Balancing the demands of climate change adaptation and mitigation in energy infrastructures – a modeling framework

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Abstract

As society gradually undergoes a transition to less carbon-intensive infrastructure systems, it must simultaneously prepare these infrastructures for the expected but unknown effects of climate change. Existing energy systems and expansions over the coming decades will have to function under conditions of increased summertime temperatures, greater variability in precipitation and higher sea levels.

How can we support the development of energy systems that effectively balance the demands of mitigation and adaptation? Our approach combines the techniques of agent-based modeling (ABM) and exploratory modeling to investigate possible evolutionary pathways of energy infrastructures. Agents in this approach represent actors in the energy infrastructure. During the course of simulation, these agents are exposed to various policy and climate scenarios. The characteristics of these scenarios affect the decisions agents make and subsequently the features of the infrastructures that develop over time. By analyzing the infrastructures that emerge across a range of policy and climate scenarios, we can identify robust policy options for fostering the development of infrastructures that effectively balance the needs for mitigation and adaptation.

This research is in its preliminary stages. We describe a "proof-of-concept" model exploring the resilience of the Dutch electricity infrastructure to climate change. This model – containing the transmission system operator, consumers, producers and import/export linkages – is connected with a power flow analysis tool, which enables capture of the functionality and limitations of the transmission grid. The model examines how seasonal and extreme weather patterns, together with basic economic and grid operation parameters, may affect the resilience of the electricity infrastructure.

Keywords: Energy infrastructures, Climate change mitigation, Climate change adaptation, Agent-based modeling,

Introduction

As the largest emitter of greenhouse gases, the energy sector must play a significant role in climate change mitigation – actions to reduce the atmospheric accumulation of greenhouse gases and the intensity of radiative forcing. The transition to a low-carbon energy system necessitates large-scale investments in renewable energy technologies, smart electricity grids and a range of other infrastructure components. If implemented, these infrastructure investments will fundamentally transform the structural characteristics and functional operation of the energy system for decades to come.

In addition to the need to mitigate climate change, however, energy infrastructures must be adapted to deal with its probable effects – rising sea levels, increased average and extreme temperatures, increased frequency of extreme rain events, more severe summer droughts, greater variability in wind patterns and solar radiation, etc. (Wilbanks et al, 2008; Bresser et al, 2005). These effects have the potential to impact energy infrastructures in a variety of ways. Rising sea levels and an increasing occurrence of extreme rain events have the potential to generate severe floods in coastal areas where a large proportion of infrastructure components are situated. Simultaneously, more frequent and longer lasting droughts have the potential to sporadically restrict the navigability of inland waterways, disrupting important supply lines for power generating facilities. Higher summertime temperatures may furthermore result in increased space cooling demand and cooling water issues at power plants.

While the need to develop energy infrastructures that balance the demands of mitigation and adaptation is clear, the task of doing so is far from straightforward. Today's energy infrastructures are complex *socio-technical systems* – dynamic assemblages of highly interconnected technical and social elements. They exhibit a high degree of complexity both in their physical and their social networks (Herder et al, 2008). Complexity in physical networks is reflected in the highly interdependent nature of subsystems, links and nodes, which means that issues in one subsystem may have far-reaching consequences for the system as a whole. Such interdependencies, for instance, can cause local failures in an electricity network to propagate into system-wide cascading blackouts.

Social complexity is manifested in the interactions amongst actors in an infrastructure system. Each of these actors carries his own set of interests and perceptions, potentially creating a situation in which no one actor can sufficiently understand a situation in its entirety (Herder et al, 2008). Market liberalization contributes an additional layer of complexity to the social network by fragmenting the planning and control of infrastructures across multiple actors with potentially divergent interests (de Vries et al, 2006).

Next to this social and technical complexity, the balancing of mitigation and adaptation needs is complicated by environmental uncertainties. One significant source of uncertainty is the nature and severity of future changes in climatic variables. The climate system is composed of an enormous number of components whose interactions have the potential to generate nonlinear behaviors that are difficult, if not impossible, to predict. The types of uncertainties this creates are difficult to effectively characterize with traditional probability distributions (Lempert et al, 2004). On top of these climate-related uncertainties, the context of energy infrastructures is characterized by uncertainties concerning the development of socio-economic variables. How will economic conditions change over the coming decades? How will different technologies disseminate across the societal landscape?

