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EDITORIAL

Focus on networks, energy and the economy

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Abstract

A sustainable and reliable energy supply constitutes a fundamental prerequisite for the future of our society. The change to renewable sources comes with several systemic changes and includes, among others, smaller and more distributed producers as well as stronger and less predictable fluctuations. Parallel developments such as the transition from conventional producers and consumers to *prosumers* and the increasing number of electric vehicles add further complications. These changes require to extend and upgrade currently existing power grids. Yet precisely how to achieve an effective, robustly operating (electric) energy system is far from being understood. This focus issue aims to contribute to a number of these upcoming challenges from the perspective of self-organization and the collective nonlinear dynamics of power grids, interacting economic factors as well as technical restrictions and opportunities for distributed systems.

1. Collective features of distributed, networked systems

During the 20th century, energy has become a major factor taking part in all aspects of life. The ubiquitous and reliable supply with energy thus fundamentally contributes to our digital communication, our mobility, the transport of goods, industrial production as well as entertainment, among others. Energy needs to be generated (or physically speaking: transformed), stored, distributed and released. The current change of our energy system from fossil to renewable sources strongly impacts not only single infrastructures such as the requirements on individual wind power plants or photovoltaic arrays. It also affects how these systems are connected to each other and thus co-act through power transmission and distribution grids. As a networked system, the grid's collective dynamics in turn influences and is influenced by yet other systems, including supply, communication and computational systems as well as the economy, through energy trading, subsidies and questions of infrastructure cost balancing.

This focus issue specifically emphasizes electric power grids as well as boundary conditions on energy systems set by our physical and economic world. As an example, power transmission grids constitute physical dynamical system with multiple nonlinear feedback and cyclic influences. Their collective emergent dynamics, conditions for stable operation, mechanisms for control and options for design are far from being fully understood due to the distributed nature of many of its dynamic, often self-organized phenomena. This is where this focus issue contributes, taking the perspective of nonlinear dynamics and econophysics, control and statistical physics of complex, mostly interconnected, networked systems.

2. New challenges

Networks of electric power systems are among the most complex systems ever built by humans and their reliable operation is an enormous challenge [1–3]. At every point in time, power generation has to be matched exactly to the demand and the losses, which amount to more than 500 GW at peak load in the interconnected European power network [4]. Thousands of generators have to run in exact synchrony, i.e. at exactly the same frequency and locked relative phases to maintain a steady power flow. And this complex system must be stable against the fluctuations of generation and demand as well as the failure of any single generating unit or transmission line. The historic dimension of this development has been highlighted by the National Academy of Engineering of the USA, who named electrification as the greatest engineering achievement of the 20th century [5].

But now restrictions in greenhouse gas emissions to mitigate climate change as well as further ecological and economic constraints put new challenges to the electric power system. Currently, electrical generation is the largest source of carbon dioxide (CO_2) emissions with approximately 35% of the total emissions [6] and we thus have to decarbonize the power system within a few decades. During recent decades, substantial progress has been made in the development of renewable energy sources, in particular wind power and photovoltaics. However, the integration of these sources into the existing grid is far from trivial and several systemic issues still have to be resolved. In fact several aspects of renewable energy generation challenge the operation of future power grids [7]:

- **Temporal fluctuations prevail.** The power generated in wind turbines and photovoltaic modules depends on the weather and the time of day and is subject to large fluctuations, which have to be balanced in some way to guarantee a stable operation.
- **How to balance spatial heterogeneities?** Suitable locations for wind turbines are often far away from the most populated regions, for instance off-shore.
- **Which grid changes are reasonable, from a dynamic and economic perspective?** Due to the above two issues, electric power has to be transmitted over large distances which may require a significant extension of the grid.
- **How do more distributed systems (self-)organize?** Wind turbines and solar cell arrays are typically much smaller and more geographically distributed than large power plants based on fossil fuel or nuclear power. Renewable sources thus have an intrinsically decentral aspect. Furthermore, there are often connected to the medium- or low-voltage distribution grid instead of the transmission grid. The power grid is thus becoming decentralized which challenges current control paradigms.
- **Distributed network control and prosumers.** In addition, also the demand is changing. The introduction of electric vehicles may increase the power demand. The development of 'smart' meters and grids may allow to control the demand as well as the generation via price incentives to maintain the power balance in the grid.

