Energy Policy 119 (2018) 196–205

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Sensitivity of energy system investments to policy regulation changes: Too many, too fast?☆

Anton Bondarev, Hannes Weigt*

Faculty of Business and Economics, University of Basel, Peter-Merian Weg, 6, 4002 Basel, Switzerland

ARTICLE INFO

JEL codes:
L51
Q48
C6
C02

Keywords:
European energy transition
Energy infrastructure
Investments
Policy design
Slow-fast systems
Blue sky catastrophe

ABSTRACT

In this paper we argue, that the interaction of energy policy regulations in the European electricity sector may be described by the slow-fast class of dynamical systems. Such systems may exhibit drastic changes in their dynamics known as bifurcations; one important being the so called blue sky catastrophe. Once reaching such a state, the slow system becomes unresponsive to the changes in the fast system. For the energy-policy nexus this translates into the energy system becoming unresponsive to policy interventions leading to a freeze in the system dynamics. Application of this result allows us to argue that caution is needed when updating economic policies to achieve a faster transition towards a low carbon energy supply structure. To avoid this risk the policy design should be aimed at long term incentive structures with less frequent but more consistent interventions.

1. Introduction

Since the 1990s, the European electricity system has been in a phase of transition. Europe is aiming for a fully integrated energy market and a decarbonised economy. This objective requires that the existing fossil fuel based electricity supply be replaced by a supply based on renewable energies and that the regulated national systems be replaced by competitive international markets. In order to achieve these ambitious targets, a multitude of policy interventions have been put in place in the last decades. The ongoing restructuring of electricity markets and the European 2020 climate and energy package—imposing a 20% cut in greenhouse gas emissions from 1990 levels, 20% share of EU energy from renewables, and 20% improvement in energy efficiency by 2020—are good examples of the complexity of these policy endeavors.

In this paper, we take up the European energy transition and the policies proposed to achieve it. We link the European energy system and potential transformation policy approaches to the mathematical properties of dynamic interlinked systems and their behavior during transition processes. In doing so, we recast the ongoing market and policy processes of the European electricity system into the framework of a slow-fast system. These systems are characterized by two or more processes with different timescales; changes in some of the components are much faster and frequent than in other components. We argue that the European electricity system includes such processes of different speeds and thereby can be described by slow-fast system dynamics.

In a next step we discuss the potential of a so called 'blue sky catastrophe',[1] studied in Turaev and Shilnikov (1995). This type of bifurcation describes the state of a dynamical system, where it goes into a cycle of infinite period and length when the timescales of the slow and fast parts of the system are sufficiently disparate.[2] In other words, during the transition from one stable system equilibrium state into another, a slow-fast system runs the risk of exhibiting frozen dynamics making the slow system unresponsive to changes in the fast system. We adapt this result to the description of the energy-policy nexus, warning of the danger that the European electricity system might become insensitive to policy regulations during its transition phase from a fossil-

☆ This research is part of the activities of SCCER CREST (Swiss Competence Center for Energy Research), which is financially supported by the Swiss Commission for Technology and Innovation (CTI) (Grant No. KTI. 1155000154s). We thank Jan Abrell, Rebecca Lordan-Perret, the participants of the 22nd Annual Conference of the European Association of Environmental and Resource Economists, and an anonymous reviewer for helpful comments and suggestions.

* Corresponding author.
E-mail addresses: anton.bondarev@unibas.ch (A. Bondarev), hannes.weigt@unibas.ch (H. Weigt).

[1] The term 'blue sky catastrophe' has nothing to do with the economic or energy related aspects we discuss in the paper but is the accepted mathematical term for the special bifurcation type we refer to.

[2] The term blue sky emerged because this describes the situation where the orbit of a dynamic system is vanishing into the blue sky (i.e. suddenly disappears). Again, this 'blue sky' association is not related to the energy context of this paper.

https://doi.org/10.1016/j.enpol.2018.04.031
Received 23 October 2017; Received in revised form 27 March 2018; Accepted 15 April 2018
0301-4215/

nuclear and regulated equilibrium to a new renewable and market driven equilibrium. As in a slow-fast system, we show too frequent interventions can lead to a breakdown of the transition process.

Slow-fast systems have been used to represent different coupled processes. Within economic applications, issues such as climate change dynamics and interactions have also been characterized as slow-fast systems. For example, the time-structured nature of the interdependencies between economic activity and state of the environment is implemented through NMPC (nonlinear model-predictive control) (e.g., Allgöwer and Zheng, 2012; Bréchet et al., 2014), where expectations over climate change are taken as piecewise constant. This effectively defines the climate subsystem as slow in comparison to the economic part of the model (the fast system). Other examples of slow-fast dynamics include ecological and economic process in the environmental field (e.g., Xepapadeas, 2010; Crépin et al., 2011; Brozović and Schlenker, 2011) or the relationship between competition and technological change (i.e., the speed of interactions between competing firms is much higher than the speed of the technological change in the economy as a whole).

In these slow-fast system applications it is argued that neglecting different timescales may lead to inefficient choices. However, the studies do not account for the risk of a blue sky bifurcation. We contribute to this literature by arguing that the energy-policy nexus can also be represented as a slow-fast system and by further revealing the specific (and rather dramatic) policy inefficiency stemming from the blue sky phenomenon.

Another strand of literature related to the transition between different system equilibria is the analysis of resilience, first coined in Holling (1973). This literature, like Walker et al. (2004) and Carpenter et al. (2001), claims that resilience is intimately linked with the tolerance of the environmental or economic system to the changes in the slow component—that is, its adaptive capacity. Resilience has also found applications to energy policy (Strunz, 2014).

We contribute to the resilience literature by accounting for the transition phase risks—that is, the regime in between the two stable equilibria. In the terms of this literature, this is the situation when the old equilibrium has already lost its resilience and the new one has not yet become resilient and the system is in transition between the two stable states. In our case, this is the European transition phase from the fossil-nuclear electricity system to a renewable one. We argue that there are additional policy risks in this situation that exhibit characteristics possibly leading to the blue sky bifurcation. From the resilience perspective, the duration of this transition phase is limited until the new state becomes stable. Therefore, it is crucial to pass through this phase without entering into the blue sky catastrophe.

During the energy transition in Europe, the electricity market will play a crucial role. First, it accounts for a large share of European greenhouse gas emissions, and second, the energy system will require significant development to accommodate intermittent solar and wind generation. So far, the transition process has already raised some concerns: the increased cost burden for renewable support and their distributional effects (e.g., Neuhoff et al., 2013); the decline in emission permit prices and the functionality of the ETS (e.g., Abrell and Rausch, 2017); backup for intermittent renewables and the capacity market debate (e.g., Petitet et al., 2017; Cramton et al., 2013); or the integration of renewables into electricity networks (e.g., Kunz, 2013).

