeable future (IPCC, 2023). While low-carbon technologies are increasingly available and economically attractive, they still have shortcomings in certain areas that prevent them from competing with established technologies (Lazard, 2023).[1]

These forces of inertia are amplified by the fact that a large proportion of the existing capital and infrastructure stock was designed for the use of fossil fuels, involving long-lived assets and facilities with high initial investments and the expectation of a long and profitable lifespan. A rapid decarbonization of the economy results in a negative revaluation of existing facalities and the corresponding assets by the market ("asset stranding") as well as in a reduction in capacity utilization (see e.g. Bretschger & Soretz, 2022, Kalkuhl et al., 2020, Rozenberg et al., 2020, and McKibben, 2012).[2] A rapid reorientation of production and consumption is therefore not generally in the interests of individual companies and households, even if it is beneficial for the economy as a whole.

Achieving important sustainability goals such as preserving biodiversity or limiting global warming to significantly less than two degrees Celsius will require fundamental

[1]In particular, the intermittent nature of renewable energy sources, like solar and wind power, poses a significant challenge as it requires reliable energy storage and backup systems to ensure a consistent power supply that aligns with energy demand, see e.g. Ambec & Crampes (2019).

[2]Assets are considered "stranded" if they suffer from unforeseen or premature depreciation, devaluation or conversion into liabilities (McKibben, 2012).

socio-economic changes and a drastic acceleration in technological progress ("disruptive" system changes, see e.g. Sharpe & Lenton, 2021, Lenton, 2020 and Otto et al., 2020). However, technological, economic and behavioral lock-ins hinder a rapid change in current development trajectories, leading to path dependencies and inertia. In addition, due to the rigidities inherent in political and economic decision-making processes, major changes are naturally difficult to plan and even more difficult to implement in a democratic process. On the bright side, there is increasing evidence from various scientific fields that complex systems can undergo disruptive system changes under certain conditions (see e.g. Lenton et al., 2022; Otto et al., 2020; Zeppini et al., 2014). For this reason, the non-linear mechanisms behind such disruptive system changes are receiving rapidly increasing attention in the scientific community (see e.g. Lenton et al., 2022; Winkelmann et al., 2022; Sharpe & Lenton, 2021; Andreoni et al., 2021; Wunderling et al., 2021; Lenton, 2020; Otto et al., 2020; Milkoreit et al., 2018 and Tàbara et al., 2018).

Building on this strand of literature, we use the concept of "tipping dynamics" as an analytical framework to study abrupt changes in established structures. Such dynamics are characterized by non-linearity and can be triggered when a tipping point is crossed. Tipping points are critical thresholds at which small changes can trigger a non-linear and self-sustaining dynamic that accelerates systemic change (Lenton et al., 2022). Near a tipping point, a small perturbation can cause a large response in the system and shift it into a qualitatively different state (Lenton, 2020).[3] A decisive factor for the occurrence of tipping points is the existence of reinforcing (positive and negative) feedback effects, which can trigger profound upheavals as a result of small initial changes. Such a highly non-linear reaction is usually difficult to reverse and explains why, for example, a certain belief or technology can develop from a minor trend to the prevailing practice in a very short period of time. New technological achievements can trigger such disruptive processes of change; but also social norms can tip and experience a non-linear development towards a qualitatively different, more sustainable equilibrium.

Tipping points in complex systems entail the risk of sudden, undesirable collapses (e.g. in ecosystems), but also opportunities for sustainability.[4] Since the crossing of tipping points can enable self-sustaining, rapid and desirable changes, the design of policies that promote and facilitate this crossing can have a major impact at moderate economic costs. The targeted promotion of crossing important thresholds can thus become a successful strategy for sustainability policy. Policy makers can consider concrete measures that trigger a positive tipping dynamic in favor of sustainability. One example in the area

[3] Based on an interdisciplinary literature overview on socio-ecological tipping point research, Milkoreit et al. (2018) propose the following common definition: "A tipping point is a threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible."

[4] Some studies question the analogy to physical systems when it comes to tipping points, see e.g. Winkelmann et al. (2022) and Bentley et al. (2014) for a discussion.

of climate policy is the promotion of renewable energies through tariffs, subsidies and mandates, which has enabled them to evolve from niche applications to mass markets. The increasing expansion of renewable energy capacities has led to a significant non-linear system response in the form of an exponential decline in technology costs (Otto et al., 2020; Green, 2019; Kavlak et al., 2018), a development that was consistently underestimated by energy forecasting models (Jaxa-Rozen & Trutnevyte, 2021; Hoekstra et al., 2017).

Kopp et al. (2016) show that the term "tipping point" was already used in the 19th century to describe (mostly technical) tipping dynamics: "The phrase 'tipping point' appears to have originated in industry, where it referred literally to the point at which an engineered system, such as a rail wagon of coal in a Yorkshire foundry (Burnley, 1871) or a cup in a tilting water meter (Hoadley, 1884), tipped over and emptied its contents." The concept became increasingly popular in the early 2000s with the publication of the book "The Tipping Point" by Gladwell (2000), which explores the idea of disruptive processes based on many controversial topics such as fashion trends or the sharp drop in the crime rate in New York City in the 1990s.

The term also gained popularity in climate science at the time and gradually replaced expressions such as "regime change" or "critical transition", which had previously been used to describe disruptive system changes (Kopp et al., 2016). However, representatives of many disciplines, including economics, still predominantly analyze linear processes such as balanced growth instead of tipping dynamics and are thus unable to capture rapid and radical socio-economic changes. We therefore show how central tipping dynamics are for sustainable development, but also point to the limits of human capacities to navigate tipping processes in order to promote sustainability.

In this paper, we develop an integrative model framework to analyze the characteristics of developments with tipping points and then provide an overview of the most important non-linear system dynamics that can occur in the context of sustainability.[5] Besides providing a comprehensive literature review involving a synthesis of established theories and lessons from previous examples, the aim of this paper is to conceptualize tipping dynamics that matter for sustainability using an integrative formal approach. Furthermore, we enrich the existing literature by presenting two case studies from economic history.

This remaining paper is structured as follows. In Section 2, we develop the methodological foundations including the non-linear relationship of important system variables and apply them in Section 3 to the fields of ecology, technology, politics, economy and society. In Section 4, we explore the topic of tipping dynamics in greater depth using two

[5] Based on qualitative review of social tipping point articles, Milkoreit (2023) emphasizes the need to discuss tipping dynamics within a conceptual framework that clearly delineates the relevant system boundaries.

illustrative examples from economic history. Finally, in Section 5, we discuss implications for research, institutions and policy in the presence of tipping processes.

2 Theoretical foundations

In this section, we illustrate the concept of tipping dynamics in a very simple integrative model framework. We consider a stock variable $X_t \geq 0$, which can, for example, have an economic meaning such as man-made physical capital, an ecological meaning such as natural capital or a political meaning such as trust capital. Time is continuous and indexed by t. The dynamics of X_t result from the interaction of two different functions.

Due to the first function, the stock increases with the help of system-inherent forces, such as investments to increase physical capital or regeneration processes to restore natural capital. The corresponding function with the stock as an argument is typically non-linear in the case of tipping dynamics. We illustrate a sigmoid (S-shaped) curve (F-function) in Figures 1a, 1c and 1d and a concave curve with a fixed intercept on the x-axis (H-function) in Figure 1b.[6]

The second function captures the system-typical decline in stocks due to influencing factors such as erosion or degradation and reflects that existing systems, whether social, technological or ecological, are stabilized by dampening feedback effects and resisting forces that counteract an expansion of stocks. The strength of this effect is captured by the constant parameter $\Omega > 0$, which, in the case of capital accumulation, stands for the depreciation rate. For simplicity, we assume this function to be linear in all the figures.

In this framework, the change in X_t also depends on the parameter E, which is determined outside the considered system, for example by politics. The parameter E can represent a permanent shift or a temporary event, i.e. an exogenous shock such as a technological breakthrough, a policy measure or a natural disaster. Using the function F, the stock X_t evolves over time according to

$$\dot{X}_t = F(X_t) - \Omega X_t + E, \tag{1}$$

for given $X_0 > 0$ and with $E \geq 0$ or $E \leq 0$. Figure 1a assumes $E_0 > 0$ and shows that the system has three equilibria, two of which are stable and one is unstable, with the tipping point lying in the middle. If X_t deviates from the tipping point X^T, the stock moves towards a stable equilibrium, i.e., below the tipping point, it moves towards the low equilibrium X^* while above the tipping point towards the high equilibrium X^{**}.[7]

[6] More specifically, these curves belong to the category of convex-concave functions, see e.g., Dasgupta & Mäler (2004) for a more technical discussion. Possible functional forms are e.g. $F(X_t) = \alpha X_t^2/(1+X_t^2)$ and $H(X_t) = (X_t - \bar{X})^\beta$, where $\alpha > 0$ and $\beta \in (0,1)$ denote parameters. However, in order to keep the analysis as general as possible, we abstract from specific functional forms in the remaining discussion.

