Third International Engineering Systems Symposium
CESUN 2012, Delft University of Technology, 18-20 June 2012

Resilience and adaptability of infrastructures – A complex adaptive systems perspective

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Abstract. *While we rely on the continuous functioning of infrastructures such as water, electricity and Internet, 100% uptime is not possible. Infrastructure systems must therefore be resilient – they must be capable of flexing in response to disruptions and recovering quickly. In this paper we explore options for supporting infrastructure resilience from a complex adaptive systems perspective. Building on work from the field of social-ecological systems, we introduce a novel definition of infrastructure resilience - the capacity to manage shifts between attractors in infrastructure operation. We define adaptability as the capacity to manage shifts between attractors in infrastructure evolution.*

To explore the usefulness of these definitions, we introduce a simulation model of an electricity network exposed to perturbations in its environment. The results of this model demonstrate how an evolutionary-level attractor shift leads to greater resilience of the modeled infrastructure. This model and the elaborated definitions can help to guide the development of future models for supporting infrastructure resilience and adaptability in line with a complex adaptive systems perspective.

Keywords. Infrastructures, resilience, adaptability, complex adaptive systems, socio-technical systems

1 Introduction

Hurricanes, floods, earthquakes, geomagnetic storms, bio-terrorism, cyber-terrorism, unanticipated human behavior and simple error – today's infrastructures are exposed to a wide range of internal and external threats. Despite these risks, we have come to rely heavily on the continuous and highly controlled delivery of infrastructure services such as water, electricity and Internet communications. As demonstrated by events such as Hurricane Katrina in 2005 and the Northeast US blackout in 2003, the consequences of disruptions in these services can be devastating.

Despite the high social and economic costs of infrastructure service disruptions, it is clear that 100% security of supply is not an option. Infrastructures are globe-spanning socio-technical systems. They are deeply embedded within their environment and most often depend on a highly stable set of social and ecological conditions for proper functioning. Failures are inevitable, and infrastructures need to respond accordingly - they must be adaptive and resilient.

Resilience is increasingly seen as an essential characteristic of future infrastructure systems (NIAC, 2009, Garbin and Shortle, 2007). Most definitions of resilience touch on a set of common themes – an ability to survive unexpected perturbation, recover from adversity and gracefully degrade (Madni and Jackson, 2009, McCarthy, 2007, Mili, 2011). Definitions such as these implicitly accept the possibility of unforeseeable disruptions and focus on the capacity of systems to handle them.

Options for supporting the resilience of our infrastructures are molded by the manner in which we conceptualize them. If we view infrastructures as simple technical artifacts, on par with mobile phones or desktop computers, we view their operation largely in binary terms. We see them as independent from their environment and view changes in this environment as threats to proper functioning. From this perspective, our options in the face threats are clear. Our primary task is to enhance the robustness of infrastructures – their ability to withstand fluctuations in their environment. If by chance these infrastructures do become non-functional, our task is to ensure that we can quickly bring them back to their original state.

We can also view infrastructures as *complex adaptive systems* (CAS) – systems whose macro-level behavior is determined by the dynamic interactions of numerous agents acting in parallel (Waldrop, 1992). From a CAS perspective, functionality is no longer a simple binary variable, but a *fitness landscape* (Kauffman, 1993) – a constantly changing multi-dimensional landscape featuring numerous possible system states or configurations, each with a particular level of fitness. Viewed through a CAS lens, an infrastructure is not independent from its environment. Rather, it adapts and co-evolves with it. Fluctuations in environmental variables are not simply threats to proper functioning, but may affect system fitness in myriad ways.

Conceptualizing infrastructures in this way affects the options we have in the face of threats. We can still seek to make an infrastructure robust and ensure its swift return to normal functioning, but we also have other options. We can try to guide the system through its fitness landscape in a targeted manner and we can support its ability to adapt and evolve with it.