Given the multitude of challenges facing the European energy market, it is unclear how fast the system can actually be transformed and which further steps will be needed to achieve the desired transition (e.g., Neuhoff et al., 2015; Finon et al., 2017). Based on slow-fast system dynamics, we argue that potential policy adjustments should account for the risk of frozen system dynamics if too many adjustments are made too fast. In other words, we argue that European energy policy interventions should be coordinated and harmonized, account in their design for potential policy interactions across sectors and countries, and be implemented with a long term focus and clear adjustment rules to give the market time to learn and adapt.

The remainder of this paper is structured as follows. Section 2 provides the basics of slow-fast systems and the conditions for a blue sky catastrophe. Section 3 links the European energy market development with the system dynamics perspective and argues that the electricity market follows a slow-fast logic and thereby is subject to the risk of frozen dynamics. Section 4 discusses the implications for Europe's energy policy and Section 5 concludes.

2. Slow-fast systems and blue sky catastrophe

Before evaluating the dynamics of the energy-policy nexus, we need to understand the general mathematical theory behind slow-fast systems and the blue sky catastrophe. In the following, we provide a short overview on the main properties relevant for our analysis. For an extended presentation and discussion of slow-fast systems we refer to an extensive mathematical literature (e.g., Smith, 1985; Rossetto et al., 1998; Zheng and Wang, 2010; Kuptsov et al., 2017).

Generally speaking, a slow-fast system (also referred to as singularly perturbed or multi-scale system) is a dynamical system composed of processes, each of which operates on a different timescale—that is, one of the processes may be treated as constant (slow) relative to the dynamics of the other (fast). In this case, changes in the fast subsystem are perceived as almost immediate jumps relative to changes in the slow process of the system.

Formally, the slow-fast system can be represented as a differential system with two dynamic variables: a slow one (x) and fast one (y). The ratio between timescales of the fast and slow variable is measured as ϵ, the time-scaling parameter.

$$\begin{aligned}&\dot{x} = f(x, y, \epsilon),\\ &\epsilon\dot{y} = g(x, y, \epsilon),\\ &x \in \mathbb{R}^n,\ n \geq 1,\ \ y \in \mathbb{R}^m,\ m \geq 1.\end{aligned} \tag{1}$$

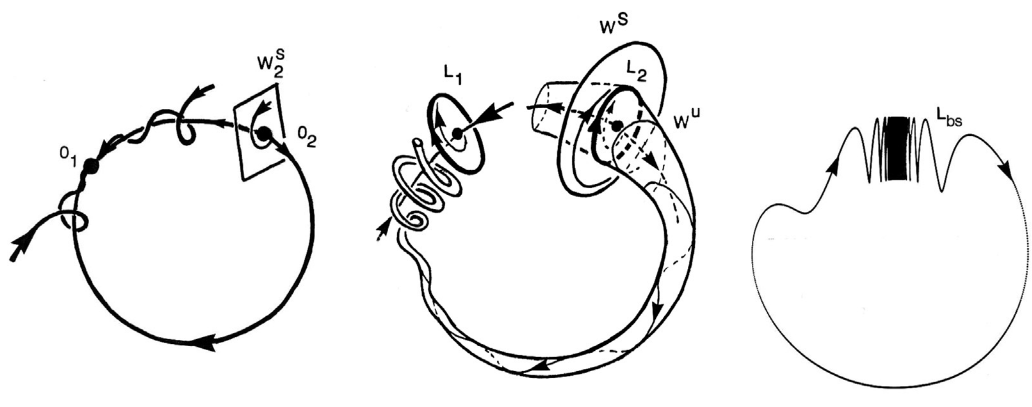
In Eq. (1), f, g are functions of the system variables and of the scaling parameter. For $\epsilon < 1$, the system follows the above defined dynamic with y as the fast system relative to x. If $\epsilon > 1$, the relationship is reversed: x being relatively fast and y slow. The closer the time-scaling parameter ϵ is to zero, the higher is the difference in the timescales of the two components of the system. In particular, if $\epsilon \to 0$ the y component is perceived as an impulse by the x component of the system, while the x component is perceived as constant by the y component. The same logic applies to systems with more than two components.

One of the crucial features of such slow-fast systems is that small changes in the timescale difference, ϵ, between the slow and fast parts may lead to drastic qualitative changes in the system dynamics known as bifurcations. One particularly intriguing type of these bifurcations is the blue sky catastrophe, described in Turaev and Shilnikov (1995).

When the dynamical system undergoes the blue sky catastrophe, the previously observed steady state equilibrium is suddenly destroyed and the system enters a new steady state that is characterized by a cycle of infinite length and period.[3] The unfolding of the blue sky catastrophe is given in Gavrilov and Shilnikov (2000). Fig. 1 (based on Gavrilov and Shilnikov, 2000) provides a schematic illustration of its dynamics.

1. Fig. 1a: There are two equilibria: one stable (denoted O_1) and another saddle-stable (denoted O_2). The system tends from O_2 to O_1 as time continues (transitionary phase).
2. Fig. 1b: Changes in the timescale difference ϵ of the underlying system variables lead equilibrium O_1 to lose stability and become the stable limit cycle L_1. Further changes in ϵ force O_2 to lose stability

[3] It is worth mentioning that the blue sky catastrophe appears simultaneously with the possible onset of chaotic behavior (Gavrilov and Shilnikov, 2000). This 'spiral chaos' could mean the uncontrolled diverging behavior of a system, which is even more dangerous than just freezing.



(a) Two equilibria (b) Two limit cycles (c) The blue sky

Fig. 1. The unfolding of the blue sky catastrophe.

also and to become an unstable limit cycle L_2. Once both O_1 and O_2 become limit cycles, the system transits slowly from L_2 to L_1 as time continues.

3. Fig. 1c: If the timescale difference increases further and passes a particular threshold, both cycles coalesce into a single cycle with infinite length and period. This situation forms the blue sky state L_{bs}.

This complex behavior may seem exotic, but recent results in the studies of the blue sky catastrophe show that any slow-fast system of at least 3 dimensions potentially exhibits this phenomenon. We summarize them as following:

Proposition 1 (*Blue sky catastrophe***).** *Any slow-fast system of at least three dimensions may exhibit the blue sky catastrophe provided the difference in velocities,* ϵ*, of the slow and fast parts of the system is sufficiently high.*[4]

To apply the logic of Proposition 1 to the ongoing energy transition, we must demonstrate that the properties of the energy transition mirror those in Proposition 1. First, we must show that the energy-policy nexus can be described by a slow-fast system of three or more dimensions, and second, that the difference in the velocities (ϵ) of this system's components is changing while we transit from one equilibrium, O_2 (the fossil-nuclear generation system), to another equilibrium, O_1 (the renewable system). If those two properties hold for the European energy transition, we have to face the challenge that during this transition the system may become unresponsive to policy impulses (enter the blue sky state).