[7] In our model, the non-linear change refers to the abrupt convergence to a new stable equilibrium when

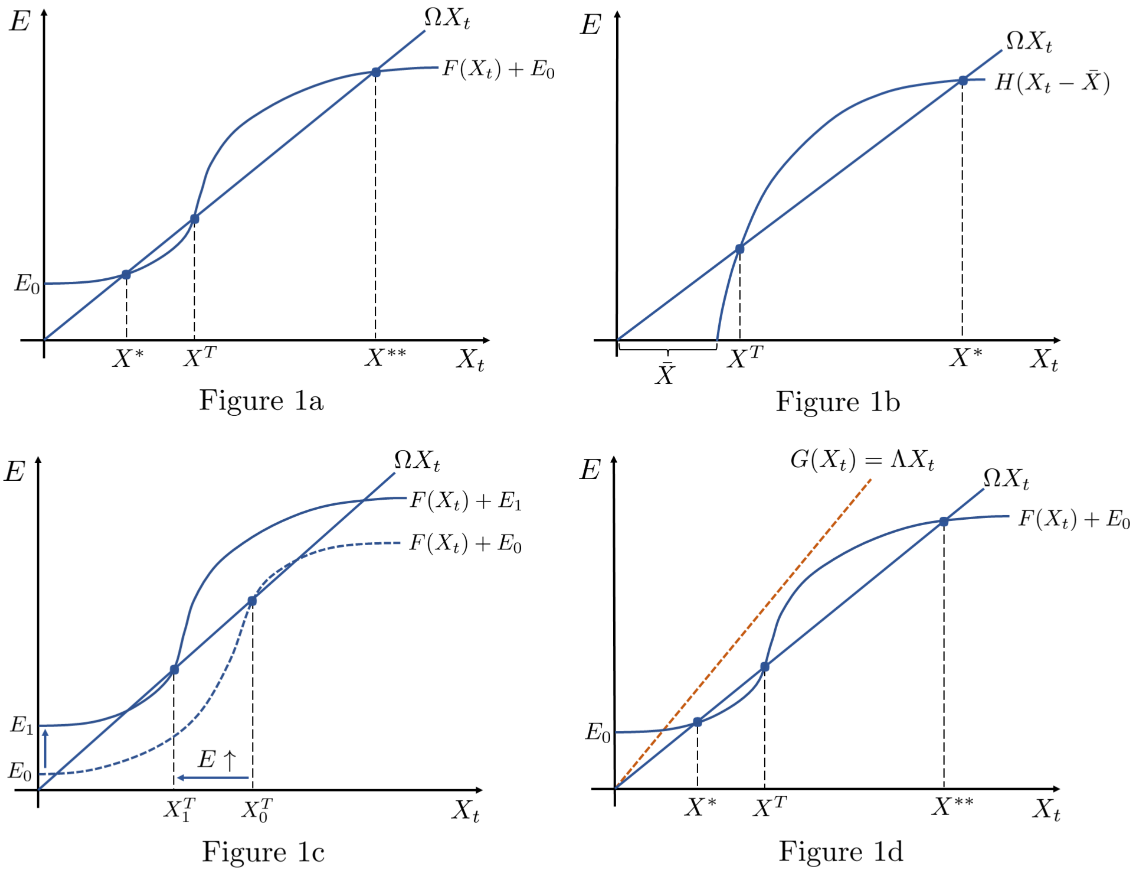

Figure 1: Theoretical model framework

The higher equilibrium is favored by society if X_t has a positive social value, as in the case of the capital stock. However, it can also constitute a non-preferred equilibrium if X_t has a negative impact on society, which is the case, for example, if X_t stands for the accumulated stock of pollution. In the following, we assume that the considered stock variables in the respective application areas have a positive social value, so that the higher equilibrium is preferred by society.

In Figure 1b, we introduce the function H to illustrate an alternative way of modelling non-linear system dynamics. This function has a positive intercept on the horizontal axis, so that X_t can only grow once a minimum stock, for example of capital, has been accumulated. With the function H, the law of motion for the stock X_t reads

$$\dot{X}_t = H(X_t - \bar{X}) - \Omega X_t + E, \tag{2}$$

for given $X_0 > 0$ and with $\bar{X} > 0$ referring to the positive intercept on the abscissa. In Figure 1b we assume that $E = 0$. Due to the fixed intercept, the function H is non-convex, which again leads to multiple equilibria that differ in terms of their stability properties.

the stock X_t passes an unstable equilibrium. It is thus straightforward to check that our framework fulfills the common definition of Milkoreit et al. (2018) and contains all model elements required to represent tipping points.

More precisely, the system has two internal equilibria, an unstable one corresponding to the tipping point (X^T) and a stable one (X^*) to the right of the tipping point. All states of the system below the tipping point cause the stock to collapse, moving it towards zero, which also represents a stable equilibrium.

Whether the function F or H better describes reality in an application area is an empirical question. Analytically, both constellations lead to a tipping dynamic. In principle, we can also analyze systems with a larger number of equilibria, but such an extension does not seem appropriate to convey the basic intuition in an overview article. In Figure 1c, we adopt the situation from Figure 1a and assume that E increases from E_0 to E_1 (e.g., due to a policy intervention), which reduces the tipping point from X_0^T to X_1^T. If E permanently assumes the value shown, the equilibria adjust to new levels; however, if the increase in E represents a temporary shock, the stock X_t might exceed the tipping point temporarily, while the long-term equilibria remain unchanged.

In Figure 1d, we compare the tipping dynamics with the sigmoid function F to the development with the linear function $G(X_t) = \Lambda X_t$, which is frequently used in economic growth theory, e.g. in the form of a balanced growth path. As is typical for linear processes, the system predicts an unlimited increase in X_t at a constant rate if $\Lambda > \Omega$.

3 Tipping points in ecology and society

In this section, we apply our model framework to different areas such as ecology, technology, politics, economy and society.

3.1 Tipping points in nature (ecological tipping)

Many natural systems exhibit non-linear dynamics. Ecosystems can experience a rapid transition to a qualitatively different state when a critical threshold is crossed. The threshold in the form of a critical parameter is the tipping point of the ecosystem. A prominent example is the abrupt transition of a lake from a clear to a turbid state caused by a human-induced accumulation of nutrients in originally nutrient-poor waters. Even if the nutrient load is greatly reduced at a later point in time, the waters often do not recover to their original clear state ("shallow lake" theory, see Scheffer, 2001). Likewise, coral reef systems can transition from a coral-dominated state to an algae-dominated state when the increase in global average temperature or ocean acidification exceeds a critical threshold (Lenton et al., 2019). Abrupt changes in equilibrium states can also occur in (permafrost) soils, oceans and forests (Dasgupta, 2021; Scheffer et al., 2001), all of which also serve as significant global carbon reservoirs, so that their preservation from tipping is important not only for their own sake, but also to prevent negative feedback effects on the climate system (Steffen et al., 2018). In addition, the coronavirus pandemic has revealed to the public that diseases can spread exponentially and remain persistent once an epidemiological threshold has been exceeded (Sims et al., 2016).

As a result of climate change, subsystems of the Earth can be identified as tipping elements that are increasingly threatened by abrupt and irreversible changes (Lenton et al., 2008).[8] Tipping elements with potentially large and irreversible impacts on human and natural systems include the Amazon rainforest, the Arctic sea ice, the Gulf Stream, the forests of the cold-temperate climate zone, the Greenland ice sheet, the Borelaen permafrost soils, the Great Barrier coral reef, the West Antarctic ice sheet and parts of East Antarctica (see e.g. Lenton et al., 2019; Lenton & Ciscar, 2013; Lenton, 2012, 2011 and Lenton et al., 2008). Tipping processes in these systems, such as the melting of the Greenland ice sheet, the dieback of the Amazon rainforest or the collapse of the Atlantic thermohaline circulation, involve a high degree of uncertainty, e.g. with regard to critical thresholds, impacts and possible interactions between the tipping elements (Wunderling et al., 2021), which has implications for optimal policy design and capital accumulation (Van der Ploeg & de Zeeuw, 2018). Using a meta-analytical integrated assessment model, Dietz et al. (2021) show that the inclusion of key tipping elements increases the expected social cost of carbon by 25%. Although the scientific understanding of tipping processes in the climate system has increased in recent years (Wang et al., 2023), the precise identification and quantification of tipping elements is a major challenge and continues to be the subject of intensive research (IPCC, 2023).

To gain a better understanding of the properties of ecological tipping dynamics, we apply the theoretical model framework from Section 2. For this purpose, we consider Figure 1a and 1c, in which the stock varibale X_t reflects the state of the ecosystem and can be interpreted, for example, as natural capital. The use of the sigmoid function F allows us to capture the non-linear dynamics that characterize certain ecosystems. If degeneration of the natural capital stock is sufficiently high so that X_t falls below the critical threshold X^T, the ecosystem abruptly changes its equilibrium state and moves towards the alternative equilibrium X^*. The tipping point thus represents a decisive threshold in the ecosystem; as soon as the stock X_t falls only slightly below this point, a permanent change to a lower ecological level occurs. The parameter E stands for external human influences and determines, among others, the position of the tipping point.[9]

However, ecosystems can also contain various positive feedback mechanisms that increase the stock of natural capital and thus contribute to the regeneration of ecosystems. Human interventions can specifically promote these positive feedback channels in order to trigger tipping processes that restore a preferred ecological state (e.g. for the rapid re-

[8] In Earth system research, a tipping element is a large-scale component of the climate system or, more generally, of the Earth system that can be set into a new state by even minor external influences as soon as it reaches a certain threshold value (IPCC, 2023).