Both the complexity of infrastructure systems and the uncertainties inherent in their environment complicate the process of developing energy infrastructures that effectively deal with the multiple challenges of climate change. The objective of this paper is to describe a modeling framework for navigating this complexity and uncertainty – an approach to modeling energy infrastructures and their interactions with climate change. This framework forms the basis of an approach for supporting the development of energy infrastructures that effectively balance the demands of mitigation and adaptation.

In pursuit of this objective, we begin in the next section by elaborating on two key building blocks of this framework – agent-based modeling and exploratory modeling. Subsequently, we introduce the framework and describe its components and structure. Following from this, we describe a preliminary deployment of this framework in the form of a “proof-of-concept” model.

Key building blocks of the framework

The framework described in this paper is composed of two key building blocks – agent-based modeling and exploratory modeling. We hypothesize that, in combination, these building blocks can enable effective navigation of the unique complexities and uncertainties that characterize the intersection of climate change and energy infrastructures.

Agent-based modeling

Agent-based modeling (ABM) is a 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 are not predefined, but emerge as a consequence of these (multitudinous) interactions.

ABM offers a number of advantages over the traditional integrated assessment techniques applied in the climate change context. It has been claimed that agent-based models can more effectively represent human decision-making processes (Pahl-Wostl, 2002) and that they can better capture the emergence of socio-economic structures (Downing et al, 2000). Furthermore, it has been suggested that they are better aligned with the policy context (Pahl-Wostl, 2002) and that they offer the potential for improved validation (Moss et al, 2001) compared with traditional integrated assessment modeling techniques.

Due to these advantages, ABM is increasingly applied in models dealing with issues of climate change mitigation and adaptation. With respect to mitigation, agent-based models have been used to explore the evolution of electricity infrastructures and its long-term consequences in terms of greenhouse gas emissions (Chappin and Dijkema, 2009; Weidlich and Veit, 2008), to assess the effects of various policies and strategies on the diffusion of low-carbon technologies (Schwoon, 2006; Stephan and Sullivan, 2004) and to evaluate the socio-economic and land-use impacts of climate policies (Bakam and Matthews, 2009). With respect to adaptation, agent-based models are most often employed to examine the socio-economic and land-use impacts of climate change, and the effectiveness of various adaptation measures in alleviating these impacts (Berman et al, 2004; Bharwani et al, 2005).

In addition to its suitability in the climate change context, ABM can be particularly useful for capturing energy infrastructures as socio-technical systems. A key advantage of ABM is that it enables us to capture the evolution of technical infrastructures as a consequence of actor decisions. Furthermore, it allows for the explicit representation of these decision making processes and the factors that influence them, as well as the bounded rationality of actors that carry them out. These characteristics enable us to capture energy infrastructures in a manner which aligns with their real-world complexity. We are able to explicitly represent various actors, including their unique interests and perceptions. And we are able to capture the fragmented nature of infrastructure planning and control.

Exploratory modeling

Exploratory modeling is a modeling process in which results are viewed as indications of possible futures rather than as predictions of a single definite future (Bankes, 1993). At the foundation of exploratory modeling is the idea of investigating multiple hypotheses about a system by broadening the assumptions underlying the system model (Agusdinata, 2008). These multiple hypotheses are then explored by way of numerous computational experiments – simulation runs corresponding to different sets of assumptions about how the world works, and testing different policy strategies. Coupled with high performance computing, application of exploratory modeling can enable the testing of a model across a large parameter space over thousands of simulation runs.

A key advantage of this technique is its capacity to effectively deal with the types of uncertainty inherent in issues of climate change adaptation and mitigation. As noted above, the uncertainties associated with climate change are difficult to effectively characterize with traditional probability distributions, whether objectively or subjectively determined. Exploratory modeling deals with this by essentially admitting to the existence of multiple plausible representations of the world, and simulating them in succession. Through the testing of different policy strategies, exploratory modeling can aid the identification of *robust* policies – policies that generate desirable outcomes across a range of possible futures. Furthermore, it can help to locate scenarios under which these strategies may perform poorly, helping to inform the development of effective hedging strategies (Lempert et al, 2004).