3. The European energy transition from a slow-fast system perspective

In this section, we provide arguments justifying that the properties of Proposition 1 hold for the case of the European energy transition and explain what an unresponsive system implies for European energy policy.

3.1. Electricity markets as a slow-fast system

Following Proposition 1, any slow-fast system with a least three dimensions has the risk of a blue sky catastrophe. It is important to notice that this definition does not require any further specification about the functional form of the processes within the slow-fast system. Therefore, a general assessment about the underlying dynamics in a system is sufficient to specify whether it falls into the slow-fast class.

For example, the general design of any industry with the two standard state variables—capital and output—can be formulated like the differential system given in Eq. (1). Capital would represent the slow process, x, and output, the fast process y. f and g would need to be "smooth enough" functions representing those two system variables. As long as the two processes have sufficiently different timescales this setup represents a slow-fast system.

For energy systems, capital represents infrastructure such as pipeline systems, refineries, or power plants. Energy system capital typically exhibit long life- and construction times. Therefore, energy infrastructure systems represents our slow system. On the other hand, the output process represents the specific commodities or services provided to consumers using energy infrastructure (e.g., electricity). Output is governed by inconsistent, short term influences (e.g., fuel price changes) and is more flexible relative to investment decisions. Energy system outputs represent our fast system.

For the European electricity system representation, one could differentiate the slow infrastructure system further into distinguished types: capital related to generation infrastructure and capital related to network infrastructure. The differentiation of the capital function is motivated by the different dynamics of the subsystems of capital. Whereas, plant investment decisions are subject to market prices and competitive pressure in liberalized electricity markets, networks remain regulated. Transmission and distribution networks represent the monopolistic bottleneck of electricity systems and require a form of regulation, even in liberalized electricity markets. Coupled with their long lifetimes and long construction times the investment dynamic follows a relatively smooth structure.

Generation infrastructure has a more dynamic investment behavior as different generation types interact: conventional and renewable. Conventional generation units exhibit long investment cycles with lifetimes between 40 and 60 years and construction times of several years. Renewable plants typically have both shorter lifetimes of 20–30 years as well as faster construction times. Consequently, the functional form of the generation investment subsystem should account for a shift in its dynamics during the energy transition: in a renewable dominated setting the dynamic should be faster and more responsive than in a fossil-nuclear setting. Such a structure could be represented by a convex-concave functional form of reaction time, ϵ, on the fraction of renewables in the system. This functional form generates a multiplicity of equilibria, see Greiner and Bondarev (2017). Or, the two plant categories could be separated by splitting them into two individually defined variables.

These capital processes are dependent on the policy process either through regulation or market incentives. While in theory the whole generation sector should be subject to competitive market incentives, this is not the case for today's European electricity markets. For instance, renewable generation is often subject to additional support mechanisms (e.g., subsidies). Similarly, the output of electricity

[4] Proof is established in Shilnikov et al. (2005) and Glyzin et al. (2008) and combined in Shilnikov et al. (2014). A general idea of it may be found in the Appendix A.

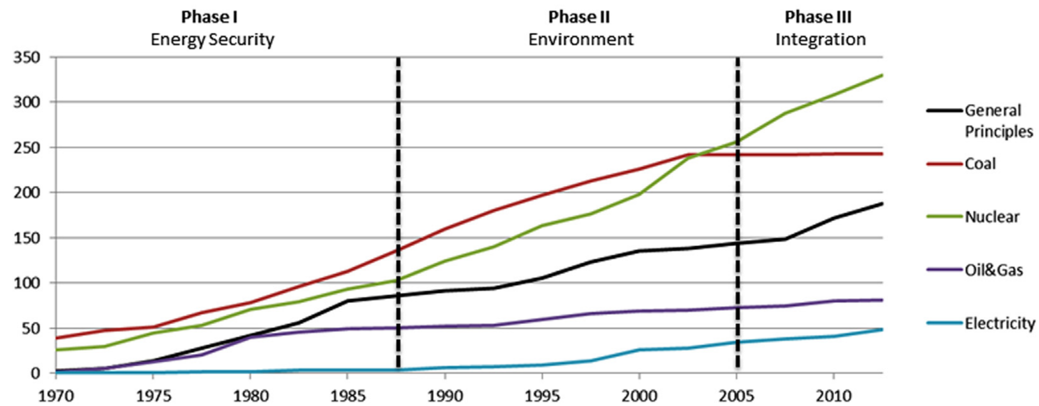


Fig. 2. Number of legislative acts on energy by the European Commission and Council of the EU (Biesenbender, 2015).

systems—the generated electricity—not only depends on the underlying infrastructure and input prices, but also, too a large degree, on market regulations and policy decisions (e.g., priority dispatch for renewables or carbon prices).

An example of this effect can be seen in coal and gas generation. Depending on the price for emission permits, or more generally emission policy, the share of gas used for total electricity production can be higher or lower even without a change in the installed capacities. This is due to the load shape in electricity systems that follows strong daily and seasonal patterns. The load shape requires that the installed capacity, coupled with storage options, be sufficient to meet peak demand. Consequently, a fraction of the capacity is idle during off-peak times allowing for shifts between plant types. Similarly, energy efficiency policies can lead to direct output reductions before an adjustment of the installed generation capacities takes place.

To capture this interaction we propose to deviate from the pure capital-output setup by directly introducing the policy process as dynamic variables, defined by the state of the economic system (the capital and output of the electricity system) and the previous state of policy vector.

Consequently, a representation of the dynamics of the European electricity-policy nexus could be achieved by a differential system with four different underlying processes:

1. A function representing the dynamics of the power plant investment process.
2. A function representing the dynamics of the network investment process.
3. A function representing the output decision process.
4. A function representing the policy making process.

The first two capital elements of electricity markets can be considered as relatively slow systems albeit with different underlying dynamics. In comparison, the output adjustments and the policy process are relatively fast. Besides the generally faster political cycles—four to five years in most countries—energy policy is also altered on a more frequent basis (see Sections 3.2 and 4). Given the interaction of the different components of electricity systems, there are multiple policy channels that impact the decisions made by electricity companies. In many countries, there are several policy measures targeting renewable support and energy efficiency in addition to environmental policies and measures related to market restructuring and network regulation. All those channels increase the likelihood that a policy change impacts the electricity system. Those measures are furthermore adjusted to accommodate new developments and thereby further increase the impact frequency.

In summary, we have shown that an electricity-policy system, as defined by the structure above, can be interpreted as a slow-fast system that meets the first requirement set out in Proposition 1. That is, we have shown the system of capital, output, and policy can be divided into subsystems with different individual velocities. While this representation may seem rather generic, the generality of the system structure is an important property of the argument: regardless of the specific functional form, as long as the system can reasonably be represented by such a structure it falls into the class of slow-fast systems. In the next section, we will show that the velocities of these subsystems have the potential to differ significantly during transitions.