[9] More generally, E denotes human intervention and, unlike the other model elements, we could in principle control it.

covery of a eutrophic lake to a clear water state, see e.g. Mehner et al., 2008 and Scheffer et al., 2001). As shown in Figure 1c, policies that lead to an increase in E can promote ecosystem recovery by allowing the natural capital stock to overcome the (reduced) tipping point X_1^T and to transition to the preferred ecological state X^{**}. Note that enabling positive tipping for the recovery of ecosystems "usually requires a much larger change in a critical control variable than what caused the original, negative tipping point" (Lenton et al., 2022). However, it is important to emphasize that the present model framework is a simplification of reality, the actual dynamics of ecosystems are complex and depend on a variety of factors.

In nature, tipping elements are not independent of each other; complex interactions can exist between them (see e.g. Wunderling et al., 2021; Krönke et al., 2020 and Cai et al., 2016). The possible collapse of the Atlantic Meridional Overturning Circulation (AMOC) due to a tipping of the Greenland ice sheet has been identified as a coupled tipping element in the Earth's climate system (Wunderling et al., 2021). The AMOC, an ocean circulation system that is crucial for global heat distribution, could be weakened or even collapse as a result of the increased inflow of meltwater into the North Atlantic. This could potentially intensify Atlantic cyclone activity and contribute to rising sea levels, which in turn adversely impacts coastal regions (Wunderling et al., 2021). This example illustrates that the tipping probability of a particular tipping element can be influenced by the behavior of other tipping elements.

Consequently, exceeding a critical threshold of a first tipping element can induce a domino effect that triggers a further tipping element or entire "tipping cascades" with several tipping elements (Wunderling et al., 2021). A tipping cascade with interacting climate tipping elements can pose a considerable risk to the economy and society (Brausmann et al., 2022). Taking potential tipping cascades into account increases today's optimal carbon price and the costs of delaying mitigation policies compared to a scenario without interacting tipping elements (Lemoine & Traeger, 2016).

3.2 Tipping points in technology (technology tipping)

Innovations are an important driver of non-linear ("disruptive") processes in the economy (Schumpeter, 1942).[10] In the past, new general-purpose technologies such as the computer, mobile telephony and the Internet have fundamentally changed the structure of the economy in a relatively short period of time (Victor et al., 2019; Andrés et al., 2010). New technologies and innovations tend to follow an S-shaped curve as they spread,

[10] The contributions of Schumpeter (1942), especially his book "Capitalism, Socialism, and Democracy" published in 1942, laid the foundation for understanding how innovation acts as a catalyst for non-linear and disruptive economic processes. Although Schumpeter (1942) did not explicitly use the term "disruptive innovation", his ideas are often cited in discussions about the disruptive impact of innovation on established markets and industries.

along which their market share may increase exponentially as soon as one or more tipping points are reached (Kemp & Volpi, 2008). The non-linear diffusion pattern reflects the fact that ground-breaking technological innovations usually start in niches before they can benefit from potential learning and scale effects, and ultimately evolve into a widespread phenomenon (Victor et al., 2019).

Among others, such tipping processes can occur when cost parity is achieved between new and established technologies (Sharpe & Lenton, 2021; Otto et al., 2020). When a new technology reaches the tipping point of cost parity, it becomes economically attractive and can prevail over existing technologies. In Norway, for example, cost parity between electric vehicles and gasoline/diesel vehicles was achieved in the early 2010s (with taxes and subsidies taken into account), which led to a significant, non-linear increase in the market share of electric cars (Sharpe & Lenton, 2021). The resulting cost advantage for battery-powered vehicles — albeit very small in magnitude — fundamentally reshaped the traditional automotive market and strongly influenced consumer behavior, see e.g. Figenbaum (2020, 2017) and Figenbaum et al. (2015).

As new technologies diffuse through markets, they tend to benefit from positive multiple reinforcing feedback mechanisms that reduce costs and improve performance, including learning, scale and network effects as well as the emergence of complementary technologies (Bretschger, 2024; Sharpe & Lenton, 2021; Arthur, 1989). Learning is an important driver of the observed cost reductions in the renewable energy sector (Arrow, 1971) and, as documented by a large number of studies (e.g. Bretschger et al., 2017; Rubin et al., 2015; Dechezleprêtre et al., 2014; McDonald & Schrattenholzer, 2001), learning rates and knowledge spillover intensities are generally higher for newer and cleaner energy technologies than for mature fossil-based technologies.

Economies of scale are also important in the context of the energy transition (Victor et al., 2019). With the expansion of production capacities, the high fixed costs associated with the installation of a fossil-free infrastructure can be spread over a larger production volume, resulting in lower total unit costs and improved cost efficiency. As a consequence, there exist huge non-convexities when building up a fossil-free infrastructure e.g. in the form of storage capacities for renewables or charging stations for electric vehicles (Bretschger, 2024; Golub & Toman, 2016).

The network effect refers to the phenomenon that a technology becomes more attractive (in terms of quality or price) the more other users have already adopted it and plays an important role for electric vehicles in connection with the charging infrastructure (Li et al., 2017). Reflecting a "chicken-egg" dilemma, the availability and accessibility of charging infrastructure has a significant influence on the acceptance and usability of electrically powered vehicles, because the more electric vehicles there are on the roads, the more charging stations are needed, which in turn encourages more people to purchase electric vehicles (Li et al., 2017).

Due to these self-reinforcing feedback effects, the costs for key renewable technologies have fallen dramatically: alone since 2010 by more than 80% for solar PV, by more than 45% for onshore wind energy and by an incredible 90% for lithium-ion batteries, and further cost reductions are expected in the future (BNEF, 2023). Based on empirically tested cost forecasting methods for energy technologies, Way et al. (2022) conclude that a rapid transition to green energy is likely to result "in trillions of dollars of net savings."

The growth rate of renewable energies has consistently exceeded expectations. While expectations for the future growth prospects of coal power were overestimated and repeatedly revised downwards (Bullard, 2020), most energy economy models have underestimated deployment rates for renewable energy technologies and overestimated their costs (Jaxa-Rozen & Trutnevyte, 2021; Hoekstra et al., 2017). For example, the levelized cost of solar energy fell by 81% between 2009 and 2019, which is twice the reduction predicted by the International Energy Agency (IEA, 2010), and the global use of solar energy in 2020 was more than ten times higher than predicted fifteen years ago (Beinhocker et al., 2018).

The data show that key renewable energy technologies such as solar and wind will soon reach the critical threshold of cost parity or have already fallen below it. They already have lower generation costs than some of the established coal, gas and nuclear power technologies and are the most cost-effective source of energy in many regions of the world (Kavlak et al., 2018; Rubin et al., 2015; Kost et al., 2013), suggesting that we are very likely facing one of the most disruptive decades in the history of the energy industry, which will completely change the current fossil-based energy system (Way et al., 2022).

Due to the self-reinforcing feedback mechanisms listed above, technology costs are likely to fall further with increasing market penetration. Policymakers can use these mechanisms to further reduce costs and activate potential tipping points. Any tipping point that gives a new technology a significant new advantage — for example, a larger market share, easier access to finance or wider social acceptance — promotes the self-reinforcing feedback mechanisms and thus technological change (Sharpe & Lenton, 2021). Once such a tipping point has been reached, political support is generally much less necessary.

The diffusion theory of Rogers (1962) provides an alternative explanation for the frequently observed non-linear, S-shaped diffusion pattern of technologies and innovations. In this theory, the S-shape curve describes the typical diffusion process of a technology over time, starting with slow adoption, followed by rapid exponential diffusion until saturation, when most potential users have adopted the technology. Such a non-linear diffusion path can be triggered when a tipping point in the form of a critical mass is reached. Reaching this tipping point is usually crucial for the success of a technology, as it enables the transition from a niche application to a widespread phenomenon. This transition generally does not evolve gradually, but is characterised by a rapid and self-sustaining dynamic in the spread of technologies.

The critical mass refers to a sufficient number of people who adopt a new technology or innovation so that the adoption rate becomes self-sustaining and leads to further growth (Lenton et al., 2022). In this regard, Otto et al. (2020) state that "documented instances of technology and business solutions show that a 17% to 20% market or population share can be sufficient to cross the tipping point and scale up to become the dominant pattern (Koch, 2011)." However, some authors such as Gladwell (2000) and Nyborg et al. (2016) argue that it must be the 'right' proportion of the population, which according to Otto et al. (2020) includes "well-connected influential individuals, trendsetters and other types of societal leaders with a high degree of agency."

