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

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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-

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[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.

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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

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[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.