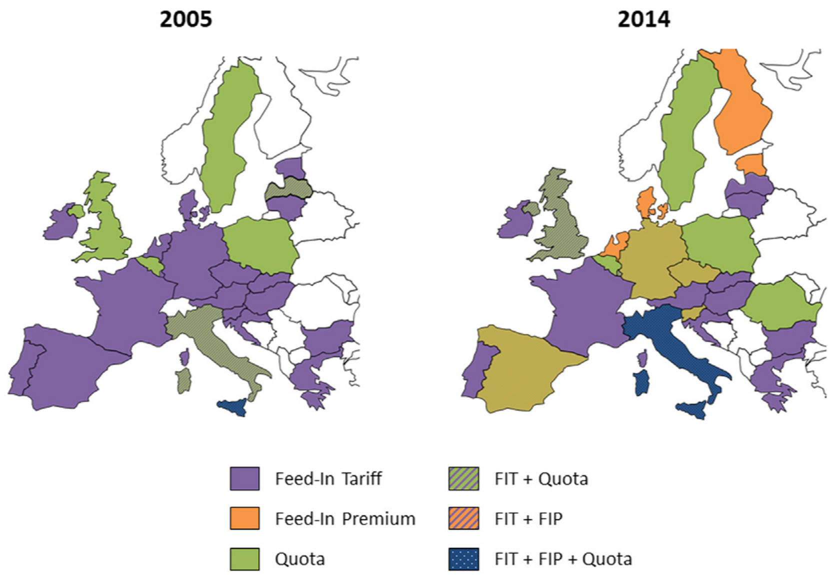
3.2. Structural changes in electricity system dynamics

The second element needed to justify that the blue sky phenomenon is a potential threat to the European electricity system is to identify whether there is a change in the relative velocities of the system's components during the transition process (which we refer to as structural changes).

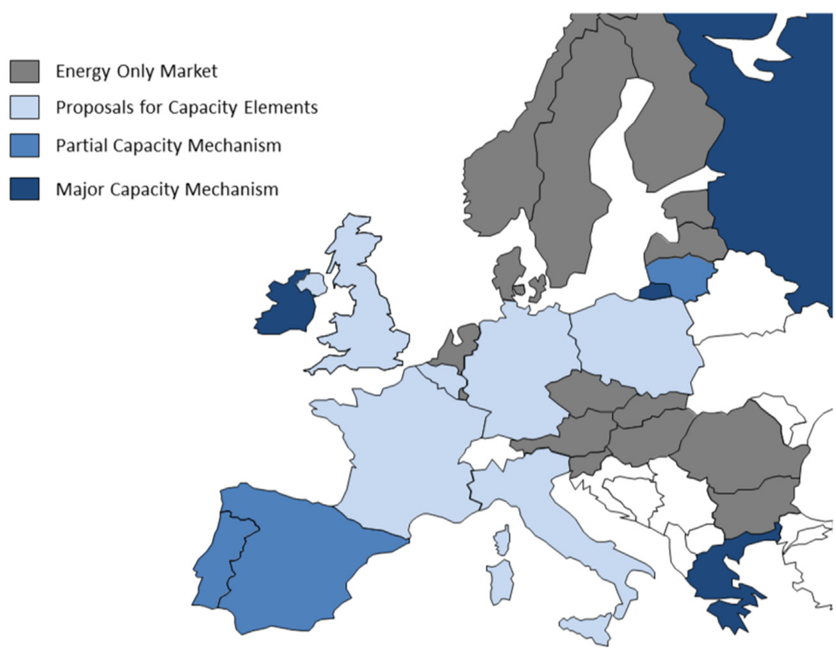
European energy markets have always been subject to multiple policy interventions and were and are often embedded in strong regulatory frameworks. Besides national laws and regulation, energy policy has been a core element of the European Union and its economic development since its first days with the European Coal and Steel Community and the European Atomic Energy Community (Kanellakis et al., 2013). Historical EU energy policy can be clustered in three stages: first, from the 1950s up to the late 1980s, the focus was mainly on energy security; second, from the late 1980s up to mid-2000s, environmental policy became a major focus; and third, since the mid-2000s, the functioning and interconnection of energy markets, renewable energy support, and energy efficiency targets were added to the policy agenda (Biesenbender, 2015). These developments have been complemented by a steady increase of energy related legislative action (Fig. 2).

Fig. 2, along with the history of European energy policy development, provides strong suggestive evidence that the increase in legislative action has also induced a change in the actual speed of policy interventions themselves and the dynamics of the underlying electricity capital-output system. In particular, three specific areas illustrate this assertion: market liberalization, renewable support, and climate policies.

Before the European liberalization process was initiated, electricity systems were regulated or state-owned vertically integrated monopolies. However, starting in the late 1980s, the first policies toward restructuring emerged cumulating in a wave of market liberalizations in Europe (e.g., Jamasb and Pollitt, 2005). The liberalization was not achieved immediately but rather was an ongoing process that required continuous monitoring and adjustments (Hogan, 2002; Joskow, 2008): incremental steps toward liberalization can be seen in the first, second, and third European Energy Packages (Directive 96/92/EC, Directive



(a) Renewable support schemes



(b) Capacity mechanisms

Fig. 3. Development and divergence in European energy policies (Fortum, 2014, Haas et al., 2011).

2003/54/EC, and Directive 2009/72/EC). In addition, the envisioned internal electricity market continues to require greater coordination of national electricity markets allowing for cross-border trade, so-called market coupling (e.g., Newbery et al., 2015), and more consistent investment planning of the national system operators (i.e., the Ten-Year Network Development Plans by the European Network of Transmission System Operators). European energy market liberalization is an example of policy interventions setting off a cascade of follow-up policies and planned interventions.

Renewable support emerged in the 1990s and took up speed in the early 2000s. Contrary to the liberalization process, renewable support schemes are typically national. Consequently, there have been varied developments of renewable policies in the different countries. Generally speaking, during the first decade until 2010 price based mechanism (especially feed-in tariffs) were applied by most countries. This phase was followed by a shift towards more market oriented and complex support schemes (i.e. a shift from tariffs to premiums or a combination of different support elements) leading to a higher divergence of support mechanisms across Europe (Fig. 3a). Furthermore, those schemes have been frequently adjusted and adapted in the last years. Although a European policy harmonization is still in discussion (e.g., Unteutsch and Lindenberger, 2014; Strunz et al., 2018), the push of the European commission towards tender based support schemes could lead to a fast convergence (i.e. Tews, 2015).