We now apply the diffusion theory of Rogers (1962) to our model framework from Section 2, with the following explanations referring to Figure 1a and 1c. The sigmoid curve of the function F reflects the empirical observation that the diffusion process of pioneering innovations and technologies proceeds not gradually (as would be the case, for example, with the function G in Figure 1d), but follows an S-shaped pattern. The stock X_t represents the population or market share of a new sustainable technology and X^T denotes the tipping point in the form of a critical mass which, once reached, induces the majority to adopt. Consequently, the system then converges to the preferred higher equilibrium X^{**}, which is characterized by a higher population or market share. The parameter E is determined by policy, for example, and influences the size of the critical mass (i.e. the position of the tipping point) as well as the extent and speed of the diffusion process.

Expectations and forecasts regarding new technologies are key for research and development, for investments, but also for politics. In the past, however, they have been highly inaccurate in some cases.[11] Conventional scenarios for renewable energies are often based on the flawed assumption that the new forms of energy will simply replace the old system on a one-to-one basis. However, history has shown that in most cases the new system was much greater than the old one it replaced (Schumpeter, 1942). For example, electric light has not only replaced candles and oil lamps, but has also opened up completely new ways of life and entailed commercial, industrial, artistic and scientific applications. The smartphone has not only replaced old mobile devices, but has created a new and much larger communication and information system that goes far beyond telephony and touches virtually every aspect of our lives. These disruptive technologies have completely

[11] Some prominent historical examples include Sir William Preece, Chief Engineer of the British Post Office, who stated in 1878 that "the Americans need the telephone, but we don't. We have enough messenger boys" (Pestov, 2017). Moreover, in 1943, IBM Chairman Thomas Watson predicted "a world market for perhaps five computers" (Carr, 2008), and in 1959, IBM said that "the potential world market for copying machines is at most 5,000" (Pestov, 2017). And as recently as 2007, the CEO of Microsoft said: "There is no chance that the iPhone will achieve a significant market share" (Szczerba, 2015). Similarly inaccurate statements have recently been made about online retail, solar energy and electromobility.

displaced their established predecessors from the market just a few years after their introduction and the new industries and markets were generally much larger than those they replaced. As with previous disruptions, the transformation of the energy system could create completely new market opportunities and pave the way for new, clean business models and applications.

3.3 Tipping points in politics (policy tipping)

Political tipping dynamics are processes that trigger fundamental and often abrupt changes in politics. Such changes can for example affect political systems, institutions, political processes or attitudes and often have a profound impact on society (Macy et al., 2021). Political tipping points can take various forms and can occur both within a political system (e.g. when votes or majorities change abruptly) and between political systems (e.g. in the event of abrupt system changes). Selected historical examples of political tipping dynamics are the enclosure process in England (Long, 2021), which created a working class without land ownership due to a change in the property system, the emancipation of slave laborers in the United States (Long, 2021) and the Arab Spring (Lang & De Sterck, 2014; Campante & Chor, 2012).

Looking at resistance campaigns from 1990 to 2006, Chenoweth & Stephan (2011) found that non-violent campaigns were twice as likely to achieve their goals as violent campaigns. Their findings also showed that those campaigns that were able to mobilize at least 3.5% of the population into sustained protest were always able to achieve serious political change; a rule that also guided the climate movement "Extinction Rebellion" in their campaigns and mobilization strategies (Hallam, 2019). The applicability of the critical mass threshold of 3.5% to climate movements is, however, critically assessed in the literature (Matthews, 2020), as the work of Chenoweth & Stephan (2011) focuses on protests in autocratic regimes and not in liberal-democratic states, where Extinction Rebellion is mainly active.

We now use the theoretical modeling framework from Section 2 to illustrate the basic idea of policy tipping. To do so, we consider Figure 1a and 1c, in which the stock variable X_t represents the trust capital in a particular political system. The sigmoid form of the function F reflects that small changes or events can have a disproportionately strong impact on the stock of trust capital. Accordingly, trust does not evolve in a linear or predictable manner (as would be the case, for example, with the function G in Figure 1d), but can undergo major disruptions. As soon as the stock of trust falls below a certain threshold value X^T, the dynamics of trust capital change abruptly and the system moves towards the lower equilibrium X^*, which is characterized by a lower level of trust.

Such an erosion of trust can lead to a system change where an existing political regime is replaced by another, for example a change from an authoritarian government to a democracy (or vice versa). The parameter E determines the position of the tipping point (i.e. the tipping trust level) and can represent various factors that foster the erosion or building of trust, such as new information, protests, political decisions, economic shocks, scandals, corruption or a lack of transparency. Clearly, context matters; the transition to a new political system is complex and depends on various factors. In addition to trust, which is our focus here, historical, cultural, geographical and economic conditions may also play a role.

Due to the complex conditions in political decision-making processes, sustainability policy can also be subject to abrupt changes; but as will argue in the following sections, these dynamics seem to follow the dictates of political economy (Bretschger & Soretz, 2022; Kalkuhl et al., 2020). In an ideal economy, good decisions are rewarded, while suboptimal decisions are penalized. Market participants are guided by price signals that are determined by supply and demand on markets and ideally reflect resource scarcities. Unfortunately, the market mechanism and thus the price signals do not work in the context of sustainability, as there are market failures when dealing with the natural environment (negative externalities, see Pigou, 1920) and problems in the management of common goods ("tragedy of the commons", see Hardin, 1968). Policy interventions can internalize these market failures by correcting distorted price signals.

Following the principles of welfare economics, a socially optimal policy in the area of sustainability balances costs and benefits within and across generations in the long term (Perman et al., 2003). Accordingly, it is common practice in economic theory to derive optimal policy measures from a frictionless framework and to recommend their immediate and stable implementation by the government. Obviously, however, environmental policy works differently in reality (Bretschger & Soretz, 2022; Kalkuhl et al., 2020). The ideal instrument for many economists, an environmental tax that is introduced once and permanently and whose value is close to or equal to the optimal level (Perman et al., 2003), can basically not be observed anywhere in the world (OECD, 2021). One of the main reasons for this is that governments are dependent on voters and policy decisions depend on political majorities, power struggles, and lobbying. Therefore, decision-makers are usually reluctant to introduce new far-reaching measures (Kattel et al., 2018; Acemoglu & Robinson, 2006), especially when a fundamental transformation of the economy and society is required, as in the case of climate policy, which may affect many potential voters and lobbying groups (IPCC, 2023; Victor et al., 2019).

However, recent experiences have shown that politics can change unexpectedly when natural disasters (such as the floods in the German Ahr Valley in 2022, see e.g. Cornwall, 2021), scientific reports, wars or legal decisions alter public opinion and thus pave the way for political action (Rásonyi, 2021). Other prominent examples include the decisions to phase out nuclear power in Switzerland (UVEK, 2017) and Germany (Polansky, 2021) following the reactor accident in Fukushima and the partial ban on diesel vehicles in

European cities such as Copenhagen, Berlin and Paris, which in the German case was the result of a rather unexpected court decision.

These examples show that sudden public attention to certain pressing issues can prompt politicians to implement measures more quickly or to fundamentally rethink existing decisions and established views in order to meet public demands, which can lead to tipping points in policy-making. Since politics is often guided by voters and public perceptions, the proportion of voters who use a new environmentally friendly technology such as electric mobility or have adopted a sustainable behavior such as vegetarian eating habits can play, besides unexpected natural disasters, a decisive role in shaping public opinion and thus in reaching tipping points in sustainability policy.[12]

Unexpected events can also trigger negative tipping processes. Warlike events or terrorist attacks, such as the attack on the World Trade Center in New York in 2001, often trigger a series of linked actions that fall short of regular political decision-making in terms of social rationality and target efficiency. Extraordinary situations can be used particularly well to assert special interests, especially in the area of security. As in the case of positive tipping points, a triggered development cannot be stopped or even fundamentally reversed in the short term.

In addition, addressing major sustainability problems such as climate change requires consistency in policy frameworks over a very long period of time so that long-lasting facilities and infrastructure can be adequately planned. However, as outlined above, in the presence of positive and negative tipping processes, the economy is confronted with political measures that are unexpected and depend strongly on the political balance of power, coalition building and lobbyism, but little on welfare-economic considerations (Bretschger & Soretz, 2022; Kalkuhl et al., 2020; Kattel et al., 2018). Accordingly, private decision-makers are confronted with the problem of policy uncertainty, which poses a particular challenge for decisions on long-term investments, which are the fundamental driver of economic growth (Pommeret & Schubert, 2018).

Two features of political uncertainty are of particular importance in this context (Bretschger & Soretz, 2022). First, it is the timing of the introduction of the policy measure, which is hard to predict for market participants, and second, the intensity of policy measures is often uncertain. These two dimensions of uncertainty may cause certain assets, especially those highly exposed to carbon-intensive activities, to lose some of their market value or become completely worthless once a policy measure is implemented ("stranded assets", see e.g. McKibben, 2012), affecting both household wealth and economic development.

[12]We refer to Fesenfeld et al. (2022) for a more detailed discussion on the politics of enabling tipping points for sustainable development.