The purpose of this paper is to explore the implications of a CAS perspective on infrastructure resilience. Drawing on insights from the field of social-ecological systems, we develop an explicit definition of infrastructure resilience from a viewpoint of infrastructures as CAS. Throughout this paper, the example of electricity infrastructures is used to illustrate the application of a CAS perspective to the exploration of infrastructure resilience. In the following section, we introduce the concept of CAS and explore its relationship with resilience as per the field of social-ecological systems. After this, we elaborate on the notion of electricity infrastructures as CAS, and provide novel definitions of infrastructure resilience and adaptability from this perspective. Finally, we demonstrate these definitions using a simulation model.

2 Complex adaptive systems, attractors and resilience

CAS are a class of systems characterized by dynamic networks of interacting agents. Holland (1992) suggests that such systems can be described in terms of three key characteristics: (1) they evolve over time as system components learn and adapt; (2) they exhibit aggregate behavior that emerges from the interactions amongst components and cannot be simply derived from the independent actions of these components; and (3) they anticipate through the decentralized development of rules that help them adapt to changing circumstances. Typical examples of CAS include the human immune system, ant colonies and stock markets.

The behavior of CAS often tends towards *attractors* – areas in phase space towards which the state of a system, due to its internal dynamics, tends over time. Sometimes CAS tend towards a particular point – a point attractor. Other times, they settle into a pattern in which they jump periodically between several points – a periodic attractor. An important characteristic of many CAS is the co-existence of multiple attractors within the phase space of a given system. While a system can reside within only one of these attractors at a particular point in time, perturbations may periodically incite a system to ”jump” between attractors.

In the domain of social-ecological systems (Berkes et al., 2003, Ostrom, 2009), the notion of multiple attractors is conceptualized in terms of a three-dimensional stability landscape featuring multiple *basins of attraction* – valleys in the stability landscape within which the system tends toward a particular attractor (Scheffer et al., 2001). The state of a system is like a marble rolling around in this stability landscape. While this marble has a tendency to stay within the same basin of attraction, changes in the stability landscape can cause it to move around within this basin or even shift to another basin. According to researchers in the field of social-ecological systems, resilience relates to “the capacity of a system to absorb disturbance and reorganize” so as to “stay in the same basin of attraction” (Walker et al., 2004). *Adaptability* is defined as the “collective capacity of the human actors in a system to manage resilience” (Walker et al., 2004).

A well-established real-world example of these concepts is that of shallow lake ecosystems. The state of a shallow lake ecosystem can exist within one of several basins of attraction (Scheffer, 1999). At relatively low concentrations of nutrients, such ecosystems tend to exist in a basin of attraction characterized by clear water and a diversity of animal life and submerged plant life. If the concentration of nutrients, e.g. phosphorus from fertilizer runoff, exceeds a particular threshold, the lake shifts to a new basin of attraction characterized by turbid water, phytoplankton blooms and a reduced diversity of submerged plant life and animal life. As per the above definitions, resilience in this case has to do with the capacity of the system to remain within the initial basin of attraction despite buffeting by nutrient inputs, and adaptability has to do with the capacity of actors to manage this.

3 Electricity infrastructures as complex adaptive systems

Conceptualized as CAS, infrastructures are not simple technical artifacts. They are complex assemblages of interacting social and technical components. From this perspective, the actors who design, own, operate, maintain and use an infrastructure’s technical components – power companies, grid operators, consumers, etc. – are viewed as integral components of the infrastructure. The dynamic interactions amongst this set of social and technical components give rise to phenomena suggested by Holland (1992) to be characteristic of CAS – evolution, aggregate behavior and anticipation. Electricity infrastructures can be seen to evolve over time as producers invest in new generators, grid operators invest in new grid components and consumers deploy new energy consuming devices (Chappin, 2011). Aggregate behavior is visible in phenomena such as electricity price spikes, large-scale blackouts and sustained chaotic oscillations in power flows (Borenstein, 2002, Nedic et al., 2006, Venkatasubramanian and Ji, 1999). Anticipation is evident in the functioning of various types of markets – day-ahead markets, reserve markets, etc. – which exist to coordinate the provision of power at a future point in time, as well as in the power flow models employed by grid operators to predict and correct for shortfalls in transmission capacity (Vrsecky and Patriatici, 2004).