Given that different national electricity markets are interconnected, changes in the policy regime of one country also has impacts on the market actors in neighboring countries. An example of such a development is the large increase of photovoltaic generation in Germany in recent years (Frondel et al., 2014). This induced a direct adjustment of the German renewable energy law in 2012 (e.g., with a significant reduction of feed in tariffs) but also led to a shift in the hourly price structures reducing the price level and the output of conventional power plants in Germany and neighboring countries (the so-called “merit order effect” (Cludius et al., 2014)). Related to renewable support is the debate on the integration of increasing shares of intermittent renewable energies into the electricity system. One of the main concerns is the need for back-up capacities and their financing, the so-called capacity market debate. There are several (national) capacity mechanisms and market approaches in place or under discussion (Fig. 3b). Changes to renewable supports and subsequent market interventions illustrate how more policy responses have arisen from increased interconnectedness.

Finally, environmental and climate related regulations gained prominence in the 1990s and still today continue to influence European energy policy. Of particular importance is the European Emission Trading System (EU ETS) (Ellerman et al., 2014). From the first discussions on greenhouse gas emission trading in 2000, it took only five years for the EU to initiate the first phase of the EU ETS. However, price levels crumbled to zero by the end of the first phase due to over allocation. The price level in the second phase (2008–2012) started rather high, but in the wake of the economic downturn and the rise of renewable energies, the price level declined and has remained below 10 EUR/ton of CO_2 since 2011. Besides the price impact on electricity market decisions, the allocation mechanism for the allowances was also changed from the first two phases (grandfathering) to the current third phase (auctioning). The imperative to initiate and correct environmental and climate regulation has led to rapid policy adjustments in Europe in recent years.

In general, Europe's energy and climate policies are highly interlinked and impact each other (e.g., Helm, 2014) and there is a multitude of further regulatory and policy decisions that have a direct or indirect effect on electricity market actors: energy efficiency policies, the restructuring on the European natural gas market, environmental regulations for fossil fuels, nuclear policy, and support schemes for electricity vehicles, to name a few. Thus, we conclude that—at least in recent years—the policy environment has become increasingly dynamic and complex.

Based on these observations, it is a plausible conclusion that the speed of the policy subsystem of the European electricity-policy nexus has increased in recent years. Connecting this conclusion to our slow-fast system model, we show there is a change in the velocity of the system during the transition process as policy makers aim to steer the overall system development consistent with the requirements of Proposition 1. These interventions—coupled with the increase in international and sectoral connections—should lead to a higher timescale difference between the investment and policy subsystems leading to an increased risk of bifurcations including the blue sky option.

3.3. Frozen transition dynamics

Continuing the argumentation of the last two subsections, we claim that the slow-fast electricity-policy system exhibits the characteristics necessary to induce the risk of a blue sky option. Then, the question remains what this actually implies for the ongoing European energy transition.

In order to get a better understanding of the resulting dynamics in this context, we can apply the basic schematic illustration of the blue sky catastrophe given in Fig. 1 to the dynamics of an energy transition process. We focus on the generation investment subsystem, but the same logic also applies to the network investment subsystem. Fig. 4 shows the basic structure of the three stages:

1. Fig. 4a: In the initial system state, the generation investment subsystem is in an equilibrium representing a fossil and nuclear power plant mix (O_2 in Fig. 1a). Even without any further policy interventions this system would gradually move towards a renewable based supply (O_1 in Fig. 1a) given the limited availability of fossil fuels and decreasing costs of renewable power plants: the normal, albeit very slow, transition process.
2. Fig. 4b: Policy interventions now alter this system state. The new renewable equilibrium will react to the policy choices; that is, renewable subsidies could alter the composition of the renewable plant mix the system would naturally transition to (the stable limit cycle L_1 in Fig. 1b). Also, the existing fossil-nuclear system equilibrium reacts to policy changes; that is, climate policy changes the preferences for specific fossil fuels and makes it unattractive to stay in a fossil-nuclear setup (the unstable limit cycle L_2 in Fig. 1b). Again, the system transits from the fossil-nuclear state into the renewable state over time. This is the desired system development for the European energy transition.
3. Fig. 4c: If policy interventions become too frequent the system runs the risk of entering the blue sky state (both limit cycles coalesce into a single one with infinite length and period). The blue sky state results in a freeze of system dynamics; instead of transiting from the fossil-nuclear into the renewable state the system remains in its current state.

Relating this structure to the European energy and electricity market history, we could define the state of the system before 1990 as an equilibrium with rather stable dynamics. Significant policy interventions were relatively infrequent and the system was regulated and not open to competition; in mathematical terms, ϵ was relatively large. The dynamics of infrastructure adjustments were stable and predictable following demand growth trends with few policy changes.

With the emergence of the market restructuring debate and growing concerns about environmental topics in the late 1980s, policy interventions started to become more frequent, a trend that continues today; ϵ is significantly decreasing. The policy system is gradually moving towards a situation with faster dynamics. This increase in policy interventions is shifting the system towards a situation with higher variations in the dynamics of the infrastructure functions. For example, the existing fossil-nuclear plant mix is becoming increasingly unattractive while renewable investments become more attractive.

Currently, the European energy system is in this transition phase where policy changes are inducing shifts in infrastructure investments. The blue sky phenomenon postulates that during this phase the risk of a ‘system freeze’ increases with the speed of policy interventions. In the case of a complete ‘system freeze,’ neither the dynamics of conventional nor renewable investments would change anymore. The system would stop reacting to policy changes. In other words, increasing the frequency of interventions to speed up the transitions process would run the risk of actually slowing or even stopping the transition process.

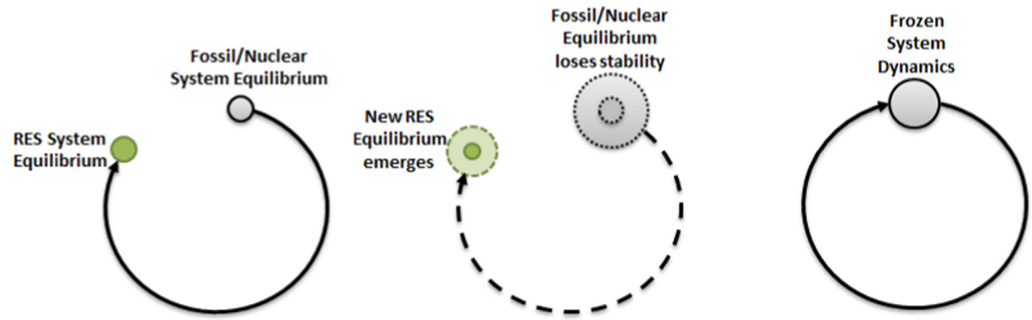
Summarizing the above described dynamic relation into a political economic conclusion we state the following:

Proposition 2 (*Policy interventions and electricity system freeze*). *The more frequent are policy regime changes in the electricity sector, the higher is the probability of a structural break in the system leading to a freeze in the slow parts of the system.*

4. Frozen system dynamics in the context of European energy policy

What policy conclusions and recommendations need to be drawn from Proposition 2 and what steps would be needed to prevent the emergence of frozen transition dynamics?