3.4 Tipping points in society and the economy (social tipping)

In general, social and economic tipping dynamics refer to profound and rapid changes in existing social and economic structures. The term social tipping point has its origins in describing the changing prevalence of an ethnically diverse population in municipalities across the United States (Grodzins, 1957).[13] In his seminal work on "Dynamic Models of Segregation", Schelling (1971) demonstrated that a small change in the initial mix of different ethnicities in a neighborhood can eventually lead to complete segregation. In his models, the tipping point describes a critical threshold at which a small change in the behavior or preferences of individuals can induce far-reaching changes and persistent patterns of spatial segregation.[14] The contribution of Schelling (1971) provides the basic idea of how small changes at the individual level can lead to significant and long-lasting changes at the societal level, and thus forms the foundation for numerous subsequent threshold models of social tipping and norm change (see e.g. Lenton et al., 2022; Andreoni et al., 2021; Otto et al., 2020; Wiedermann et al., 2020; Zeppini et al., 2014 and Granovetter, 1978).

Social tipping dynamics typically manifest themselves as a spreading process in social networks in the form of opinions, behaviors, ideas and norms (Lenton et al., 2022; Otto et al., 2020). By prescribing which behaviors should be rewarded and which ones should be punished, social norms play an important role in shaping and regulating human behavior in societies. Social norms and behaviors are evolving rapidly and are reinforced by social feedback effects that promote certain norms and behaviors in a society or group (Nyborg et al., 2016). Individuals are influenced by the actions and decisions of those around them. The underlying positive feedback mechanism of social contagion occurs when "the adoption of a norm or behavior makes it easier for the next person to adopt it through imitation (Lenton et al., 2022)." Since social norms are backed by societal sanctions, changing norms is often hindered by the desire to avoid the costs associated with the transition to a new norm. Accordingly, many individuals prefer to conform if they expect others to do the same. They do so to avoid social sanctions, even if a change in norms would be socially beneficial. However, when a critical number of people adopt a new norm, the social incentives reverse and drive a rapid change towards an alternative state

[13]The expression was first used in a scientific American article on racial segregation by Grodzins (1957), who applied the term "tip point" to a critical proportion of non-whites in US neighborhoods beyond which the proportion of whites abruptly declined (Kopp et al., 2016).

[14]More specifically, Schelling (1971) applies agent-based models to show that even a small change in individual preferences is sufficient to trigger a cascade of location changes. When individuals realize that they are in the minority, they move in the hope of finding an environment with a higher proportion of like-minded people. This in turn causes other individuals to re-evaluate their surroundings and possibly relocate as well. Agents have a tolerance threshold, i.e. a minimum percentage of like-minded people in their neighborhood below which they move, and the tipping point occurs when enough people change their decisions and move to accommodate their preferences. At this point, segregation in the community can increase exponentially as more and more people reinforce the trend toward segregation and further polarize the spatial distribution.

(Andreoni et al., 2021). The pressure to conform to existing social conventions and the sudden breakaway are thus essential components of non-linear social processes.

A popular theory in behavioural science about the diffusion of norms states that the pressure to conform to social norms creates tipping points which, once passed, generate a self-sustaining dynamic that drives societies towards an alternative equilibrium (see e.g. Andreoni et al., 2021; Centola et al., 2018; Nyborg et al., 2016 and Bell et al., 1996). Decision changes triggered by social pressure can thus lead to tipping points where a broad social consensus can be overturned by a group with a minority viewpoint once a critical mass is reached. Recent experimental findings by Centola et al. (2018) suggest that committed minorities of around 25% can change the prevailing social conventions of a group.

However, predicting when societies will reach such a tipping point is a major challenge (Andreoni et al., 2021; Scheffer et al., 2012). For example, the speed with which the gender gap in American higher education disappeared in the early 1970s as women shifted their goals from homemaking to careers, surprised even knowledgeable observers (Jones, 2009). Although social and economic theories have identified a number of factors that may gradually influence the likelihood of tipping (Andreoni et al., 2021), it remains difficult to determine exactly when social tipping will occur, as model predictions hinge on specific assumptions, including individual threshold distributions, cultural elements and the structure of social networks (see e.g. Andreoni et al., 2021; Zeppini et al., 2014 and Granovetter, 1978).

Social contagion through imitation and social pressure can therefore be an important driver for the accelerated adoption of sustainable behaviors and norms. One example in this regard is meat consumption. There is growing empirical evidence that social norms for (excessive) meat consumption have changed significantly in recent years among certain consumer groups (particularly young consumers in industrialized countries) as a result of social interactions (Spiller et al., 2021; Otto et al., 2020). This change in behavior has created new market opportunities for companies offering alternative proteins: The market for plant-based foods in the United States reached a volume of 7.4 billion dollars in 2021, an increase of 54% compared to 2018. It thus grew three times faster than the market for animal products (Formanski, 2021). If an increasing number of people begin to adopt a vegetarian diet, this could lead to a tipping point where vegetarianism becomes the dominant social convention, which spreads rapidly and self-sustainably throughout society. Policy can facilitate this process by developing a common societal understanding of the benefits of adopting more sustainable norms (Andreoni et al., 2021).

We now discuss the characteristics of social tipping dynamics using the theoretical model framework from Section 2, with our explanations referring to Figure 1a and 1c. The sigmoid function F allows us to capture the non-linear nature of certain norm and behavioral changes, where the stock variable X_t represents the proportion of the population that has adopted a particular sustainable behavior or norm. Once a critical population mass X^T is reached, the pressure to conform to a collective norm can lead to social contagion and thus to a self-sustaining momentum that drives most (or all) of the population to adopt the behavior, so that the system then moves towards the preferred equilibrium X^{**}.

Near the tipping point, even a small increase in the proportion of people adopting a particular sustainable behavior can lead to rapid diffusion and widespread acceptance. It is therefore important to consider the non-linear nature of norm dynamics and actively use them to drive positive social change. The parameter E determines the size of the critical mass (i.e. the position of the tipping point) as well as the extent and speed of the norm adoption process and can, for example, represent an external shock, such as an abrupt change in the human norm system, i.e. in the system of moral and behavioral norms that influence what is desired and rewarded in society.

Critical thresholds also play an important role in development economics in the form of so-called poverty traps in less developed countries (Rosenstein-Rodan, 1943; Azariadis & Drazen, 1990). Such a trap refers to significant economic, social and political thresholds that must be overcome for successful development (Azariades & Stachurski, 2005). It has therefore been argued that developing countries need an external initial boost in the form of major financial support in order to overcome poverty traps; yet the success of this support is often critically assessed in political reality (Kraay & McKenzie, 2014; Kraay & Raddatz, 2007).

In our model from Section 2, poverty traps can be mapped using the function H (Figure 1b), where the stock variable X_t represents the (broadly defined) capital. The intercept $\bar{X}$ represents a minimum amount of capital or investments that must be built up in order to be able to generate economic growth. This results in a non-linear relationship between capital growth and the possibility of escaping the poverty trap. More specifically, small changes in the capital stock that are below the minimum amount of capital $\bar{X}$ have no significant effect on growth. Positive feedback effects that generate sustained growth can only occur once a minimum level of productive capacity in the form of capital has been accumulated. Once the tipping point X^T is reached, the system can move to the new equilibrium X^*, which allows for a higher capital stock and thus a higher income level. The external boost, represented by the parameter E, can include various factors that influence capital growth, such as government investment in education or infrastructure.

4 In-depth examples of tipping dynamics

In this section, we focus in detail on two specific tipping dynamics from economic history. First, we consider the history of electric cars. The competition between automotive technologies (steam, electric and fuel engines) from 1900 onwards was characterized by a series of different tipping events that triggered a disruptive change in favour of the internal combustion engine. As a second example, we look at the electrification process in Switzerland at the beginning of the 20th century, which was driven forward decisively at that time due to specific tipping events. The examples illustrate the characteristics of developments with tipping events and are particularly revealing with regard to the goal of sustainability.

4.1 Tipping events in the history of electromobility

On April 29, 1899, an automobile reached a speed of 100 kilometers per hour for the first time in human history. From today's perspective, it seems surprising that this record was achieved with an electric car. Back then, it was unclear whether electric or combustion engines were going to replace steam-powered vehicles. A look back in the history of electric cars reveals the importance of tipping processes and established structures for the historical development of electric vehicles. Following Rickenbach (2022), Høyer (2008) and Cowan & Hultén (1996), we divide the history of electric cars into four phases and explain the most influential events and milestones for each of these phases. The history of the early automotive industry suggests that the interplay of several tipping events gave the gasoline car a decisive advantage in the early 1910s.

Kick-off and Early Records (1821-1911)

In 1888, the German machine manufacturer Andreas Flocken developed the first electrically powered car, which featured innovative accessories for its time, such as pneumatic wheels and electric headlights.[15] A decade later, racing driver Camille Jenatzy showed what was possible with electric motors in terms of speed. In 1899, he reached a speed of 105 kilometers per hour with his rocket-like looking electric racing car "La Jamais Contente", which made it the first car in history to exceed the mark of 100 kilometers per hour. In addition to top speeds, the ranges of the first commercially produced electric cars also improved, with some of them achieving a range of over 100 kilometers. In the same year, the designer Ferdinand Porsche presented a hybrid car, which was the first vehicle to have an additional combustion engine alongside two electric motors.

