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Sensitivity of energy system investments to policy regulation changes: Application of the blue sky catastrophe

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Sensitivity of energy system investments to policy regulation changes: Application of the blue sky catastrophe

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May 11, 2017

Abstract

In this paper we argue, that the interaction of technology and economic policy regulations in the energy sector may be described by the so-called slow-fast class of dynamical systems. It is known that such systems may exhibit the blue sky catastrophe, a special type of bifurcation. Application of this result allows us to argue that caution is needed when updating economic policies in the energy sector to avoid the onset of catastrophic developments in the system's transformation, when energy system dynamics becomes unresponsive to policy updates.

Keywords: energy infrastructure, investments cycle, economic policy, slow-fast systems, blue sky catastrophe.

JEL classification: L51, Q48, C6, C02

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1 Introduction

The European energy policy aims to achieve a fully integrated European energy market and decarbonisation of the economy in the long run. This requires a transition of the current fossil fuel based supply structure towards a supply that is mainly based on renewable energies. In order to achieve this ambitious target a multitude of policy interventions have been put in place in the last decades. The European 2020 climate and energy package - imposing a 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables, and 20% improvement in energy efficiency by 2020 - is a good example of the complexity of this endeavor.

Within this transition the electricity market will play an important role as it covers a large share of Europes greenhouse gas emissions and will require a significant system shift to accommodate intermittent solar and wind generation. However, the development in the last years has raised some concerns about the feasibility of the current transition path. The increasing share of renewables not only requires significant back-up capacities that need to be financed but also the adjustment of the electricity network to allow a better exchange between surplus and deficit regions. At the same time the subsidized renewable energies push wholesale prices down and reduce demand for conventional power plants. This has put many large utilities into cost pressure forcing them to write off part of their assets and retire capacities leading them to also demand some form of subsidies - the so called capacity market debate. Overall, currently it is unclear how fast the system can actually be transformed and which further steps will be needed to achieve the desired transition.

In this paper we recast the ongoing market and policy processes of the European electricity system into the class of slow-fast systems, which are characterized by two or more processes with different time scales. The distinguishing property of such a system is that some of its components are changing much faster than the others. We first argue that the European electricity system includes such processes of different speeds and next discuss the potential of a blue sky catastrophe, studied in (Turaev and Shilnikov, 1995) for this system.

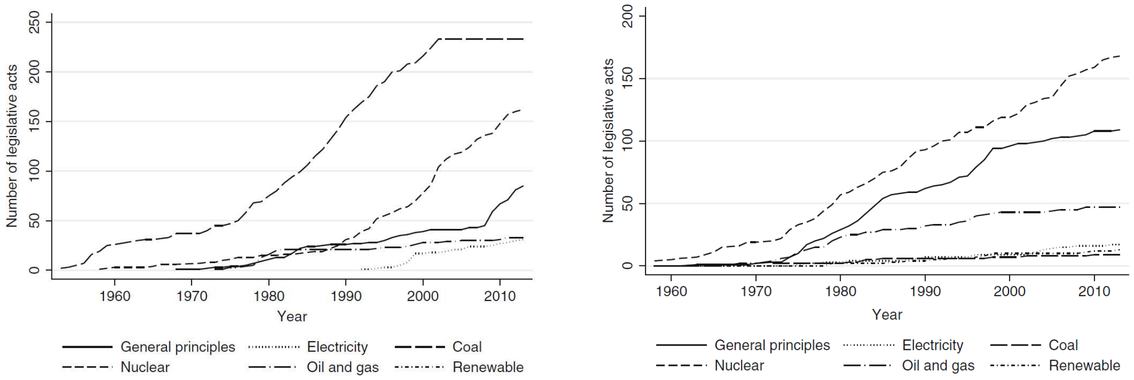
The blue sky catastrophe essentially describes the state of a system, when it goes into cycle of infinite period and length when time scale differences between slow and fast parts of the system is high enough. We adapt this result to the description of energy policy system which results in the danger of the system becoming insensitive to policy regulations.

The remainder of this paper is structured as follows. Section 2 provides a review on the European energy policy process and the current system status and open debates. Section 3 provides the basics of slow-fast systems and the needed conditions for a blue sky catastrophe. Section 4 applies these basics to the European electricity market introducing a formulation of the electricity market as slow-fast system and relating the blue sky catastrophe possibility to ongoing market and policy dynamics. Section 5 discusses the implications for Europe's energy policy and Section 6 concludes.