Together, the techniques of agent-based modeling and exploratory modeling provide a basis for navigating the unique complexities and uncertainties characterizing the intersection of climate change and energy infrastructures. The next section describes how these building blocks are employed in the context of the proposed framework.

A framework for balancing mitigation and adaptation

The impacts of climate change and actions to mitigate it play out across multiple societal domains – environmental, socio-economic, technical and policy – and across multiple timescales – from minutes to days to years to decades. An example serves to illustrate this. In the summer of 2003, a severe drought and heat wave struck much of Western Europe. Temperatures rose to above 40 degrees Celsius in parts of France and Germany. Forest fires broke out in Portugal, and melting glaciers caused avalanches and flash floods in Switzerland. While the events of 2003 cannot be directly linked to long-term climate change, current climate models suggest that such events are likely to occur with increasing frequency in the decades to come. Thus, the events of 2003 provide a window into the sorts of dynamics – in particular the timescales and societal domains – that may be relevant as the impacts of climate change become more pronounced.

On a short time scale (minutes to days), the 2003 drought and heat wave had an immediate impact on electricity use. An analysis by Rothstein, et al (2007) notes a dual impact on electricity consumption as a consequence of the 2003 heat wave – an increase in the intensity of electricity demand and changes in the course of the electricity load curve due to changes in the daily routines of electricity consumers. On a medium timescale (days to months), the 2003 drought and heat wave affected amongst others the functioning of thermal power plants. This was particularly severe in France, where a drop in the level of inland waterways and an increase in their temperature caused cooling water problems for a number of thermal power plants. This incited the temporary shut-down of several nuclear generators, and necessitated the issuance of temporary legal exemptions from water temperature limits for several power plants (De Bono et al, 2004).

On a longer timescale, the events of 2003 initiated or fed multiple discussions about the needs for longer-term adaptation measures for dealing with the impacts of climate change (Rademaekers et al, 2011; Poumadere et al, 2005). Anecdotal reports also suggest that the heat wave may have increased the market penetration of residential air conditioning (Tagliabue, 2003), potentially contributing to a longer-term shift towards higher summertime peak electricity consumption levels.

This series of events illustrates the relevance of multiple timescales – from minutes to decades – and multiple domains – environmental, socio-economic, technical and policy – in capturing interactions between energy infrastructures and climate change.

Description of the framework

The framework presented here is an approach to modeling energy infrastructures and their interactions with climate change. The aim of this framework is to enable the evaluation of policy measures and other strategies with respect to: (1) their effect on the resilience of energy infrastructures to climate change, and (2) their capacity to reduce energy sector greenhouse gas emissions. Pursuant of this aim, the framework seeks to capture the following pertinent aspects of energy infrastructures and their interactions with climate change:

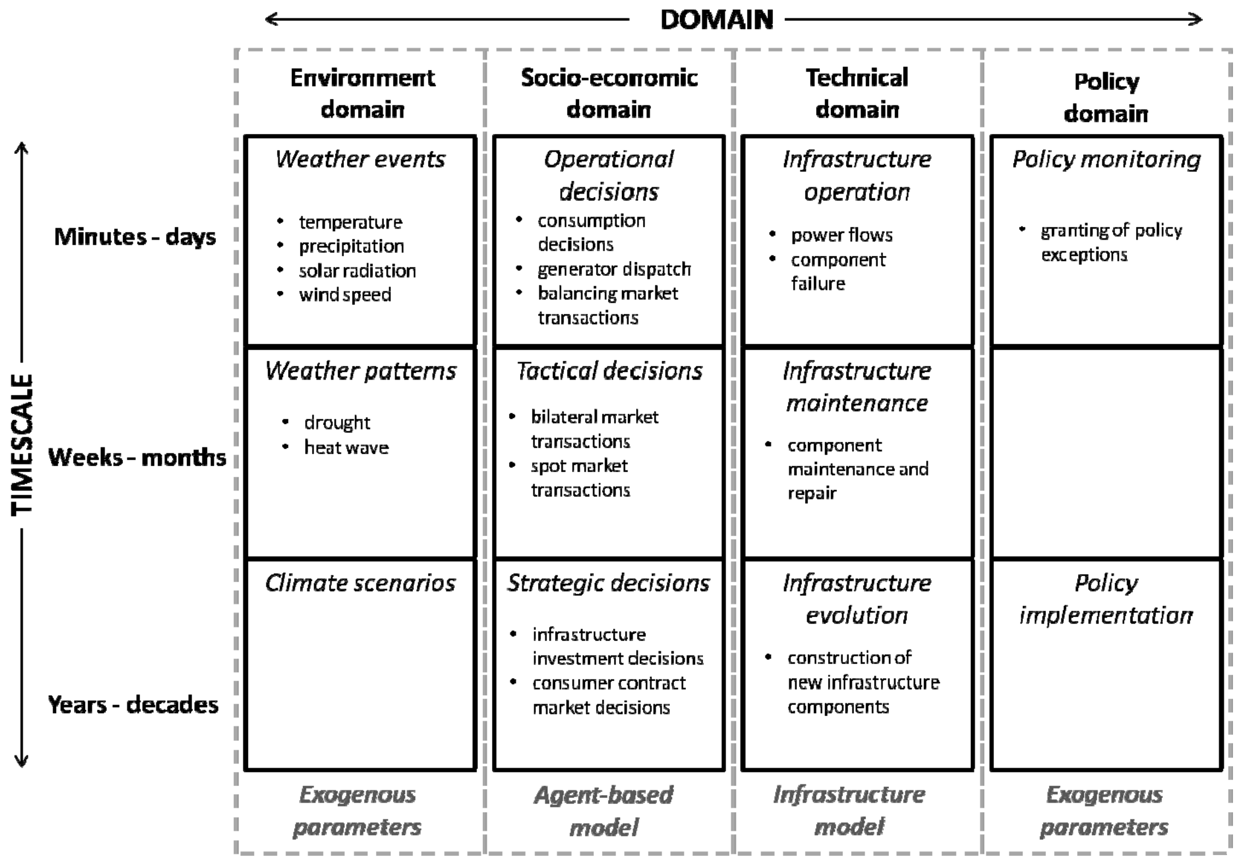
1. The multiple scales of time and the multiple societal domains across which the impacts of climate change and actions to mitigate it play out.
2. The most relevant elements of the system's technical and social complexity – interdependencies amongst technical subsystems, links and nodes, and interactions amongst numerous actors with diverging interests and perceptions.
3. Key uncertainties in the system with respect to the nature and severity of climate change and socio-economic developments.

The manner in which these 3 aspects are captured within the modeling framework is illustrated in Figure 1. The first aspect is captured via the explicit inclusion of dynamics within and interactions across multiple scales of time and multiple societal domains. The framework captures 3 different timescales – from minutes to years – and 4 different societal domains – environmental, socio-economic, technical and policy. The intersections of these timescales and domains divide the framework into 12 components, with each component containing a set of elements and relationships pertaining to the specific domain and timescale.

The second aspect is captured in two ways. First, social complexity is captured via the explicit representation of relevant actors, their decision-making processes and their interactions with one another. The representation of social complexity is aided by the use of agent-based modeling, which allows us to literally "play out" decision making processes and actor interactions, and observe their consequences across different timescales. Second, technical complexity is captured through the representation of relevant physical infrastructure components – power plants, grid components, etc. – the interactions of these components, and their evolution over time. The representation of technical complexity is aided by the use of equation-based infrastructure models, an instance of which is described in the next section. Interactions between social and technical components are realized in practice by creating explicit links between the agent-based model and the infrastructure model.

The third aspect is captured through the use of exploratory modeling. Uncertainties with respect to the development of climate variables – temperature, rainfall, etc. – and economic variables – commodity and electricity prices, economic growth, etc. – are *parameterized*. In other words, the values of these variables are altered across many (e.g. thousands) simulation runs in order to effectively capture associated uncertainties.

Figure 1: Structure of the framework. The framework is organized along 2 dimensions – timescale and societal domain. The intersections of timescales and domains divide the model into 12 components.