Electric vehicles really took off around the turn of the century. In 1897, the bestselling

[15] The basis for electromobility was laid by experimental physicist Michael Faraday in 1821 with the discovery of electromagnetism. In 1834, the American Thomas Davenport used the new drive mechanism to build the first purely electric DC (direct current) motor, which created the conditions for inventors to work on faster carriages that did not require horses. An important pioneer at this time was the Frenchman Gustave Trouvé, who presented the first electrically powered tricycle at the International Electricity Fair in Paris in 1881, which was considered the forerunner of the first electric cars. This vehicle could travel at a speed of 12 kilometers per hour and had a range of around 26 kilometers. The first petrol engine, also installed in a tricycle, was developed four years later by Carl Benz. From 1897, the first electrically powered taxis travelled through London and New York, Vienna and Berlin soon followed.

car in the United States was an electric vehicle, and the share of electric cars on America's roads was significantly higher than that of gasoline-powered vehicles. In 1900, 40% of vehicles in the United States were powered by steam, 38% by electricity and only 22% by fossil fuels. Back then, it seemed that battery-powered cars could win the race for road dominance.

Electric cars were popular because, unlike petrol-powered vehicles, they did not require the laborious process of cranking up the engine. Thanks to the energy from batteries, it was possible to drive off immediately. At the same time, petrol engines were regarded as "noisy stinkers", which was particularly annoying in cities. Electricity, on the other hand, was considered as the "juice" of the new age, which seemed to make everything possible and which could also be stored: in heavy but increasingly powerful batteries. At the beginning of the 20th century, when electric propulsion was one of the three most promising drive technologies along with steam and gasoline propulsion, research in the field of battery capacity achieved considerable improvements.[16] However, this phase of technical progress in electromobility came to an abrupt halt at that point. The reasons for this were rather random historical events that triggered a disruptive development in favour of the gasoline car.

Technological (1912) and Economic (1913) Tipping Events

The rise of electric cars continued beyond the turn of the century. Sales of electric cars peaked in 1912, but abruptly leveled off in the same year when a far-reaching invention came on the market (Høyer, 2008). The American Charles F. Kettering introduced the electric starter motor (Starting-Lightning-Ignition) for gasoline-powered cars (Boyd, 1968), which made the strenuous cranking process of starting the gasoline engine superfluous. This novelty contributed significantly to the spread of gasoline cars, as they became more convenient and accessible to a wider population. Moreover, the electric starter motor was introduced at a time when sales of gasoline cars were beginning to rise very quickly, so the momentum shifted in favor of petrol vehicles. Cowan & Hultén (1996) assess the significance of this invention at the time as follows: "The arrival of the SLI (Starting-Lightning-Ignition) in gasoline cars in 1912 was the concluding disaster for the electric car. There are two reasons. First, it eliminated the need for a crank start, which was one of the most undesirable features of the gasoline car. This removed one of the perceived advantages of the electric vehicle, namely that women could drive them. Second, the SLI concentrated the R&D efforts of battery manufacturers on mass production techniques for relatively low capacity batteries, rather than on increasing storage capacity, which would have been necessary for the competitive position of the electric

[16] In the nineties of the 19th century, battery capacity was around 10 watt hours per kilogramme. In 1901, this capacity had improved to 18 watt hours per kilogram, and by 1911 it was already at 25 watt hours per kilogram (Cowan & Hultén, 1996).

vehicle."

The invention of the electric starter motor was (in retrospect) a technological tipping event that changed the automotive landscape at the time and had far-reaching implications for the further development of electric cars in the 20th century.[17] One year later, the rise of the petrol car was further boosted by Taylorism and factory automation. Low-cost mass production was introduced earlier and promoted more rigorously in the gasoline car industry than in the competing electric car industry. Manufacturers such as Henry Ford began producing vehicles with internal combustion engines on assembly lines in 1913, allowing them to be sold at lower prices (Wilson, 2014). As a result, electric cars became a rarity in the 1920s, while the availability of large-scale production capacities and the resulting price advantage created a mass market for gasoline cars.

In a counterfactual historical analysis, the early 1910s were probably the decisive years in which the gasoline car was able to win the competition for the automobile market (for the time being). From this time onwards, the market share of petrol-powered vehicles increased exponentially, and eventually reached a market share of almost 100%, mirroring a typical S-shaped diffusion pattern. From then on, electric vehicles were only used in niche markets. Gradually, gasoline-powered vehicles were able to replace the old electric cars. The electric car was left behind because it was much more expensive than a gasoline-powered vehicle; it also had heavy batteries on board and a disadvantage in terms of range. In addition, crude oil was available at low cost and powered more and more machines, industry and cars, which in turn fostered the emergence of filling stations. This development was accompanied by an image change: the loud petrol engines were successfully positioned as a sign of strength and power through clever advertising. The technological progress of batteries in terms of their storage capacity stagnated until the 1990s.

Renaissance with Political Resistance (1990-2005)

It was not until the 1990s that promising approaches to electromobility emerged again. This was partly due to the Gulf War, which made dependence on oil appear problematic, at least temporarily. In addition, environmental regulations were tightened in California. The California legislation of 1990 ("Clean Air Act" and "Zero Emission Vehicle (ZEV) Mandate") mandated that at least 2% of newly registered cars must be emission-free by 1998 and 10% by 2003.[18] To comply with this law, car manufacturers in the United

[17]Although the invention of the electric starter motor for petrol cars was an important milestone for the automotive industry, it is important to consider the historical context and not to exaggerate single tipping events. In this regard, Winkelmann et al. (2022) point out that "much attention is often paid to the specific triggering event, but it is rarely one single actor or action which accounts for the entirety of the tipping process. Rather a full account needs to be made of all of the previous and related processes that have further placed the system towards criticality, allowing for such changes to become more likely."

[18]The introduction of legislation marked a paradigm shift. In this regard, Collantes & Sperling (2008) note that "the adoption of the ZEV mandate is a rare example of non-incremental policy innovation.

States were forced to develop zero-emission vehicles.[19] California's ZEV mandate is often credited as a catalyst for clean automotive technologies, while other, more critical articles view the ZEV mandate as a policy failure, see e.g. Collantes & Sperling (2008) for a discussion.

However, several years passed before electric cars were actually able to establish themselves on the market. The main reason for this delay was political resistance from the oil and automotive industries, but also from the governments of the United States and California, as well as from consumers. These established players tended to resist change in the automotive market, so that its development was highly path-dependent in most historical phases. In the case of the automotive industry, this path dependency manifested itself mainly in the innovation and investment decisions of car manufacturers (Aghion et al., 2016), in the attitudes of consumers (Cowan & Hultén, 1996) and in the political lobbying power of the oil and automotive industries (Collantes & Sperling, 2008) who campaigned for the preservation of fuel-powered cars. This constellation is the reason for the major resistance to the introduction of electric cars. As a consequence, vehicles powered by fossil fuels were able to dominate the market for decades and alternative drive technologies had little chance of gaining market share in the automotive market for practically the entire century, despite their known ecological advantages.

Developments since 2006

An important technological milestone was reached in 2006 with the launch of the Tesla Roadster. The sports car, which was sold from 2008, was the first electric car suitable for highways and longer distances and set new standards with a range of around 350 km and a top speed of more than 200 kilometers per hour.

After almost a century of oil-powered dominance, electric cars, which have long been written off, are now starting to catch up. Rising fuel costs, stricter environmental regulations and new developments in battery technology require and enable a shift in thinking. Since 2010, the cost of lithium-ion batteries has fallen by almost 90% and forecasts indicate that these cost reductions are likely to continue in the future (BNEF, 2023). Policy has been and continues to be an important driving force behind this process.

The mandate proposed a disruption of the status quo, presenting the auto industry with a tremendous challenge and implying a new energy paradigm for transportation."

[19] Between 1996 and 1999, General Motors attempted to gain market share in the electric segment with the EV1 ("Vehicle One") model. Just over 1,000 units of the compact class car were launched on the market and were primarily made available to selected customers. These were leasing contracts — General Motors remained the owner of the vehicles. After the law was relaxed and reversed under pressure from the oil and automotive industries, the manufacturers collected the vehicles again against the will of the users and subsequently scrapped most of them completely. In addition, General Motors was unable to provide long-term safety guarantees due to the lack of replacement production. In 1997, Toyota launched the Prius, a first version of the later successful plug-in hybrid. Toyota also delivered around 1,500 units of the electrically powered RAV4 SUV. Only the Toyota Prius managed to achieve cult status, especially in California, with the newly sparked environmental awareness. A number of Hollywood stars appeared in the Prius to demonstrate their commitment to the environment.

The history of electromobility is evolving rapidly, with further important milestones in the future. In a cross-party resolution passed in 2016, the National Council in Germany called for no more cars with combustion engines to be registered from 2030 (Schmidt, 2016). In the meantime, a ban on new registrations of combustion vehicles is being discussed in the European Union for 2035; strict regulation for combustion engines is therefore foreseeable for the whole of Europe.