3.1 Basins of attraction in infrastructure operation

From a perspective of electricity infrastructures as CAS, the phase space of an electricity infrastructure can be conceptualized as a stability landscape composed of multiple basins of attraction, each corresponding to a particular *mode of operation*. These modes of operation may be characterized by key variables such as a particular network frequency and demand-side voltage, and a specific percentage of load demand satisfaction. One basin of attraction within this landscape can be thought of as representing the "normal functioning" of the infrastructure. In most of the industrialized world, this is a wide, deep basin that is characterized by a set of states nested around a network frequency of 50 Hz, a demand-side voltage of 220V or 110V and a load demand satisfaction of 100%. The tendency of an electricity infrastructure to remain within this basin is a function of numerous interactions amongst the system's social and technical components.

While electricity systems in most industrialized countries spend the vast majority of time within this basin, the area within its boundaries does not represent the full range of possible system states. Every so often, we experience a catastrophic shift to a different attractor – an "uncontrolled blackout". Like the flip in a eutrophic lake, this is an uncontrolled shift to an attractor characterized by a vastly different set of conditions – 0% load demand satisfaction, a network frequency of 0 Hz and a demand-side voltage of 0V. A shift to this attractor often occurs when the system is pushed to the edge of its "normal" basin of attraction, and suddenly experiences a change in the stability landscape. In the case of the 2003 Italian blackout, for instance, this landscape change was triggered by a flashover towards a tree on a major high voltage link between Switzerland and Italy (Berizzi, 2004).

Other basins of attraction also exist. One such basin of attraction can be thought of as a brownout – characterized by a relatively stable lower voltage and reduced load demand satisfaction. Another is a rolling blackout (load shedding) – a basin characterized by periodically fluctuating power flows and load demand satisfaction. In most power systems of the industrialized world, these basins are rarely seen in practice, and are used largely to prevent a catastrophic flip to an uncontrolled blackout. Unlike the uncontrolled flip to a total blackout, shifts to brownouts and rolling blackouts are controlled in the sense that they are a result of deliberate actions on the part of the system's social components.

3.2 Basins of attraction in infrastructure evolution

The examples above highlight attractors in the operational performance of electricity infrastructures. However, we can also identify attractors on a longer timescale – in the *evolution* of infrastructures. From an evolutionary perspective, an attractor can be seen as a stable combination of technologies and institutions. The current basin of attraction in most electricity systems of the industrialized world might be labeled "fossil thermal centralized". It is an attractor dominated by fossil fuel combustion technologies, a vertically operated power system, a heavily redundant grid structure and an expectation of constant load demand satisfaction. However, one can also imagine an alternative basin of attraction - labeled e.g. "renewable distributed small-scale" - characterized by widespread renewable and distributed generation technologies and a more horizontally operated grid composed of numerous flexibly coupled micro-grids.

Attractors at the levels of operational performance and infrastructure evolution are not independent of one another. The operational performance of an infrastructure is constrained by its institutional and technological context. For instance, the ability of system operators to employ demand-side management as a strategy for mitigating peak loads depends on the existence of a set of enabling technologies and institutions, such as smart meters and dynamic pricing. Likewise, the evolutionary path of an infrastructure – e.g. a shift between attractors at the evolutionary level – may be affected by events at the operational level. For instance, the 2011 tsunami and subsequent nuclear accident in Japan has seemingly accelerated the shift of Germany away from nuclear energy (BBC, 2011), although it remains to be seen whether this will constitute a shift to a new evolutionary attractor. These sorts of cross-scale interactions can be compared with the notions of "revolt" and "remember" in Holling's model of panarchy[1] (Holling et al., 2002).