2 Overview of the European energy policy and electricity market development

Due to their importance for modern economies energy markets are subject to multiple policy interventions and are often embedded in strong regulatory frameworks. The European energy markets are no exception. Beside national laws and regulation, energy policy has been a core element of the European Union since its first days with the European Coal and Steel Community and the European Atomic Energy Community. Following (Biesenbender, 2015) the 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. These developments have been complemented by a steady increase of energy related legislative action (Figure 1).

A perfect example for the role of energy policy on market developments are the European electricity markets. The European electricity systems have been regulated or state owned vertically integrated systems with either a nationwide or regional monopoly struc-



(a) European Commission

(b) Council of the EU

Figure 1: Number of legislative acts on energy (taken from: Biesenbender, 2015)

ture for most of the 20th century. Starting in the late 1980s first concepts of restructuring those systems emerged cumulating in a wave of market liberalizations in Europe (e.g. see (Jamasb and Pollitt, 2005)). The liberalization was no one-shot event but an ongoing process that required continuous monitoring and adjustments.[1] Within Europe three major directives were issued to initiate and adjust the restructuring process: The first Energy Package (Directive 96/92/EC) implemented common rules and lead to the market opening, the Second and Third Energy Package (Directive 2003/54/EC and Directive 2009/72/EC) focused on convergence requiring a regulatory body, regulated third party access, unbundling and full market openness. The main objective of the market restructuring is a liberalized, market-based, Europe-wide electricity market (Internal Electricity Market). This required a further coordination of the so far national electricity markets allowing for cross border trade (the so called market coupling, e.g. see (Newbery, Strbac and Viehoff, 2015)) and a 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). Nevertheless, even after two decades of market restructuring the envisioned integrated EU electricity market is not yet achieved.

Parallel to the market restructuring a second stream of policy interventions emerged in the 1990s, took up speed in the early 2000s and is largely reshaping the European elec-

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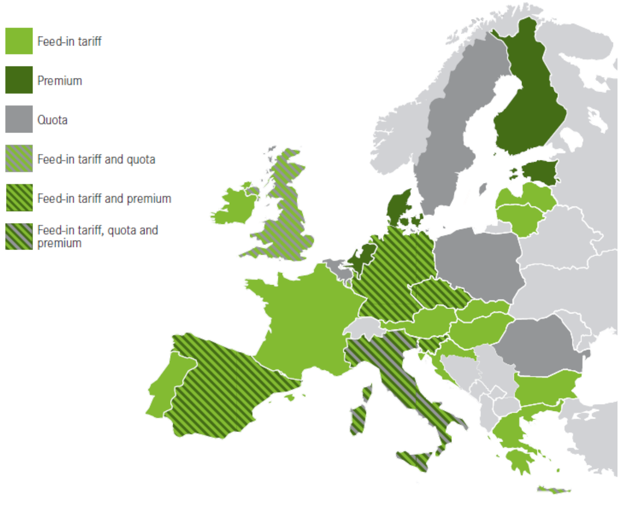
[1] i.e. termed ”reforms of reforms” by (Hogan, 2002); see also (Joskow, 2008)