3. Theoretical and practical progess

The complexity and variety of these challenges calls for cooperations across scientific disciplines [2, 3]. This *New Journal of Physics* focus issue collects contributions from the physics of complex systems to the understanding and improvement of supply networks, energy systems and energy economics.

The stable operation of a power grid requires all generating units to rotate at exactly the same frequency. As recently highlighted in a model derivation by Filatrella *et al* [8] the essential phase dynamics of power grids directly link to the nonlinear physics of weakly coupled oscillator networks such as those characterized by the Kuramoto model [9, 10], compare also Manik *et al* [11]. In 2012, the Filatrella et al model has been extended to the dynamics of large networked grids by Rohden *et al* studying the impact of decentralization [12, 13], followed by dozens of related model studies. A contribution by Nishikawa and Motter to this focus issue provides a comparative analysis of different models for power grid dynamics which are used to assess the existence and stability of this synchronous state [14]. The stability of the synchronous state beyond the linear regime is analyzed by Schulz *et al* [15]. They quantify global stability by the size of the basin of attraction, i.e. the fraction of initial conditions which relax to the synchronous state. They find that dead trees in power grids are particular dangerous because small perturbations at the connecting root node of the tree can destroy synchrony, while detour options generally improve global stability.

The temporal fluctuations of wind power generation is one of the main challenges for the integration of many renewables. Pesch *et al* analyze wind power time series and uncover their long temporal correlations [16]. Based on this observation they provide a new stochastic model for the generation of synthetic wind power time series, which can be applied for the dimensioning of storage and backup infrastructures in future highly renewable power systems, compare [17, 18].

The demand side will also undergo significant changes in future power grids. The fluctuations of renewable energy generation can be partly compensated if the consumers adapt their demand. A commonly advertised solution is the 'smart grid' concept that includes to centrally collect time-resolved consumption and generation data and feeding back a price signal to incentivize production and consumption changes that stabilize operation. A new, decentralized smart grid approach is presented by Schaefer at al [19], who propose to set the electricity tariff as a direct function of the local grid frequency. The general concept is that in times of scarcity the frequency will decrease and the tariff will increase such that consumers have a local incentive to reduce their demand [20]. Schaefer show that this decentralized method provides an efficient market and may even improve the transient stability of the grid. However, one has to accept rather large fluctuations of the grid frequency and all control schemes, whether decentralized or not, need to be implemented with great care to avoid collective instabilities.

The role of electric vehicles in future power grids is analyzed in two contributions [21, 22]. Gajduk *et al* [21] show that the vehicles can significantly improve the transient stability if (de-) charging is adapted to the momentary generation. They provide a quantitative estimate using network data sets, thereby highlighting the enormous potential of electric vehicles in stabilizing grid dynamics. The control scheme Gajduk et al suggest can be realized in a completely decentralized way using the local grid frequency as a measure of the momentary power balance, similar to the proposal of Schaefer *et al* [19]. However, current distribution grids may reach their limits if too many electric vehicles have to be charged at a time as shown by Carvalho *et al* [22]. Notably, congestion sets in abruptly when the number of arriving electric vehicles increases, resembling a first-order phase transition. Carvalho *et al* also highlight the importance of control strategies by comparing two different optimization schemes—the maximization of the total power flow versus a protocol called 'proportional fairness' —both subject to the condition that the voltage drop in the grid must be within the security limit. They conclude that the naive maximization of the power flow will lead to a level of large inequality of the charging time at different nodes nodes which may be socially unacceptable.

The power transmission grid will become much more heavily loaded in the future, at least transiently, due to the strong fluctuations and the often remote locations of renewable energy sources [23]. Still it has to be guaranteed that the power system is stable even when a transmission line or a generating units fails (a so called $N - 1$ error [24]), which will require a substantial extension of the transmission grid. Dewenter and Hartmann provide a detailed statistical analysis of such $N - 1$ errors [25]. If a transmission line fails, the power flow has to be rerouted, and the grid must provide sufficient backup capacity to allow for this rerouting. Dewenter and Hartmann then calculate the statistics of the necessary total backup capacity for ensembles of random networks. This is used to characterize the topological features making networks resilient or vulnerable.