4 Infrastructure resilience and adaptability - definitions

The existence of multiple basins of attraction in the operation and evolution of electricity infrastructures provides us with a basis for defining infrastructure resilience in a manner comparable to resilience in social-ecological systems – the capacity of a system to *stay within the same basin of attraction* (Walker et al., 2004). On an operational level, defining resilience in this way might relate to the capacity of the system to remain within a basin of "normal functioning" despite various perturbations. This definition notably excludes the possibility for dealing with perturbations through temporary shifts to other basins of attraction such as brownouts, rolling blackouts and demand-side management. In the field of social-ecological systems, such shifts are captured by the notion of *adaptability* – the capacity of

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According to the definition of Holling, et al. (2002), revolt implies an upward linkage between scales and remember implies a downward linkage.

human actors to manage resilience (Walker et al., 2004). Insofar as these non-catastrophic, controlled shifts imply an ability to adapt and degrade gracefully, however, they are important components in definitions of infrastructure resilience. This suggests that the definition of resilience from the field of social-ecological systems may not be directly applicable in the case of infrastructures.

On an evolutionary timescale, the notion of a basin of attraction approaches the concept of a regime in transition theory – a set of dominant practices, rules and shared assumptions within a socio-technical landscape (Rotmans et al., 2001). The field of transition management deals with the issue of socio-technical *lock-in* – the tendency for regimes in socio-technical systems to resist structural change that would enable them to adapt to new demands from their environment, in particular sustainability (Kemp et al., 2007). From the perspective of resilience as the capacity of a system to remain within a particular basin of attraction, this capacity for socio-technical regimes to persist despite myriad pressures from and changes within their environments may be said to constitute a form of socio-technical resilience (Smith and Stirling, 2008). On one hand, this resilience may be desirable in that it contributes to the long-term provision of valued goods such as electricity. On the other hand, such resilience can inhibit change even when environmental developments threaten the capacity of the system to provide its intended function. This, too, suggests that the definition of resilience from the field of social-ecological systems may not be directly applicable in the case of infrastructures.

Against the background of these important distinctions between social-ecological resilience and socio-technical/infrastructure resilience, we define infrastructure resilience as *the capacity to manage shifts between attractors for the purpose of preserving an infrastructure service*[2]. This definition inherently reflects the notion of infrastructures as complex adaptive systems with multiple attractors, and emphasizes the reality that it may not always be desirable to preserve the operation of an infrastructure within the same basin of attraction. It also takes into account the centrality of concepts like adaptation, learning and graceful degradation to infrastructure resilience, as reflected in existing literature.

While the notion of managing shifts between attractors may be applicable on both an operational and an evolutionary timescale, it is useful to be able to differentiate between dynamics on these two timescales. For this reason, we use the term *adaptability* to describe the capacity to manage shifts between attractors on an evolutionary level, and apply the term resilience exclusively to the operational level. An adaptable infrastructure is thus one that is able to shift between evolutionary attractors in order to meet new demands or adjust to environmental fluctuations.

Use of the term "manage" here implies a key role for the social components of an infrastructure system, but is not intended to exclude purely technical solutions.

5 Demonstration model

The model described in this section captures the structure and function of an electricity network exposed to perturbations in its environment. These perturbations take the form of fluctuations in temperature and shifts in the frequency of extreme weather events of the sort that might be expected as a consequence of climate change. In this sense, the model represents a real-world problem – the potential vulnerability of electricity infrastructures to climate change. However, it is not intended to reflect the real-world dynamics of electricity infrastructures in response to climate change, nor to provide insight into how resilience can be achieved under such conditions. The purpose of the model described in this section is to demonstrate the definitions of resilience and adaptability as described above.

The model employs the technique of *agent-based modeling* (ABM). ABM is a computer simulation modeling technique centered around the concept of agents – autonomous software entities with the fundamental ability to make independent decisions (Macal and North, 2007). In the process of developing an agent-based model, agents are conceptualized to represent actors in a real-world system, such as individuals, organizations or nations. These agents are assigned various attributes and decision making rules and then are released and allowed to interact within a defined digital simulation environment. Macro-level patterns emerge as a consequence of these (multitudinous) interactions.