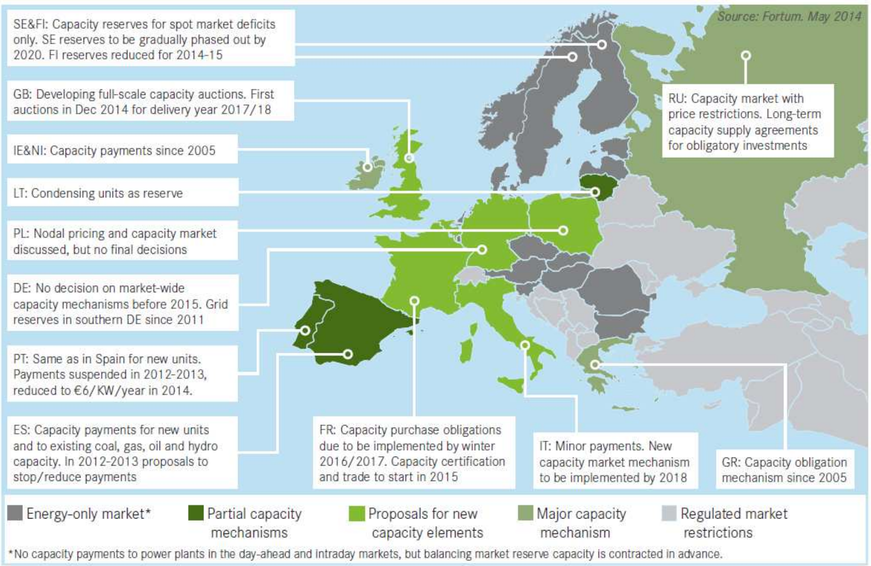
tricity systems in recent years: renewable energies. Contrary to the liberalization process renewable support schemes are largely national and a consistent European convergence and harmonization is still in discussion (e.g. see (Unteutsch and Lindenberger, 2014), and (Strunz et al., 2015)). Consequently there is large divergence between national support mechanisms (Figure 2a) and a large difference in the share of renewable energies across countries. Given the interconnection of the different national electricity markets changes in the policy regime of one country have 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, Shmidt and Vance, 2014). This induced a direct adjustment of the 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 (the so called merit order effect, see (Cludius et al., 2014)). This impact of renewable energies coupled with their intermittent nature and concerns about system stability and security has spurred debates about the need for financing systems for back-up capacities. There are several capacity mechanisms in debate including establishment of capacity markets, capacity payments or strategic reserves (Figure 2b). Similar to the renewable support the debate is still mainly on a national level but the implementation in one country will also impact market actors in other countries.

A third policy aspect impacting electricity markets are environmental and climate related regulations. Of particular importance is the European Emission Trading System (EU ETS), the largest cap-and-trade system for carbon emissions yet (see (Ellerman, Marcantonini and Zaklan, 2014)). From the first discussions on greenhouse gas emission trading in 2000 it took only five years till the first phase of the EU ETS was initiated. After initial high price levels of more than 25 EUR/t prices crumbled to zero by the end of the first phase due to over allocation. The price level in the second phase (2008-2012) again started rather high but in the wake of the economic downturn and the rise of renewable energies has given in and remained below 10 EUR/t since 2011. Beside the price impact on electricity market decisions also the allocation mechanism for the allowances was changed from the first two phases (grandfathering) to the current third phase (auctioning).



Source: European Commission/Eurelectric

(a) Renewable support schemes


Source: Fortum. May 2014

SE&FI: Capacity reserves for spot market deficits only. SE reserves to be gradually phased out by 2020. FI reserves reduced for 2014-15

GB: Developing full-scale capacity auctions. First auctions in Dec 2014 for delivery year 2017/18

IE&NI: Capacity payments since 2005

LT: Condensing units as reserve

PL: Nodal pricing and capacity market discussed, but no final decisions

DE: No decision on market-wide capacity mechanisms before 2015. Grid reserves in southern DE since 2011

PT: Same as in Spain for new units. Payments suspended in 2012-2013, reduced to €6/KW/year in 2014.

ES: Capacity payments for new units and to existing coal, gas, oil and hydro capacity. In 2012-2013 proposals to stop/reduce payments

FR: Capacity purchase obligations due to be implemented by winter 2016/2017. Capacity certification and trade to start in 2015

IT: Minor payments. New capacity market mechanism to be implemented by 2018

GR: Capacity obligation mechanism since 2005

RU: Capacity market with price restrictions. Long-term capacity supply agreements for obligatory investments

*No capacity payments to power plants in the day-ahead and intraday markets, but balancing market reserve capacity is contracted in advance.

(b) Capacity mechanisms

Figure 2: Divergence in European energy policies(taken from: Fortum, 2014)

In addition to those three main policy channels impacting electricity markets a multitude of further regulatory and policy decision have a direct or indirect effect on electricity market actors, like energy efficiency policies, the restructuring on the European natural gas market, further environmental regulations for fossil fuels, the nuclear debate, and E-Mobility support schemes, to name a few. Thus it is obvious that the decision making process for electricity companies needs to account for a highly dynamic policy environment. The inherent challenge already leads to direct financial impacts for many large energy utilities (e.g. see The Economist, 2013), ongoing debates about support mechanisms for needed investments in generation and networks, and discussions on a more consistent European policy (Rüdinger et al., 2014).

Within this paper we argue that the above described development of the European electricity market resembles structures of slow-fast system. Following this line of reasoning the system may be subject to significant disturbances and freezed dynamics if policy interventions occur too frequently. Thereby providing a theoretic reasoning for a more consistent and coordinated energy policy within Europe if the envisioned transition towards a sustainable energy supply is to be achieved.