First, note that we do not postulate that the European electricity system is already in a state of frozen dynamics. Given the development so far and the expected system developments and adjustments, the European electricity system is likely within the transition phase with an



(a) Normal Transition Process (b) Policy Interventions (c) Blue Sky State

Fig. 4. The unfolding of the blue sky state in an energy system.

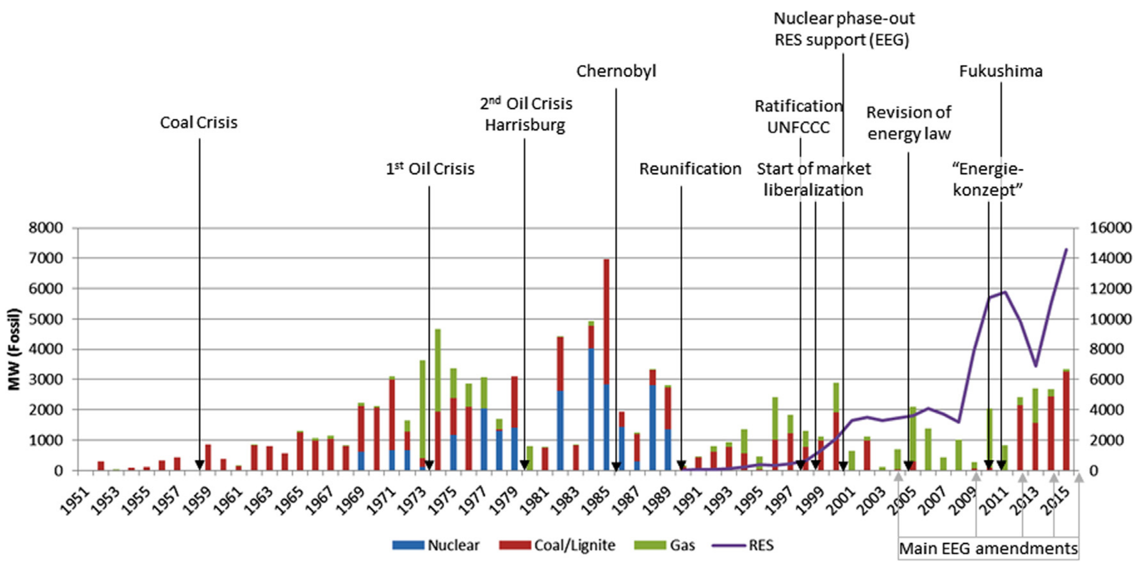


Fig. 5. Power plant investments and major policy/market events (investment data derived from Bundesnetzagentur and Umweltbundesamt, policy events based on Renn and Marshall, 2016).

increased velocity of the policy interventions as given by Fig. 4b. Germany can be seen as a reasonable example for this statement. Fig. 5 shows the policy development and the power plant investments in the last decades.

While it is obvious that the frequency of policies increased, the investment system does not seem to show a direct feedback or a freeze of its reaction. Keep in mind that a 'system freeze' does not mean a breakdown of the system nor that no further investments will occur. It entails a freeze in the slow component: investment in power plant infrastructure. At least for Germany, this is not yet observable. There is still a gradual shift from the fossil-nuclear dominated mix towards a higher share of renewables induced by the support policies.

The challenge stemming from the risk of a blue sky phenomenon is how to react to the ongoing system development. Given the envisioned transition of the electricity system towards a renewable dominated generation portfolio, large scale investments in generation (ca. 300–500 GW of renewable and conventional capacity need to be installed in each coming decade, (see Capros et al., 2013)) and network capacities (ca. 150 bn EUR, see the Ten-Year Network Development Plans by ENTSOE) will be needed. If those expected developments do not materialize as planned, policy makers are likely to alter the policy framework.

Examples for such discussions and adjustments are alterations of renewable support mechanisms: the 2012 renewable moratorium in Spain; the 2012 photovoltaic amendment of the German feed-in tariff; the switch to a tender system in Germany in 2017; the altered rules for the three trading phases of the EU ETS; or the capacity market debate stemming from the financial troubles of many large utilities (Butcher, 2013). All these alterations increase the uncertainty for investments and can easily render investment plans unprofitable.

The ongoing developments show that a transition between system equilibria is not necessarily a smooth process. The risk of a system freeze may indeed be a real threat if investment incentives are changing too frequently. The natural reaction to unwanted developments is to further alter and adjust policies. Given the increasing complexity of the European energy policy framework and the increasing market interlinkage, the likelihood of adjustments increases with the number of implemented policies. This could lead to a self-reinforcing cycle.

A related interpretation of this potential development is the perception of regulatory risk by firms. If firms perceive policy changes become too frequent and unpredictable, firms may only make changes in investments that are not vulnerable to fluctuations in the regulatory framework. This is basically the frozen nature of the system in case of a blue sky catastrophe. Two examples of those uncertainties and their impact on investment are the EU ETS and the ongoing capacity market debate. Currently, phase IV of the EU ETS, covering the time frame from 2021 to 2030, is under discussion. As investment decisions carried out today will remain in operation until at least 2040, the uncertainty about the long-term market rules has direct impacts on the resulting investment projects. Similar, the perceived need for additional financing instruments for back-up capacities to cope with the intermittent nature of renewables has led to multiple national discussions on adjusting or implementing capacity mechanisms (Fig. 3b). The uncertainty on when and what type of mechanisms will be implemented sets incentives to postpone investments until the mechanisms are in place to benefit from the associated financial flows.

Following the logic of the presented slow-fast dynamics, an ideal policy approach is aimed at long-term incentive structures with less frequent but more consistent policy interventions. To avoid a system freeze, the policy process should provide relatively stable and predictable implications for market actors. The lower frequency of interventions gives participants time to learn and adapt to the new market realities. This does not mean that the policy framework should be unresponsive to system developments. However, the adjustments should be part of the policy design ex-ante and not imposed ex-post; for example, linking the renewable support levels to quantity targets or imposing price caps and floors in quota mechanisms.

This interpretation of the policy dimension of the slow-fast system dynamics also provides a linkage with the debate on policy commitment and the literature on time inconsistency and policy making under uncertainty. For example, Habermacher and Lehmann (2017) assess under which conditions long-term policy rules should be applied in an energy and climate policy context. Our above presented conclusion that the policy design should provide a reliable long term framework oriented at the desired transition process mirrors the conclusion of Habermacher and Lehmann that a rule-based commitment represents the optimal policy approach. If a state-contingent commitment is not practical they show that in many cases a long term commitment is preferable to discretion to adjust policies to new developments. The risk of a blue sky bifurcation adds a further argument to favor long term commitments over (too frequent) policy adjustments.