5.1 Model setup

The model contains two types of agents – producers of electricity and consumers of electricity. These agents exist within an environment that is characterized by a temperature and by the periodic occurrence of extreme weather events. Each agent possesses a particular set of *technologies,* and makes decisions about how to deploy these technologies – consumers possess loads (electricity consuming devices) and producers possess generators (electricity producing devices). Each time step, consumer agents decide how much electricity to use and producer agents decide how much electricity to produce. The amount of electricity that consumer agents use depends on the temperature at that time step – consumers demand more electricity at higher temperatures. Generation is equalized across all producers such that the total generation each time step is equal to the total amount of electricity demanded by consumers.

Consumers and producers are linked by way of a set of interconnected links and buses – an abstracted representation of a power grid. Each link in this grid has a particular capacity, a ceiling on the amount of electricity it can transport at any given time. Each time step during the course of a simulation, the flows of power through these lines are calculated by a linked power flow analysis program.

Links may be taken out of commission for several time steps by the occurrence of extreme weather events. During the period over which these links are out of commission, they cannot transport power. This may increase the amount of electricity flowing through nearby links, or may cut off certain consumers from receiving the power. If too many links start exceeding their set capacity and/or have been destroyed by extreme weather events during a particular time step, a cascading blackout occurs.

The consequence of a cascading blackout is that all links go out of commission for a set number of time steps and consumers are completely cut off from the grid for this time.

A final aspect of the model, and what makes it a relevant demonstration of infrastructure adaptability, is that consumer agents can be given the ability to adapt by investing in distributed generators. At the start of a simulation, no consumer possesses a distributed generator – all consumers are completely reliant on the grid for their electricity. However, consumers may independently decide to invest in distributed generators if they are exposed to frequent shortfalls in electricity supply, e.g. in the form of repeated blackouts. Consumers are not able to invest in distributed generation every time step, but are only allowed to do so every 10 time steps. This is intended to reflect the longer timescale on which investments in new technical components take place (the evolutionary timescale) relative to operational aspects, which occur every time step.

5.2 Simulation and results

This section summarizes the results of 2 runs of the simulation model described above. First, we summarize the results of a case in which consumers are not able to invest in new technical components. Second, we describe the results of a case in which consumers are able to adapt by investing in distributed generators. In both cases, the simulation starts with a randomly generated infrastructure network. Each time step during the course of a simulation, consumers demand electricity, producers generate electricity and the grid transports electricity from generators to loads. The frequency of extreme weather events and the temperature are initially set to relatively low levels. During this initial part of the simulation, the first and the second case generate similar results. Every so often an extreme weather event occurs, causing a link in the grid to fail. But because of redundancy in the grid network, consumers generally do not lose power and, in the second case, they remain sufficiently satisfied not to invest in distributed generation.

After 200 time steps, we drastically increase the temperature and the frequency of extreme weather events. This causes greater loading of the grid, an increase in the frequency of line failures and even periodic blackouts. It is in this second portion of the simulation that the results from the 2 cases begin to diverge. In the first case, consumers have no capacity to adapt and are doomed to endure periodic power losses for the remainder of the simulation. After experiencing several rounds of power losses, many of the consumers in the second case, however, start investing in distributed generation, making them less dependent on the grid to meet their electricity demands. These consumers continue to invest in distributed generation until they are sufficiently satisfied with the degree to which their electricity needs are met. Figure 1 illustrates some key results from the two simulated cases.