3 Slow-fast systems and Blue-sky catastrophe

We first make a short overview of slow-fast system dynamics and its main features.

The slow-fast system (or singularly perturbed, or multi-scale) is the dynamical system characterized by sufficiently different time scales of the processes combined in the system. Sufficiently different means that one of the processes may be treated as constant (slow) relative to the dynamic of the other (fast). In this case changes in the fast subsystem are perceived as almost immediate jumps by the slow component of the system. Such systems are actively studied recently, see for example (Zheng and Wang, 2010) and they find applications in different fields, including environmental economics, see for example (Xepapadeas, 2010) on consequences of the environment and the economy having different time scales.

Formally the slow-fast system may be represented in general as:

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

where ϵ represents the time-scaling parameter and f, g are functions of system variables and this scaling parameter. As long as $\epsilon < 1$, the y system is *fast* relative to x system (which is then *slow*). As long as $\epsilon > 1$ the relationship is reversed, with x being relatively fast and y slow.

The closer this parameter is to zero, the more the difference in the time scales or speeds of two components of the system. 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. Thus slow-fast systems is a generalization of previously studied singularly-perturbed systems, see for example (Smith, 1985). The study of slow-fast systems is an emerging area in applied mathematics since 1990s, with one example study being (Rossetto et al., 1998).

In general the analysis of slow-fast system amounts to studying the limiting behavior of a singularly-perturbed system (with $\varepsilon \to 0$)[2] and then accounting for slow dynamics between the equilibria of the fast system. It then turns out that varying time scale ε we may obtain dynamics of the slow-fast system as bifurcations of the underlying singularly-perturbed system. In particular in 3 dimensions the so-called blue sky catastrophe may be observed.

The blue-sky catastrophe itself has been established in (Turaev and Shilnikov, 1995) and series of follow-up papers as one of the types of co-dimension 1 bifurcations[3] which happens only for systems with more than 2 dimensions. This phenomenon describes the state of the system, when it enters a periodic orbit (cycle), characterized both by infinite length and infinite period in time. The bifurcation parameter is chosen as depending on

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[2] here and further on we denote by ϵ the given fixed time scales difference and by ε the underlying varying parameter

[3] co-dimension 1 bifurcation is a bifurcation with only one parameter variation

the difference in time scales ϵ and we denote it by $\mu(\varepsilon)$. In particular, when the blue sky catastrophe happens, the following is observed:

1. There exist two steady-states, saddle-type stable and asymptotically stable for $\mu < \mu^*(\varepsilon)$;
2. As time increases, orbits which do not lie in the manifold of the saddle steady-state lead to the stable one;
3. For $\mu > \mu^*(\varepsilon)$ there exists a single limit cycle;
4. Length and period of this cycle tends to infinity as $\mu \to \mu^*(\varepsilon) + 0$.

Illustration of such a situation is given by the Figure 3 (adapted from (Shilnikov et al., 2005)): At $\mu < \mu^*(\varepsilon)$, the system has two equilibria: a stable one L^+ and a saddle-stable one L^-. The orbits which do not lie in the stable manifold of L^- tend to L^+ as time increases. At $\mu > \mu^*(\varepsilon)$ the system has a single and attracting limit cycle L_μ, which length tends to infinity as $\mu \to \mu^*(\varepsilon) + 0$. The Blue Sky catastrophe happens once parameter μ crosses the curve $\mu^*(\epsilon)$ from the right, e. g. μ decreases (the difference in time scales between slow and fast subsystems increases).

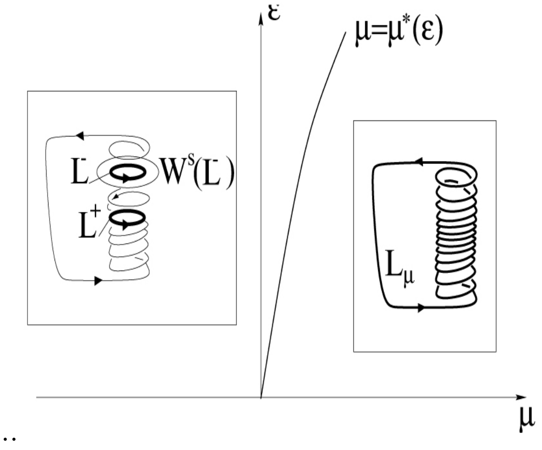

Figure 3: Illustration of the Blue Sky catastrophe at $\mu^*(\varepsilon)$

We claim that under the condition of sufficiently different time scales of fast and slow subsystems the bifurcation in the fast system will lead to the catastrophic (in the sense defined later) dynamics of the slow system and the other way around.