Summarizing, the risk of a blue sky phenomenon with frozen system dynamics calls for well-structured, harmonized interventions across Europe. Implementing too many individual policy targets and national approaches without accounting for the high interaction among targets and between cross-border electricity systems, runs the risk of destabilizing the desired transition. The proposed focus on a stable energy policy framework is also in line with the ongoing discussions on a more consistent European policy (Rüdinger et al., 2014; Böhringer et al., 2016).

5. Conclusion and policy implications

In this paper, we propose an analogy between the ongoing European energy transition with the theory of slow-fast systems. Through this analogy, we identify potential insights from system dynamics for policy design. We postulate that the energy-policy nexus can be described by the interplay of a slow process—the investments dynamics in generation and network infrastructure—with a relatively fast system—-describing the policy regime and its changes. Given such a structure, the energy policy system may be subject to the so-called blue sky catastrophe, a situation in which frequent policy changes may paralyze the transition between energy regimes by discouraging new investments.

Of course, a European energy regime transition away from fossil-nuclear generation towards a renewable electricity supply will require policy interventions. The insights from this system dynamics analysis offer a comprehensive policy logic: aim for rather infrequent but consistent long-term policy interventions, aligned with the investment cycles of the underlying industry, and account for cross-sectoral and cross-border interrelations. A temporary slowdown in the dynamics of investments should not necessarily be interpreted as a call for more interventions, since it might well be the case that such a temporary slowing is followed by a period of very active changes as soon as the actors in the industry learn and understand new rules of energy policy.

A next step, beyond the scope of this paper, is the actual quantification and calibration of the postulated slow-fast system to the European electricity system to identify at which frequencies of policy interventions the system has an increased risk of unwanted dynamics.

Appendix A. Sketch of the proof of Proposition 1

In describing the proof below we closely follow Shilnikov et al. (2005). Proofs for 1-dimension, fast and 2-dimension, slow structures may be found in Glyzin et al. (2008) and are analogous. In what follows, we tried to capture the main points necessary for the proof while keeping the generality of an argument intact.

1. Rescale the time parameter by setting $\tau = \epsilon t$ the system (1) becomes

$$\begin{aligned} x' &= \epsilon g(x, y, \epsilon),\\ y' &= h(x, y, \epsilon) \end{aligned} \tag{A.1}$$

where prime denotes the derivatives of x, y with respect to newly defined time τ and let $\epsilon \to 0$:

$$\begin{aligned} x' &= 0,\\ y' &= h(x, y, \epsilon) \end{aligned} \tag{A.2}$$

calling thus defined y-component of the system a *fast* subsystem and x-component a *slow* subsystem.

2. Study possible dynamics of the transformed system (A.2). It turns out, that (putting aside strange attractors), the fast system goes to either stable equilibria or to the periodic orbit. When such equilibria are exponentially stable, they depend smoothly on x. We thus obtain a smooth attracting invariant manifold of the system (A.2): it consists in (x, y) space of equilibrium curves M_{eq} and/or two-dimensional cylinders for limit cycles M_{po}.
3. Such a manifold near any equilibrium (or periodic) point of subsystem y' forms a center manifold of the system (A.2). Thus smooth attractive invariant manifolds $M_{eq}(\varepsilon)$, $M_{po}(\varepsilon)$ exist for any sufficiently small ε for the initial system (A.1).
4. Find equilibrium and periodic states of the fast subsystem from

$$\begin{aligned} h(x, y, 0) = 0 &\to y = y_{eq}(x) \subset M_{eq},\\ h(x, y, \tau) = 0 &\to y = y_{po}(\tau, x) \subset M_{po} \end{aligned} \tag{A.3}$$

with period of τ being $T(x)$.

5. Define the dynamics of the slow component as

$$\dot{x} = g(x, y_{eq}(x), 0) \tag{A.4}$$

$$\dot{x} = \varphi(x) = \frac{1}{T(x)} \int_0^{T(x)} g(x, y_{po}(\tau, x, 0)) d\tau, \tag{A.5}$$

for equilibrium and periodic orbits of the fast subsystem respectively.

6. Study the critical values of x that cause bifurcations of the fast subsystem, denote thresholds associated with stable branches $M_{eq}(x)$ by $x_0^*,..,x_k^*$.
7. Study the dynamics of the fast system going from x_{j-1}^* to x_j^*. It turns out that fast system slowly drifts from preceding values to the next ones, i.e. from x_{j-1}^* to x_j^* with equilibrium at x_{j-1}^* becoming a saddle-stable while x_j^* is asymptotically stable.
8. Once $j = k$ (i.e. all stable equilibria are exhausted), the unstable manifold tends to the periodic one, M_{po}.
9. Study the dynamics of periodic manifold M_{po} over changing x. It turns out to tend to initial saddle or asymptotically stable manifolds M_{eq}^0 or M_{eq}^1. Three different scenarios are possible.
10. Embed the slow-fast system (A.1) into one parameter family (defined by the time-scale depending parameter $\mu(\varepsilon)$). By construction, the Poincare map for x has two fixed points for $\mu < \mu^*(\varepsilon)$ on the attracting manifold $M_{po}(\varepsilon)$.
11. Consider a small neighbourhood U surrounding $M_{po}(\varepsilon)$ and M_{eq}^j. The Poincare map for x would undergo bifurcation colliding two stable orbits into one at $\mu = \mu^*(\varepsilon)$.
12. The blue sky catastrophe happens as soon as this single orbit attracts all others and is a limit cycle, which period and length tends to infinity.
13. The rest of the proof consists in studying those Poincare maps T_0, T_1 transversing μ^* and proving that their superposition is a contraction (implying unique limit cycle L_μ) and number of iterations are required to return from one part to the other tends to infinity while approaching $\mu^*(\varepsilon)$.

References

Abrell, J., Rausch, S., 2017. Combining price and quantity controls under partitioned environmental regulation. J. Public Econ. 145 (C), 226–242.

Allgöwer, F., Zheng, A., 2012. Nonlinear Model Predictive Control. Progress in Systems and Control Theory. Birkhäuser, Basel.

Biesenbender, S., 2015. The EU's Energy Policy Agenda: Directions and Developments. Springer, London, pp. 21–40.

Böhringer, C., Keller, A., Bortolamedi, M., Seyffarth, A.R., 2016. Good things do not always come in threes: on the excess of overlapping regulation in EU climate policy. Energy Policy 94, 502–508.

Bréchet, T., Camacho, C., Veliov, V.M., 2014. Model predictive control, the economy, and the issue of global warming. Ann. Oper. Res. 220 (1), 25–48.

Brozović, N., Schlenker, W., 2011. Optimal management of an ecosystem with an unknown threshold. Ecol. Econ. 70 (4), 627–640.