The chief aim of the framework – the identification of robust policies and strategies that effectively balance needs for mitigation and adaptation – is similarly achieved through the parameterization of policy levers. Variables such as investment strategies carried out by economic actors, or subsidies/taxes implemented by public sector actors, are altered across simulation runs to test possible impacts of different policies across a range of climate and socio-economic scenarios. The next section describes a preliminary implementation of this framework in the form of a "proof-of-concept" model.

A "proof-of-concept" model

As a preliminary test of the framework described above, a "proof-of-concept" model has been developed. This model focuses on the high-voltage electricity infrastructure in the Netherlands and its key interactions with climate change. As prescribed in the previous section, the model incorporates multiple societal domains and multiple timescales. Social complexity is captured using an agent-based model, in which the decision making processes and interactions of multiple actors are specified. Technical complexity is captured using a power flow analysis model, which is linked with the agent-based model and enables analysis of electricity grid performance at each time step of the agent-based model. Uncertainties are captured via the simulation of multiple climate change scenarios.

The proof-of-concept model links two modeling techniques – agent-based modeling and power flow analysis. Agent-based modeling is used to capture the long-term evolution of the electricity infrastructure as a consequence of actor decisions. Power flow analysis is used to calculate the flows of power through the components of the grid, and the degree to which consumer demand for electricity is met at each time step. The agent-based model has been constructed and simulated in the Netlogo platform (Wilensky, 2011). Power flow analysis is carried out using the numerical computing package Matpower (Zimmerman et al, 2011). A software link between the Netlogo platform and Octave (an open-source numerical computing program) was custom-developed to enable dynamic interaction between the two software platforms.

While the model successfully captures all aspects of the framework described in the previous section, it does so in a highly simplified way. The decision making procedures of agents are highly abstracted, the structure of the high-voltage electricity grid has been simplified and only a handful of climate and policy scenarios are tested. Furthermore, the model focuses exclusively on assessing the resilience of the modeled infrastructure to climate change, and leaves out aspects associated with mitigation.

Due to these simplifications, the model does not provide extensive insight into the effectiveness of strategies for balancing adaptation and mitigation needs. However, the model does serve as a fruitful test of the framework described above, and provides insights into how this framework can be effectively translated into a powerful set of tools for testing policies and strategies.

Setup of the model

The proof-of-concept model is composed of 4 elements – agents, technologies, decision rules and an environment. Agents are the social elements of the system. Each agent possesses a particular technology, or set of technologies. During the course of a simulation, agents have to make decisions (e.g. how much electricity to use, how much to produce, how to invest). These decisions are made according to defined decision rules. Agents, together with their technologies and their decision rules, exist within an environment, the characteristics of which affect the decisions agents make.

Four types of *agents* are represented in the model. Each of these agent types represents a particular category of actor in the real-world system. The types of agents include:

- *Consumers*: Consumers in the model represent all consumers of electricity in the Netherlands. There is no differentiation between different types of consumers, e.g. large vs. small, commercial/industrial vs. private. There are multiple consumer agents in the model. To maintain simplicity, the number of consumer agents does not change over time.
- *Power companies*: Power companies in the model represent all producers of electricity in the Netherlands. There is currently no differentiation between different types of power companies. For purposes of simplicity, the number of power companies does not change over time.
- *Transmission system operator (TSO):* The TSO represents the Dutch transmission system operator TenneT. There is only one TSO in the model.

- *Neighboring countries:* Neighboring countries represent those countries (including the consumers and producers within them) with which the Netherlands has a high-voltage power link. There are four neighboring country agents in the model, representing Germany, Norway, Great Britain and Belgium.

Each agent in the model is assigned certain *decision rules*. Consumers decide how much electricity to use; power companies decide how much electricity to produce; the TSO decides when, where and how to make repairs to the grid and add capacity; and neighboring countries decide how much electricity to produce and consume. These decision rules are currently very simplistic in nature – they are placeholders for more complex decision rules which will be implemented in the future.

- *Consumers* decide how much electricity to use based on the current temperature, and a reference consumption level, which grows over time.
- *Power companies* decide how much electricity to produce based on the temperature and a reference production level.
- The *TSO* automatically makes repairs every time a component he possesses fails. The TSO invests in new lines according to one of four pre-defined investment strategies (see below).
- *Neighboring countries* decide how much electricity to produce and consume based on the difference between the total demand of consumers and the total production of power companies in the Netherlands.