For that we use two important results, established in (Shilnikov et al., 2005) and (Glyzin et al., 2008) and combined in (Shilnikov et al., 2014). We summarize them as following:

Proposition 1 (Blue sky catastrophe)
Any slow-fast system of at least 3 dimensions may exhibit the so-called blue sky catastrophe provided the difference in velocities of slow and fast parts is sufficiently high.

Proof is contained in aforementioned papers. A general idea of it may be found in the Appendix. We now apply this result to the energy policy system.

4 Energy systems and the blue-sky catastrophe

Once we think of the connection of two different in nature processes, this connection can easily be represented as a slow-fast system. In economics of climate change, for example, the time-structured nature of the interdependencies between economic activity and state of environment is implemented through NMPC (nonlinear model-predictive control, see for example (Allgöwer and Zheng, 2006), (Brechet et al., 2011)), where expectations over climate change are taken as piecewise-constant effectively defining climate subsystem as slow in comparison to the economic part of the model. Another example is the different time scales of ecological and economic processes, which is discussed in the paper (Xepapadeas, 2010). The relationship between competition and technological change is yet another example: the speed of interactions between competing firms is much higher than the speed of the technological change in the economy as a whole, nevertheless they do inter-depend on each other.

The most immediate example is the system describing political and economic interactions. Policy interventions may be anticipated by the economic system as a very fast process (impulse or perturbation) and could switch the dynamics of the whole system from one steady trajectory to the other. This interdependence may be analyzed on different levels, from the country-wide economy to specific sectors and their regulative measures. We are mostly interested in the latter and apply the ideas of the slow-fast systems to the economic-political feedbacks in the energy sector.

We claim that an energy-political system may follow the pattern of slow-fast system and therefore can potentially be subject to a blue-sky catastrophe if the difference in velocities of slow and fast parts is sufficiently high.

4.1 Electricity markets as a slow-fast system

As a specific case of energy system we use electricity markets that are subject to multiple policy interventions. We differentiate the infrastructure representation into conventional generation related capital K_G, renewable generation capacities K_R and network related capital K_N. Furthermore we assume that the dynamic relation between the policy and market regime P and the output Y is on the same time frame:

$$\begin{aligned} \dot{Y} &= F_1(Y, K_G, K_R, K_N, P); \\ \dot{P} &= G(Y, K_G, K_R, K_N, P). \end{aligned} \tag{2}$$

$$\begin{aligned} \dot{K_G} &= F_2(Y, K_G, K_R, K_N, P, \epsilon); \\ \dot{K_R} &= F_3(Y, K_G, K_R, K_N, P, \epsilon); \\ \dot{K_N} &= F_4(Y, K_G, K_R, K_N, P, \epsilon); \\ \epsilon\dot{P} &= G(Y, K_G, K_R, K_N, P, \epsilon). \end{aligned} \tag{3}$$

The output of electricity systems - the generated electricity - is largely subject to the available electricity infrastructure but also depends on the underlying input prices and market regulations (i.e. priority dispatch for renewables). Policy induced changes on the later aspects can already lead to significant output changes in an electricity system before infrastructure adjustments are realized. An example of this effect is the role of coal and gas generation. Depending on the price for emission permits, or more generally the emission policy, the share of gas in 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. Coupled with the limited storage possibilities this requires that the installed capacity needs to be high enough to cover the highest load level. Consequently, in most other situations a fraction of the capacity is idle allowing for shifts between plant types. Similar also energy efficiency policies can lead to direct output reductions before an accommodating adjustment of the installed generation capacities takes place.

The basic output-policy interactions are extensively analyzed in the literature. In the stylized setting (2) one could expect usual bifurcations patterns, like fluctuations of output and delayed responses. One such example is recent (Gori et al., 2015), where the existence of delays in response leads to the Hopf bifurcations in the system. However the comparable time-scales of output and policy dynamics makes the system robust to the blue-sky catastrophe type scenarios. This is not the case for the level of capital and investments.