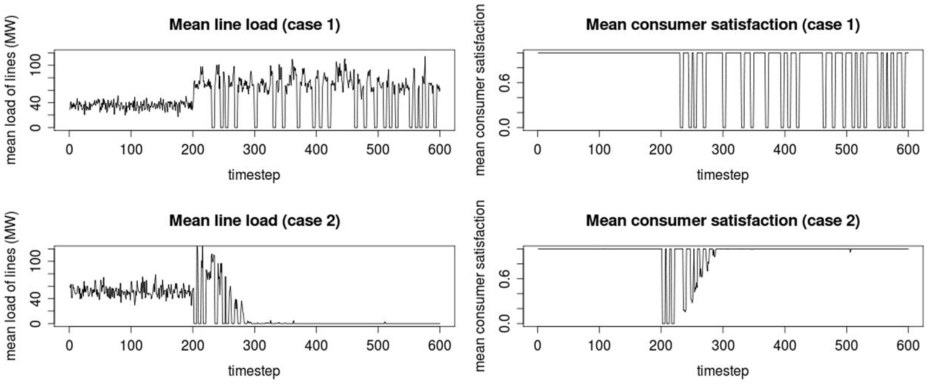

Figure 1: Key results from the 2 simulated cases. In the first case, power flows and consumer satisfaction fluctuate wildly for the duration of the simulation after 200 time steps. In the second case, power flows gradually drop and consumer satisfaction gradually levels after 200 time steps, as the amount of distributed generation in the system grows. Consumer satisfaction refers to the degree to which consumer demand for power is met at a particular point in time (1 = complete demand satisfaction, 0 = no demand satisfaction)

5.3 Analysis

Figure 2 relates the results of the 2 cases described above to the definition of resilience elaborated in the first part of this paper. As illustrated in Figure 2, 3 attractors can be identified in the results of the first case. The 1st attractor incorporates the set of system states that occurs during the first portion of the simulation. This attractor is characterized by moderate levels of electricity consumption and relatively high line loads. The 2nd and 3rd attractors emerge only during the second portion of the simulation, after temperature and extreme event frequency have been increased. The 2nd attractor corresponds to a situation of high line loads and a high quantities of power consumed. Although they appear distinct from one another in Figure 3, the 1st and 2nd attractor can also be thought of as a single attractor, since they both correspond to "normal" operating conditions within the power system.

The 3rd attractor is clearly distinct from the 1st and 2nd attractors, corresponding to a completely different ”mode of operation” of the modeled system. It is a point attractor characterized by zero consumption and zero line loads – an uncontrolled blackout. While this attractor appears as only a single point in Figure 3, it is actually composed of a number of points on top of one another – the state occurs repeatedly during the course of a simulation.

As illustrated in Figure 2, attractors 1/2 and 3 can also be seen the results of case 2. However, in this case we also see the emergence of a 4th attractor. This 4th attractor occurs during the latter half of the second portion of the simulation, after consumers have invested in significant amounts of distributed generation (see Figure 1). This attractor is characterized by relatively high levels of consumption and extremely low line loads, because consumers have become less reliant on the grid. Importantly, as can be seen in the bottom right plot of Figure 1, it is also characterized by high levels of consumer satisfaction.

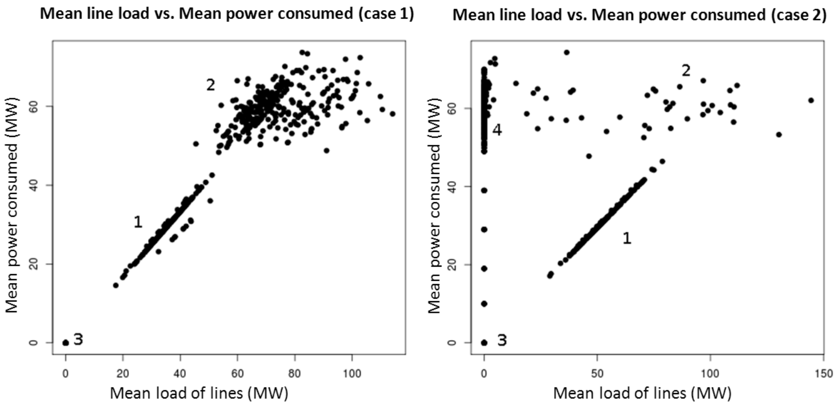

Figure 2: On an operational timescale, 3 attractors can be seen in the results of the first case, and 4 attractors can be seen in the results of the second case.