Butcher, B., 2013. How to lose half a trillion euros. Economist.

Capros, P., Vita, A.D., Hoeglund-Isaksson, L., Winiwarte, W., Purohit, P., Bottcher, H., Frank, S., Havlik, P., Gusti, M., Witzke, H., 2013. EU Energy, Transport and GHG Emissions Trends to 2050 – Reference Scenario 2013. Publications Office of the European Union, Luxembourg.

Carpenter, S., Walker, B., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4 (8), 765–781.

Cludius, J., Hermann, H., Matthes, F.C., Graichen, V., 2014. The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: estimation and distributional implications. Energy Econ. 44, 302–313.

Cramton, P., Ockenfels, A., Stoft, S., 2013. Capacity market fundamentals. Econ. Energy Environ. Policy 2, 2.

Crépin, A.-S., Norberg, J., Mäler, K.-G., 2011. Coupled economic-ecological systems with slow and fast dynamics modelling and analysis method. Ecol. Econ. 70 (8), 1448–1458.

Ellerman, A., Marcantonini, C., Zaklan, A., 2014. The EU ETS: eight years and counting. Robert Schuman Centre for Advanced Studies Research Paper 2014/04, Robert Schuman Centre for Advanced Studies.

Finon, D., Keppler, J.-H., Roques, F., 2017. Special section: towards hybrid market regimes in the power sector. Energy Policy 105, 547–549.

Fortum, 2014. Fortum energy review august 2014. Fortum energy reviews 2014/08. Fortum.

Frondel, M., Schmidt, C.M., Vance, C., 2014. Revisiting Germany's solar cell promotion: an unfolding disaster. Econ. Anal. Policy 44 (1), 3–13.

Gavrilov, N., Shilnikov, A., 2000. Example of a blue sky catastrophe. Am. Math. Soc. Transl. 200 (2), 106–399.

Glyzin, S.D., Kolesov, A.Y., Rozov, N.K., 2008. Blue sky catastrophe in relaxation systems with one fast and two slow variables. Differ. Equ. 44 (2), 161–175.

Greiner, A., Bondarev, A., 2017. Optimal R&D investment with learning-by-doing: multiple steady-states and thresholds. Optim. Control Appl. Methods. http://dx.doi.org/10.1002/oca.2301. (Online first publication).

Haas, R., Panzer, C., Resch, G., Ragwitz, M., Reece, G., Held, A., 2011. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. Renew. Sustain. Energy Rev. 15, 2.

Habermacher, F., Lehmann, P., 2017. Commitment vs. discretion in climate and energy policy. CESifo Working Papers 6355, CESifo.

Helm, D., 2014. The European framework for energy and climate policies. Energy Policy 64, 29–35.

Hogan, W.W., 2002. Electricity market restructuring: reforms of reforms. J. Regul. Econ. 21 (1), 103–132.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1–23.

Jamasb, T., Pollitt, M., 2005. Electricity market reform in the European Union: review of progress toward liberalization & integration. Energy J. 11–42 (SI).

Joskow, P.L., 2008. Lessons learned from electricity market liberalization. Energy J. 9–42 (SI).

Kanellakis, M., Martinopoulos, G., Zachariadis, T., 2013. European energy policy – a review. Energy Policy 62, 1020–1030.

Kunz, F., 2013. Improving congestion management: how to facilitate the integration of renewable generation in Germany. Energy J. Vol. 34 (4).

Kuptsov, P.V., Kuznetsov, S.P., Stankevich, N.V., 2017. A family of models with blue sky catastrophes of different classes. Regul. Chaotic Dyn. 22 (5), 551–565.

Neuhoff, K., Bach, S., Diekmann, J., Beznoska, M., El-Laboudy, T., 2013. Distributional effects of energy transition: impacts of renewable electricity support in Germany. Econ. Energy Environ. Policy 2 (1).

Neuhoff, K., Ruester, S., Schwenen, S., 2015. Power market design beyond 2020: time to revisit key elements? DIW Berl. Discuss. Pap. 1456.

Newbery, D., Strbac, G., Viehoff, I., 2015. The benefits of integrating European electricity markets. Cambridge Working Papers in Economics 1509. Cambridge University.

Petitet, M., Finon, D., Janssen, T., 2017. Capacity adequacy in power markets facing energy transition: a comparison of scarcity pricing and capacity mechanism. Energy Policy 103, 30–46.

Renn, O., Marshall, J.P., 2016. Coal, nuclear and renewable energy policies in germany: from the 1950s to the energiewende. Energy Policy 99, 224–232.

Rossetto, B., Lenzini, T., Ramdani, S., Suchey, G., 1998. Slow-fast autonomous dynamical systems. Int. J. Bifurc. Chaos 08 (11), 2135–2145.

Rüdinger, A., Spencer, T., Sartor, O., Mathieu, M., Colombier, M., Ribera, T., 2014. Getting out of the perfect storm: towards coherence between electricity market policies and EU climate and energy goals. IDDRI Working Papers 12/2014. IDDRI.

Shilnikov, A., Shilnikov, L.P., Turaev, D., 2005. Blue-sky catastrophe in singularly perturbed systems. Mosc. Math. J. 5, 269–282.

Shilnikov, L.P., Shilnikov, A.L., Turaev, D.V., 2014. Showcase of blue sky catastrophes. Int. J. Bifurc. Chaos 24 (08), 1440003.

Smith, D., 1985. Singular-Perturbation Theory: An Introduction with Applications. Cambridge University Press, Cambridge.

Strunz, S., 2014. The German energy transition as a regime shift. Ecol. Econ. 100, 150–158.

Strunz, S., Gawel, E., Lehmann, P., Söderholm, P., 2017. Policy convergence as a multifaceted concept: the case of renewable energy policies in the European Union. J. Public Policy 1–27. http://dx.doi.org/10.1017/S0143814X17000034.

Tews, K., 2015. Europeanization of energy and climate policy: the struggle between competing ideas of coordinating energy transitions. J. Environ. Dev. 24 (3), 267–291.
Turaev, D.V., Shilnikov, L.P., 1995. Blue sky catastrophes. Dokl. Akad. Nauk 342 (05), 569–599.
Unteutsch, M., Lindenberger, D., 2014. Promotion of electricity from renewable energy in Europe post 2020 – the economic benefits of cooperation. Z. für Energ. 38 (1), 47–64.
Walker, B., Holling, C.S., Carpenter, S., Kinzig, A., 2004. Resilience, adaptability and trasformability in social-ecological systems. Ecol. Soc. 9 (2) (5(online)).
Xepapadeas, A., 2010. Modeling complex systems. Agric. Econ. 41, 181–191.
Zheng, Y., Wang, Z., 2010. Delayed hopf bifurcation in time-delayed slow-fast systems. Sci. China Technol. Sci. 53 (3), 656–663.