The differentiation of the capital function into three individual functions is motivated by the different dynamics of each subsystem. Conventional generation units exhibit long investment cycles with lifetimes of 40 to 60 years and construction times of several years leading to a rather slow system. In liberalized electricity markets they are subject to competition. Renewable capacities have slightly lower expected lifetimes of ca. 20 years and can often be constructed in less than one year. Contrary to conventional generation they are often either completely or partly financed by specific support mechanisms. Finally, the electricity network exhibits long lifetimes and similarly long construction times like conventional generation. Being the monopolistic bottleneck of electricity systems they remain regulated even in liberalized electricity markets. In addition the physical properties of meshed electricity networks lead to complex interactions of energy infrastructure and electricity output. In summary, the three capital elements of electricity markets can be considered as relatively slow systems albeit with different dynamics.[4]

In comparison, the policy and market regime P is a rather fast system. Beside the generally faster political cycles - four to five years in most countries - energy policy is also altered on a more frequent basis as shown in Section 2. 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

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[4] it is relatively straightforward to transform the system (3) to the 3-dimensional one, taking renewable capital as a share of the total one to put the system in the exact framework of Proposition 1.

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.

Summarizing, a electricity system as defined by (3) can be interpreted as a slow-fast system with differences in the velocities of the different sub-systems; conventional generation and the network being the slowest and the policy and market regime the fastest. As long as policy interventions are frequent, the system (3) has qualitatively different dynamics from (2), and the picture is not limited to fluctuations around equilibrium or transitions from one such equilibrium to the other.

4.2 Electricity markets and blue-sky catastrophe

Given the structure of electricity systems as slow-fast system (3) we claim that there exists a possibility of a blue sky catastrophe. In what follows the specific functional forms employed in the system (3) are not important except for the fact of ϵ being sufficiently small.

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 with a stop of adjustments in the electricity infrastructure.

Proof: Amounts to identifying elements of (3) necessary to apply the Proposition 1.

Recall that the dynamics of a slow subsystem is defined for each equilibrium state of the fast subsystem. The equilibrium state of the fast subsystem is the particular energy policy regime. The change in policy regime is the switch from one policy subsystem equilibrium to another. The frequency of these changes is measured by parameter ε. As soon as $\varepsilon \to 0$ it holds true that $\mu(\varepsilon) \to 0$. Thus there exists some value of ε for each $\mu(\epsilon^*) = \mu^*(\epsilon)$ and we observe a blue-sky catastrophe. In the case of electricity systems the function $\mu(\varepsilon)$ could measure the speed of implementation of new policy regimes as a function of the speed of policy decision-making.

Now how can we interpret the blue-sky catastrophe in the electricity-policy system? First, observe that the blue-sky catastrophe is the transition from the state with two periodic solutions (stable and saddle) to the state where they merge into one periodic solution of long period, tending to infinity at some crucial value of the parameter. The periodic solution means investment and output generation cycles of some (finite) period. One of this cycles is stable and the other is repelling. This is the situation for small $\mu(\epsilon)$, i. e. frequent policy interventions. From the other side, with less frequent interventions we have only one cycle with longer period. This equilibrium is characterized by series of bursting oscillations followed by the period of stable development. From the policy viewpoint this situation is more desirable, since there is only one possible dynamics of a system. However, reducing the time between policy interventions, we face the possibility not to transit into the first state with two equilibria, but rather to send the system in the infinitely long flight if policy parameter crosses the threshold $\mu^*(\epsilon)$. This would be observed as the stable state of the system without fluctuations and with freezed parameters.

Translating this to the European energy and electricity market history as presented in Section 2 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; i.e. ϵ was relatively large. The dynamics of infrastructure adjustments were stable and predictable following demand growth trends and few policy impulses like decisions on the role of nuclear; i.e. $\dot{K_G}$ and $\dot{K_N}$ were relatively constant.

With the emergence of the market restructuring debate and growing concerns about environmental topics in the late 1980s the system gradually moved towards a situation with faster dynamics. Policy interventions became more frequent from the 1990s onward; i.e ϵ significantly decreased. This shifted the system towards a situation with higher variations in the dynamics of the infrastructure functions; i.e. $\dot{K_G}$, $\dot{K_N}$ and $\dot{K_R}$ became more volatile.