The market shares of petrol and electric cars are likely to converge again in the near future. This time, however, electric cars have a better chance of winning the competition. With increasing market penetration, electric cars further benefit from the aforementioned reinforcing feedback effects that reduce costs and improve performance. As a result, batteries, a determining factor of the cost of an electric vehicle, are becoming increasingly cheaper (BNEF, 2023), which is boosting sales and prompting the automotive industry to devote an increasing proportion of its investment to electric cars (BNEF, 2023). In many countries, electric cars are about to reach the tipping point of cost parity, which may mark the beginning of a self-sustaining dynamic that accelerates the spread of battery-powered cars. Following the example of Norway, the market share of electric cars in these countries is likely to experience a non-linear increase in the future (Sharpe & Lenton, 2021).

4.2 The electrification of Switzerland — the story of unique tipping events

Since the beginnings of the second industrial revolution — the electrification of the economy and society — Switzerland has been one of the countries in which electrification began relatively early according to historical data (Gugerli, 1996).[20] The favorable topography of the Alpine region offered good conditions for the construction of hydropower plants.[21] In addition, the early electrification of the Swiss Federal Railways was of great importance for the emerging electricity sector at the beginning of the 20th century.[22]

The foundations for the electrification of Switzerland based on hydropower had already been laid before the outbreak of the First World War, but in the following years the electrification process in Switzerland was driven forward in an unprecedented manner. This process, however, was by no means uniform or linear, but was characterized by

[20] As a domestic energy source, hydropower has been used to generate electricity in Switzerland since the 1880s. Until around 1910, Switzerland had the highest electricity output per capita in the world (Landwehr, 2021).

[21] According to an estimate by Gugerli (1996) covering all Swiss power plants, distribution companies and pipeline infrastructure, an investment volume of 671 million Swiss francs was achieved by 1914.

[22] As documented by the Historical Dictionary of Switzerland (Paquier, 2010), 77% of the rail network in Switzerland was already electrified in 1939, while the average in other European countries was only 5%. An even higher number can be found in Landwehr (2021), who reported that 93% of rail transportation was already electrified in 1939.

decisive tipping events that forced Switzerland to move away from its dependence on coal and to promote the expansion of hydropower for electricity generation.

The shortage of coal during the First and Second World Wars was the main driver for the rapid electrification of Switzerland and the entire Alpine region (see e.g. Landwehr, 2021; Kupper, 2016 and Paquier, 2010). During this time, there were considerable difficulties with the supply of coal. Coal was the most important source of energy and Switzerland, unlike Germany and France, did not have any significant reserves of its own.[23] Due to its dependence on foreign coal, Switzerland's energy supply was very fragile in times of war and therefore reliant on alternative energy sources.

In an overview article on the Swiss energy history, Kupper (2016) state in this regard that "the main driving force behind Switzerland's early entry into hydropower and its institutional foundation was the lack of its own coal deposits [...]. Thus, in times of fuel shortages such as during the two world wars, 'white coal' replaced 'brown' coal, especially in the industrial and commercial sector, and encouraged self-sufficiency efforts [...]. In contrast to countries with abundant coal deposits, Switzerland pushed for the expansion of hydropower and electrification. A strong electricity industry equipped with its own financing instruments, in which the public sector was also involved alongside private companies, made a significant contribution to expanding and supplementing the traditional and coal-based energy regime. It built extensive networked infrastructures (reservoirs, power plants, power lines) and thus transformed the Swiss landscape into an energy landscape."

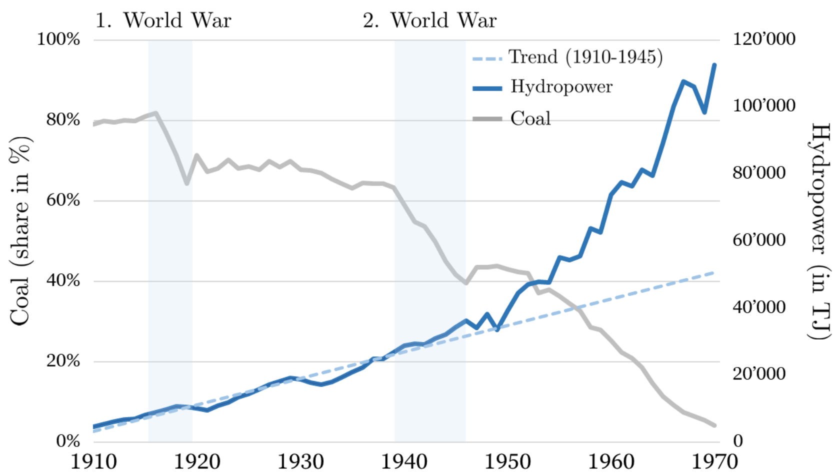

Figure 2: Gross energy consumption for coal (share in %) and hydropower (in TJ)[24]

The two world wars thus represent important tipping events for the Swiss energy landscape, as they forced Switzerland to (inevitably) accelerate the expansion of hydropower. As shown in Figure 2, the share of coal in gross energy consumption fell abruptly during

[23] In contrast to Germany, coal was not used to generate electricity, but mainly for heating and industry.
[24] Own figure based on data from Switzerland's overall energy statistics (SFOE, 2023).

the two world wars and converged towards zero in the following years. Gross energy consumption of hydropower, on the other hand, experienced a non-linear increase after the Second World War and was able to decouple from the linear trend extrapolated on the basis of the years 1910-1945, which is shown in Figure 2 by the light blue dashed line.[25]

The lack of its own coal forced Switzerland to move away from its traditional energy source and to build the infrastructure required for a large-scale electricity industry, such as hydropower plants and transmission grids. This expansion required high investments, which were made both by private players such as banks and (multinational) stock corporations as well as by the government.[26] The latter also financed the provision of education systems, the training of skilled workers and the development of knowledge stocks.[27] Occasionally there was also resistance to the new form of energy: hydropower constructions were perceived as an intrusion into the landscape, which nature and landscape conservationists wanted to preserve.

In retrospect, the coal shortage during war times completely changed Switzerland's energy supply and triggered a disruptive development in favor of electricity. While coal became less and less important after the Second World War, the consumption of crude oil rose sharply, which had to do with the rapid expansion of private transportation and the replacement of coal heating with oil heating systems.[28] At the time, the increasing use of electricity was seen as a sign of progress and modernity, and Switzerland was able to keep pace with technological progress thanks to the early and decisive promotion of electrification (Paquier, 2010).

Due to the war between Russia and Ukraine and the resulting gas shortage, Germany is currently in a similar situation as Switzerland at the beginning of the 20th century. After decades of meeting its energy needs to a large extent with cheap gas from Russia, Germany is now at a crossroads in terms of its energy policy (Bundesnetzagentur, 2022).

[25] Milkoreit (2023) notes that historical examples are often labeled as tipping processes in retrospect without presenting any evidence of tipping ("retrospective labeling"). It is therefore important to provide evidence for certain characteristics of a tipping process, especially for non-linearity.

[26] Between 1950 and 1973, an average of around 1.5% of Switzerland's gross domestic product (i.e. around half a billion Swiss francs) was invested annually in the expansion of hydropower capacities (Kupper, 2016).

[27] From development to widespread use, electricity required high investments in the development and expansion of knowledge and infrastructure, e.g. in education systems, power plants and transmission grids. Accordingly, the electrification process in Switzerland can be modeled by the function H (Figure 1b) from Section 2, where X_t corresponds to the accumulated capital stock in the electricity sector and $\bar{X}$ to the minimum production capacity in the form of capital that must be accumulated through investments in order to be able to generate a positive electricity output. The coal shortage during the two world wars represented an external shock that forced Switzerland to build up the infrastructure and generation capacity necessary for a nationwide electricity industry (e.g. construction of power plants and educational facilities as well as expansion of the electricity grid), so that Switzerland was able to move to the equilibrium with a high capital stock in the electricity sector after the Second World War.

[28] Due to the enormous increase in the importance of oil in the energy balance of the post-war period, the share of hydropower in gross energy use stagnated despite the enormous increase in installed capacity between the end of the Second World War and 1970 (SFOE, 2023).

The gas shortage is also likely to be a tipping point that could prompt Germany to move away from its dependence on fossil fuels and continue to drive forward the expansion of renewable energy sources.

5 Implications for research, institutions and policy

Non-linear developments are of great importance in nature, technology, politics, society and the economy. The social relevance of tipping processes for sustainability arises from the overpowering influence of established, environmentally intensive structures in shaping future development. Established social, economic and political systems tend to promote self-stabilising mechanisms that resist change, resulting in path-dependencies and inertia. This can be caused, for example, by infrastructural inertia due to long-standing investment cycles, by behavioural inertia due to acquired habits or by cultural and political inertia due to traditions and power structures. In addition, human intuition and the ability to form expectations about non-linear, dynamic changes in the future are generally limited.

This constellation is the main reason for the great resistance to a rapid transformative change in favor of sustainability. Tipping dynamics can counteract these preservation-oriented patterns. If they promote sustainable development, they are certainly desirable from a social and economic perspective. Political measures should therefore aim to identify important tipping points and use them to promote sustainability. Since tipping processes are characterized by disproportional causality, i.e. small changes can have large systemic effects, identifying the triggers of tipping points can help decision makers to design policies that have a large environmental impact at moderate economic costs.