The necessary grid extensions will require huge capital investments which must be distributed to the grid operators in a reasonable way. Obviously, operators which utilize the grid most should contribute strongest. Tranberg *et al* propose a method to distribute costs inspired by the study of diffusion on complex networks [26]. The key step of this method is to trace back the power flow over each line to the exporters and importers causing the flow. The authors apply this method to a future fully renewable power grid in Europe. Based on estimates for the local generation and load in each country they calculate the necessary grid extensions and the distribution of costs. The authors argue that simpler local schemes are not appropriate as they systematically discriminate subgrids which are localized in the geographical center of the interconnected network.

One option to mitigate congestion effects is the use of flexible AC transmission system (FACTS) devices. Frolov et al analyze whether the modification of the inductance of a limited number of transmission lines can be used to reroute power flows in order to avoid impeding overloads [27]. They present an optimization method to place a minimum amount of series compensation devices in a given power grid. The original optimization model is numerically intractable, but Frolov et al develop efficient heuristic algorithms guided by a physical analysis of the problem. They demonstrate the feasibility of their approach and discuss potential application in network planning in a second article [28].

The energy sector constitutes a central building block of our economy and our welfare, as emphasized by Kümmel and Lindenberger [29]. Using methods from statistical thermodynamics they discuss the role of technology constraints and analyze economic equilibria beyond the standard neoclassical results. Their model fits extremely well to historical econometric data. In particular, the influence of energy input on the output, as measured by the output elasticity, is much larger than one would naively expect from its relatively small cost share of only 5%. Berg et al analyze a more detailed economic model, which describes the flow of financial assets and real physical goods between different sectors in a consistent way (a 'stock-flow consistent model') [30]. The industry sector is further disaggregated by integrating IO tables. This model is used to analyze the dynamical stability of an economic system, in particular the response to energy price shocks. Similar to Kümmel and Lindenberger they find that the response to energy price changes is much larger than expected from simpler economic models due to indirect multiplier effects: The demand for energy is generally inelastic, i.e. it does not change with the price. Thus households have to compensate the price shock by reducing the demand for other goods which can then trigger a nationwide recession. As another major point, Berg *et al* offer a coarse model predicting thermodynamic limits of energy usage on planet earth per se. If energy usage increases as it did during the last three centuries, the fraction of energy dissipated to heat and thus heating the atmosphere would quickly become so large that temperature rise become unbearable, even if all supply were be generated without any greenhouse effects.

Methods from statistical physics are also valuable to analyze the dynamics of general economic networks. Kondor *et al* show analyze the network of transactions of the digital currency system Bitcoin [31]. They show that the evolution of a macroscopic quantity, the market price, can be recovered from rather little information about the microscopic structure of the trading network. To achieve this reduction of complexity, Kondor *et al* use a Principle Component Analysis (PCA) to extract the most important features of the time series of the transaction network. Oya *et al* make use of different network theoretical measures to predict imminent transitions in the time evolution of complex networks, in particular in the time series of foreign currency exchange rates [32]. Shortly before a transition occurs fluctuations increase and the network of exchange rates decomposes into a strongly correlated core and a less correlated periphery.

4. Our future in a networked world

The articles of this focus issue contribute to modeling and solving particular questions and problems about the highly distributed systems handling our energy supply and economy—now and in the future. Taken together, these contributions point to a large variety of new questions, several of them broad scale. How shall we design, run and control our future energy system to make it viable and dynamically robust? How shall we contain our energy usage, limit heat dissipation on earth, regulate production and demand, and mitigate failures? How do we adapt our economic systems in particular if they interact with the major factor to sustain our future—energy. Or more broadly, in the light of the challenges facing us through the ever more networked systems in an ever more globalized world: how do we manage to survive this century?

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