Given that the objective of the European electricity transformation process is the transition from the past equilibrium with stable dynamics of the $\dot{K_G}$ and $\dot{K_N}$ aspects towards a future equilibrium with relatively stable dynamics in the $\dot{K_R}$ and subsequent $\dot{K_N}$ parts of the system, policy interventions are a necessity. In other words, the transition from a fossil based to a renewable electricity system does not happen by itself. Currently, the system is in the transition phase between the equilibira. The blue sky catastrophe postulates that within this transition phase the risk of a system freeze increases with the speed of policy interventions. This would translate into a situation in which neither the dynamics of conventional nor renewable investments would change anymore meaning the system would stop to react to policy impacts.

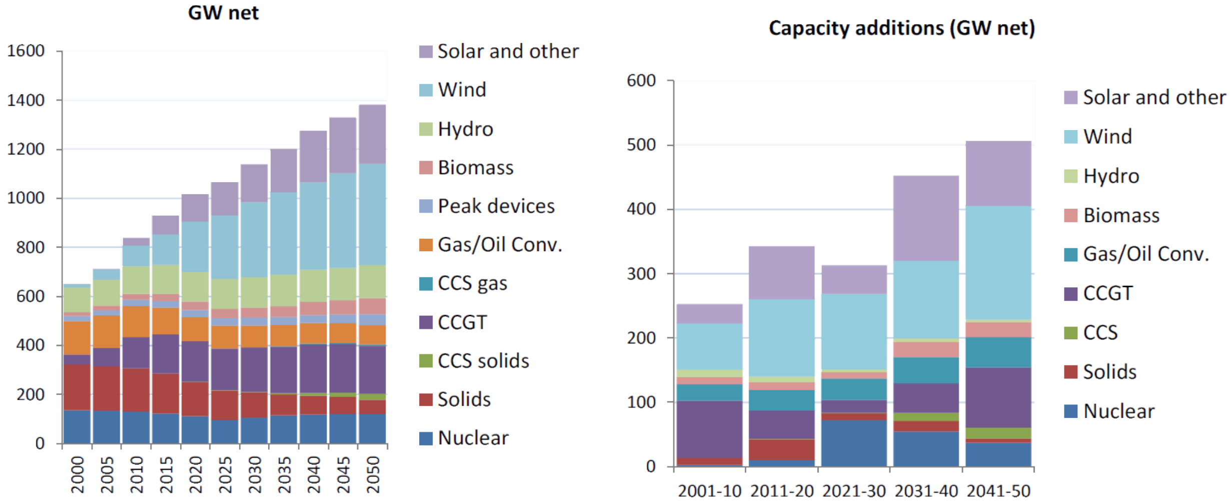
5 Implications for European energy policy

Following the argumentation of the previous section we state that the European electricity market follows the characteristics of a slow-fast system and therefore energy policy needs to account for the risk of a blue sky catastrophe. Given the expected development of the electricity system towards a renewable dominated generation portfolio (EC, 2014) large scale investments in solar and wind generation will be needed in the next decades (see Figure 4). However, also significant investments in conventional power plants will be needed, especially in gas fired plants. Finally, also the expected network extensions as indicated in the Ten-Year Network Development Plan 2014 of the ENTSO-E amount to 150 bn EUR.

The structure of the dynamics indicates that policies and respective changes in the short term output will be the driving forces in the dynamics of the above mentioned investments. The current market conditions however raise doubts whether this transition can be achieved.

The increase in renewable energies already led to a strong decline of wholesale market prices and thereby to reduced revenues for conventional generation limiting their possibility for investments. Further policy measures like the ongoing adjustments of the European emission trading scheme or the back and forth of the German nuclear phase-out increased the investment uncertainty for conventional generation. Also renewable investments are subject to uncertainties as they are largely dependent on the different national support schemes. Changes in those schemes can easily render investment plans unprofitable. Examples of such sudden shifts are the renewable moratorium in Spain or the photo-voltaic amendment of the German feed-in tariff, both in 2012.

As indicated in Section 2 many large utilities currently face financial troubles, had to write off parts of their assets due to low market prices, and have lower credit ratings



(a) Installed power capacities

(b) Projected capacity additions

Figure 4: European Energy Trends to 2050 (EC, 2014)

which limit their possibility to finance the needed large scale investments (The Economist, 2013). We do not want to postulate that this situation of the current European electricity system means that it already passed the threshold and is in an equilibrium without fluctuations and with freezed parameters. But the ongoing developments show that a transition between system equilibria is not necessary a smooth process. The risk of a system freeze may indeed be a real threat if investment incentives are changing on a too frequent basis.