The attractors in Figure 2 correspond to operation timescale attractors – they correspond to different "modes of operation" in the modeled power system. The emergence of the fourth attractor, however, becomes possible only because of simultaneous attractor shift on an evolutionary timescale – a shift in the technological composition of the system. During the first portion of the simulation, consumers do not own any distributed generators. After enduring several bouts of power loss, however, they start investing heavily in distributed generation. Their investments change the technological composition of the system, driving it towards a new attractor on an evolutionary timescale. This phenomenon is illustrated in Figure 3.

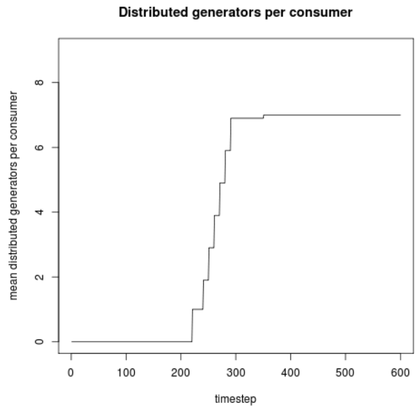

Figure 3: The results of the second case demonstrate a shift in the technological composition of the system – a shift to a new evolutionary-level attractor.

What can we say about the resilience and adaptability of the modeled systems in cases 1 and 2? Upon being perturbed at 200 time steps, neither system demonstrates resilience - the capacity to manage shifts between operational attractors to preserve service. Both systems begin oscillating between an attractor corresponding to "normal functioning" and uncontrolled blackouts. Provision of the relevant infrastructure service – electricity – is not preserved. While not initially resilient, the system in the second case demonstrates adaptability. It evolves towards a new technological attractor which, in time, endows the system with greater resilience.

The observed shifts in attractors in this model are driven by modifications in environmental variables – the temperature and the frequency of extreme weather events. It is interesting to note that, in the first case, restoring the system to the initial environmental conditions (low temperatures and a low frequency of extreme events) causes the system to return to its initial attractor. In the 2nd case, this does not occur. When the temperature and the frequency of extreme events are returned to their "pre-climate change" levels, the system moves to yet another new attractor, corresponding to low line loads and moderate consumption. The reason for this is that the system cannot "undo" the technological changes that have occurred.

This is an illustration of path dependence, a phenomenon that is often seen in the evolution of real-world infrastructures, and a significant contributor to technological lock-in. While the ability to invest in distributed generation enables consumers to adapt to the changed environmental conditions, it locks the system in to another technological configuration. This suggests that adaptability is not about endowing the system with a specific adaptive capability – e.g. an ability for consumers to invest in distributed generation – but with a more general capacity to adapt as conditions demand.

7 Conclusions

The purpose of this paper has been to explore the implications of a complex adaptive systems (CAS) perspective on infrastructure resilience. Building on work from the field of social-ecological systems, we developed an explicit definition of infrastructure resilience from a viewpoint of infrastructures as CAS – *the capacity to manage shifts between attractors in infrastructure operation* to preserve an infrastructure service. In arriving at this definition, we differentiated between dynamics on an operational and an evolutionary timescale. We introduced the term *adaptability* to describe the capacity to manage shifts between attractors in infrastructure systems on an evolutionary timescale.

In a world where our infrastructures are exposed to an increasing array of threats, 100% security of supply is not an option. We must conceptualize our infrastructures in a way that expands our possibilities for supporting their capacity to deliver valued services in a turbulent environment. A CAS perspective can help to enable this. By providing a theoretical basis for conceptualizing infrastructure resilience in line with a CAS perspective, this paper provides a foundation for supporting the development of resilient infrastructures. Future work will focus on identifying key factors for supporting the development of resilient and adaptable electricity infrastructures - how can we endow infrastructure systems with a capacity to manage shifts between attractors, both in operation and evolution?

Acknowledgements. This work is supported by the Knowledge for Climate program, project INCAH – Infrastructure Networks Climate Adaptation and Hotspots.

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