Each of the aforementioned agents possesses one or more *technologies*. Consumers possess a load; power companies possess a generator; the TSO possesses links and buses; and neighboring countries possess both a generator and a load.

- *Load:* All consumer agents possess a load technology. The load represents all electricity-consuming devices and facilities possessed by the agent. Currently, a load is characterized by a single property – a real power demand. Each load is linked to a particular bus.
- *Generator:* All power companies possess a generator technology. The generator represents all power production equipment owned by the power company. There is currently no differentiation between different types of generators. Generators are currently characterized by a single property – a real power output. Each generator is linked to a particular bus.
- *Link:* The TSO owns a number of links. These links represent power lines of the Dutch 380kV grid. Links are characterized by several properties, such as capacity, resistance, reactance, a real power input and a real power output.
- *Bus:* The TSO owns a number of buses. These buses represent nodes in the Dutch 380kV grid, e.g. substations, busbars. Buses are characterized by several properties, such as a geographical location (coordinates), a voltage magnitude and a real power demand.

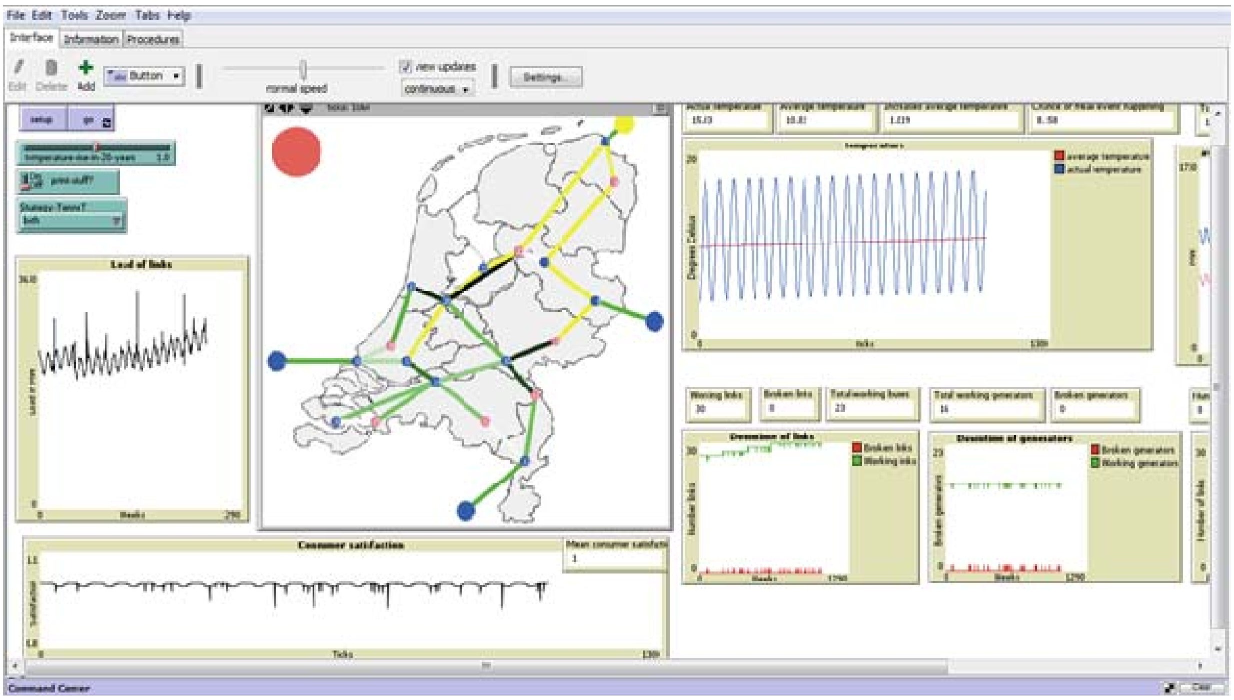
Agents and technologies exist within an *environment*. This environment is characterized by 2 properties – a temperature and extreme weather events. Both the level of the temperature and the frequency of extreme weather events change over time. These 2 features are used to capture climate change in the model – temperature increases over time and extreme weather events occur with increasing frequency over time. The temperature of the environment is used by agents to determine consumption and production of electricity. Extreme weather events occur at various geographical locations, causing specific components of the electricity grid to fail.