A related interpretation of this potential development is the perception of regulatory risk by firms. If firms assume policy changes become too frequent and unpredictable they may stop to include those aspects in their decision process. In other words, the risk of regulatory changes is perceived so high that only those system adjustments are carried out that do not depend on the regulatory framework. This is basically the freezed nature of the systems (2) and (3) in case of a blue sky catastrophe.

A threat the ongoing challenges of the European electricity system poses is that in order to address the multitude of different system issues policy makers may increase the amount of policy measures. For example the threat of insufficient investment security for conventional generators is a driving force of the ongoing capacity market debate in Europe. As indicated in (Betz, R., Cludius, J., Riesz, J., 2015) there are currently several different national approaches in discussion increasing the incentives to postpone investments until the mechanisms are in place.

However, following the logic of the presented slow-fast system dynamics the risk of a blue sky catastrophe actually translates into a contrarian policy approach. To avoid a system freeze the policy process should provide relatively stable and predictable implications for market actors and therefore calls for well-structured harmonized interventions. A focus on too many individual policy targets without properly accounting for their interactions and on national approaches without accounting for the high interaction between cross-border electricity systems runs the risk of not achieving the desired transition.

6 Conclusion

We apply the recent results in the theory of slow-fast systems to the energy policy. We find that frequent policy changes may lead not to the speed up in energy transition but rather freeze all new investments conservating the system. In bifurcations theory this is known as a blue-sky catastrophe. It is worth mentioning, that the state with infinite length and period appears simultaneously with the possible onset of chaotic behavior, as it is noted in (Gavrilov and Shilnikov, 2000). This 'spiral chaos' could mean the uncontrolled diverging behavior of a system, which is even more dangerous than just freezing.

To avoid both these possibilities, the energy policy should not change rapidly nor frequently, but rather should be adapted to the industry investments cycle. Thus the temporary freezing of investments into conventional energy should not be interpreted as a call for more interventions, since it might well be the case of that such temporary freeze 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.

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Appendix: Sketch of the proof of Proposition 1

In describing the proof below we closely follow (Shilnikov et al., 2005). Proof for 1-dim. fast and 2-dim. slow structure may be found in (Glyzin et al., 2008) and is analogous. In what follows we tried to capture 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

$$\begin{aligned} x' &= \epsilon g(x, y, \epsilon), \\ y' &= h(x, y, \epsilon) \end{aligned} \tag{4}$$

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

$$\begin{aligned} x' &= 0, \\ y' &= h(x, y, \epsilon) \end{aligned} \tag{5}$$

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 (5). It turns out, that (putting aside strange attractors), the fast system goes to either stable equillibria or to the periodic orbit. When such equilibria are exponentially stable, they depend smoothly on x. We thus obtain smooth attracting invariant manifold of the system (5): it consists in (x, y) space of equilibrium curves M_{eq} and/or two-dimensional cyclinders 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 (5). Thus smooth attractive invariant manifolds $M_{eq}(\varepsilon), M_{po}(\varepsilon)$ exist for any sufficiently small ε for the initial system (4).

4. Find equilibrium and periodic states of the fast subsystem from

$$\begin{aligned} h(x, y, 0) = 0 &\to y = y_{eq}(x) \subset M_{eq}, \\ h(x, y, \tau) = 0 &\to y = y_{po}(\tau, x) \subset M_{po} \end{aligned} \tag{6}$$

with period of τ being $T(x)$.

5. Define the dynamics of the slow component as

$$\dot{x} = g(x, y_{eq}(x), 0) \tag{7}$$

$$\dot{x} = \varphi(x) = \frac{1}{T(x)} \int_0^{T(x)} g(x, y_{po}(\tau, x, 0)) d\tau, \tag{8}$$

for equilibrium and periodic orbits of the fast subsystem respectively.

6. Study the critical values of x which 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 (4) 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 $\mu < \mu^*(\epsilon)$ on the attracting manifold $M_{po}(\varepsilon)$.

11. Consider a small neighbourhood U surrounding $M_{po}(\varepsilon)$ and M_{eq}^j. The Pincare map for x would undergo bifurcation colliding two stable orbits into one at $\mu = \mu^*(\varepsilon)$.

12. 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 required to returnfrom one part to the other tends to infinity while approaching $\mu^*(\varepsilon)$.