As the world's socio-economic system is currently trapped in a state in which it is still heavily dependent on the use of fossil fuels, tipping point interventions have the potential to break this barrier by triggering tipping dynamics in various sectors, and thereby paving the way for disproportionately rapid decarbonization. The contributions of Lenton et al. (2022) and Otto et al. (2020) have identified potential tipping point interventions in the area of climate policy, which include measures such as removing fossil fuel subsidies, promoting decentralized renewable energy generation, coordinating and promoting complementary fossil-free technologies and infrastructure, building carbon-neutral cities, divesting fossil fuel-related assets, disclosing all implications of fossil fuels, and strengthening education and environmental engagement. In addition, subsidies for clean technologies and taxes on polluting technologies can be specifically designed with the aim of triggering tipping points and thus a disruptive development in favor of fossil-free technologies more quickly and in a more targeted manner. The same can also apply to certificate solutions or bans and standards.

As in the case of ecosystems, a triggered tipping point can induce an upward-scaling tipping cascade that infects other parts of the economy (Sharpe & Lenton, 2021). For example, electric vehicles can be specifically promoted with subsidies in order to bring them below the critical threshold of cost parity with diesel/petrol vehicles. The subsidy-driven increase in sales of electric vehicles will further reduce the cost of batteries, making energy storage cheaper for the power sector, which in turn will support the cost-efficient integration of renewable energies into the electricity grids (Sharpe & Lenton, 2021). Tipping of the transport sector towards battery-powered vehicles could therefore activate further tipping points in the power sector and thus accelerate decarbonization.

The measures can be financed from specific sources or from general tax and revenue funds. The form of financing advocated by economists — a tax on polluting activities ("polluter-pays principle") — faces resistance in political reality, as polluters are also voters who want to avoid additional costs (see e.g. Swiss vote on the CO_2-Act, BAFU, 2021). If the taxation of polluting activities is politically blocked, the theory of tipping points leads to a new approach for a successful environmental policy: In a first phase, green technologies should be significantly supported financially through general government funding until a technological and/or political tipping point is reached. Once a critical threshold is achieved at which the cost advantage is in favor of the new technologies, they will establish themselves on the market, as the example of electromobility in Norway has shown (Figenbaum, 2020).

Once a political tipping point is reached at which the median voter adopts the new technology, the political majority can enforce an efficient environmental policy and the "polluter-pays principle" and decide whether and how to refinance the subsidies of the first phase. As soon as a desired new technology is widespread enough, political majorities can be found more and more quickly to restrict the old technology, as voters who have switched to green technologies are less likely to oppose further tax burdens or regulations. With more companies, households, sectors and regions switching to "green", the political process could accelerate and trigger a cascade of political tipping points. The general goal of maximizing welfare through an efficient and fair policy is not changed, but it is realized in phases due to the existence of important tipping points. This approach promises great advantages for decarbonization under the given political and economic restrictions at all levels, nationally and internationally.

Note that the presented strategies fundamentally differ from the concept of social cost of carbon, which is used in traditional economics to estimate the economic damages associated with each additional ton of carbon emissions released into the atmosphere. The optimal carbon price, which internalizes the external effects of climate change and equates the marginal abatement costs across all sources of emissions, does not necessarily correspond to a level that triggers tipping points, see e.g. Sharpe & Lenton (2021) for a more detailed discussion. Furthermore, a carbon price that is the same for all sectors of the economy may be much lower than needed to activate tipping points in some sectors, while being much higher than needed in others (Sharpe & Lenton, 2021), suggesting that optimal carbon pricing should be complemented by technology-specific policies that activate the above-mentioned self-reinforcing feedback effects (e.g. learning processes, network effects or economies of scale), and thereby bring the costs of clean technologies below that of dirty technologies.

Identifying and activating tipping dynamics thus becomes one of the central political challenges. If it becomes possible to incorporate tipping dynamics into policy making, the success of policy can improve significantly as described. However, the ability to actively shape development depends on whether tipping points can be predicted and tipping dynamics can be controlled, for which there are well-founded and legitimate concerns about the skills and knowledge required.[29] Both natural and socio-economic systems are characterised by a high degree of uncertainty and complexity and are closely interlinked through co-evolutionary dynamics, making it difficult to anticipate or control tipping dynamics (see e.g. Gaupp et al., 2023; Milkoreit, 2023; Wunderling et al., 2021; Scheffer et al., 2012 and Rammel et al., 2007). As highly complex processes in socio-economic systems are generally characterised by emergence and surprise, there is only limited scope for active control. The exact position at which tipping may occur is generally largely unknown. While decision-makers are often aware of the possibility of critical thresholds in the various application areas, there is generally a high degree of uncertainty about the exact location of the tipping points.

In order to avoid unnecessary complexities, most economic models abstract from non-linearities, which is why they cannot or only insufficiently depict disruptive long-term changes.[30] Linear models can be inadequate in many applications, as they cannot capture the complexity and potential for sudden changes and disruptions. Disregarding tipping processes in economic models can severely distort predictions. As already outlined, the World Energy Outlook published by the International Energy Agency has consistently underestimated the growth of solar and wind energy capacities. One of the main reasons for the large discrepancy between the forecasts and the historical data is that the applied models postulated a linear growth pattern, while history shows exponential growth in the capacities of new renewable technologies (Roberts, 2015). If policy recommendations are only derived from linear models without tipping points, the desired systemic changes can usually not be achieved. We therefore suggest that further research on economic and social processes should increasingly move away from the prevailing linear representation of processes and pay more attention to non-linear developments, without, however, dis-

[29] Or, more generally, concerns about human agency, i.e. the human capacity or ability to change the course of events or the outcome of processes; see e.g. Gaupp et al. (2023) for a discussion on the role of agency in social tipping processes.

[30] One recent exception is the contribution by Bretschger (2024), who integrates an S-shaped productivity curve for renewable energies into a dynamic macroeconomic model and finds that learning and economies of scale in new energies mitigate the costs of reducing emissions and increase the speed of decarbonization.

regarding the fact that many socio-economic changes are incremental and not instances of tipping.[31]

By analyzing and quantifying different tipping dynamics, a deeper understanding of the underlying system dynamics and interactions can be gained. In order to capture the non-linear relationships in the respective application areas, a careful calibration of important system variables is required. The functions introduced in Section 2 represent two prominent options; however, more complex, non-linear relationships are also conceivable. A suitable functional form must be determined for each model variant and application area, whereby the exogenous forces bundled in E must be analyzed and quantified separately.

Information plays a central role in the formation of political majorities and therefore also for the emergence of political tipping points. The increasing importance of social media for the formation of political opinion has not reduced the problem of blurred information, but rather accentuated it, as the various social groups often communicate in their own "bubbles" and have become more difficult to reach for external information. A positive aspect of the new media is that the general openness of the information channels enables a rapid dissemination of important scientific contributions and independent information to the public. The new information channels thus represent an important counterweight to the usually biased information policy of the established providers on the market, who generally advocate a continuation of the existing technologies that they dominate.

The final assessment of the aim to incorporate tipping dynamics into concrete policy-making is therefore mixed. On the one hand, the ability to control when and how societies reach tipping points has significant implications for social well-being, optimal policy design and sustainability. The potential gains and societal opportunities of tipping processes that promote sustainability appear to be high. On the other hand, there are numerous well-founded reservations due to the uncertainties and complexities associated with sustainability policy and the correct prediction of tipping points. Moreover, the consequences of interventions in a complex adaptive system can by definition never be fully predicted. Political, social and economic tipping points, just like technological ones, were often not foreseen in the past and were usually only understood in hindsight (Milkoreit, 2023; Andreoni et al., 2021; Wunderling et al., 2021). The two case studies from economic history have impressively documented that disruptive changes were mostly the result of unexpected, random tipping events and can therefore only be predicted or governed to a limited extent. In addition, in Section 3, we have already referred at various points to the incorrect forecasts and the prominent misjudgements and controversial assessments made by experts in the past.

[31] The contribution of Milkoreit (2023) emphasizes that there is a tendency to "see the world through tipping-point glasses", which could lead to an overuse of the concept.

In order to successfully trigger tipping dynamics in favor of sustainability and to avert negative tipping processes, the most appropriate institutional framework conditions possible must be defined. The existing processes are not well suited in this regard. Due to the path dependencies discussed above, the established players on the markets generally follow a linear way of thinking, i.e. a continuation of past developments. This behavior often tends to be transferred to political decisions. The same can apply to experts who are too close to market activities or are even part of the market themselves, for example as employees of affected companies.

The successful identification of tipping dynamics should therefore be detached from short-term business on markets and in politics. It could be entrusted to an independent panel of experts. Such a panel should strive for the highest possible quality of decisions in the area of sustainability and ideally be able to act both long-term and independently. A moderate proposal for policymakers is therefore to create an independent, interdisciplinary and high-ranking body of experts specifically on the subject of tipping processes and to allow this body to play a prominent role in the political opinion-forming process.

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