Simulation and experiments

Figure 2 illustrates a typical simulation run. A simulation proceeds in time steps, with each time step representing 1 week of real-world time. A simulation proceeds for 1040 time steps, or 20 years of real-world time. During each time step, the same sequence of events occurs:

1. *Environmental variables are set:* The temperature is set and extreme events (may) occur. The temperature varies seasonally and increases gradually over time to represent the effects of climate change. Extreme events occur at random locations and times, but with increasing frequency over time.
2. *Agents set supply and demand:* Based on the temperature, consumers and neighboring countries determine their electricity demand, and power companies and neighboring countries determine their electricity supply.
3. *Grid topology is determined:* As a consequence of extreme weather events, grid components may fail. The failure of these components creates a new grid topology.
4. *Load flows are calculated:* The grid topology, together with the demand and supply values of various agents/technologies are passed on to Matpower, which performs a load flow calculation. The outputs of this calculation are the power flows over links and voltages at buses.
5. *Metric values are calculated:* Based on the outputs of the load flow calculation, the values of various metrics are calculated. Chief amongst these is consumer satisfaction, which is a measure of the degree to which the electricity demand of a consumer has been met in the current time step.
6. *The TSO invests in new capacity and repairs failed components:* The TSO repairs all failed components, and follows his pre-defined investment strategy to invest in new links and new link capacity.

Figure 2: Screenshot of a simulation of the "proof-of-concept" model



Experimentation consisted of performing a number of simulations under different parameter conditions. The parameters that were varied during experimentation included the severity of climate change (no climate change to very severe climate change) and the investment strategy of the TSO. Four investment strategies for the TSO were tested:

1. *No investment:* The TSO makes no new investments
2. *Investment in new links*: The TSO creates new links at predefined locations at set time steps during the course of a simulation.
3. *Investment in increased capacity:* The TSO does not build any new links, but increases the capacity of existing links at various points during the course of a simulation
4. *Investment in new links and increased capacity:* The TSO both builds new links and increases the capacity of existing links at various points during the course of a simulation

During the course of experimentation, 20 different unique parameter sets were tested – each of the 4 investment strategies was tested at each of 5 different climate scenarios. Several repetitions were performed at each unique parameter set to provide a sense of the "average" behavior produced by each parameter set.

The results from these models were tracked using two metrics: the mean consumer satisfaction – a measure of the degree to which consumer demand for electricity is met – and the average load of lines in the electricity network. Of the 4 tested investment strategies, it was found that a strategy focused on the construction of new links was most effective in both increasing consumer satisfaction and reducing line loads across the climate scenarios tested.

Discussion

The proof-of-concept model proved a fruitful test of the framework described in the previous section. It demonstrated the technical feasibility of implementing the framework and the suitability of the selected toolset to capture pertinent elements and relationships lying at the intersection of energy infrastructures and climate change. Furthermore, the process of developing and testing of the proof-of-concept model revealed that a significant challenge in implementing the framework lies in finding an appropriate balance between complexity and simplicity in system representation.

As described in the introduction, the energy infrastructure is an inherently complex system. Inevitably, modeling this system necessitates a degree of abstraction. In the proof-of-concept model, all components of the system – agent decision-making procedures, the properties of technical components, the characteristics of climate change scenarios, etc. – were maximally abstracted. In future implementations of the framework, a necessary and challenging task will be to identify those elements and relationships of the real-world system that are essential to identifying robust policy strategies.

One possible approach to dealing with this, and the approach which is currently being pursued, is to implement the framework not as a single model, but as a set of simulation *modules*. Each of these modules corresponds to one of the grid elements illustrated in Figure 1 – operational decisions, strategic decisions, infrastructure operation, infrastructure evolution, etc. – and contains elements and relationships relevant to the specified timescale and domain. More ambitiously, multiple versions of each module may exist, with each version representing the relevant aspects of the system at a higher or lower fidelity. These modules could then be mixed, matched and simulated in different ways to address the needs of different research questions. This approach comes with its own host of challenges – for instance, how to realistically manage multiple versions of each module – but seems promising in its ability to balance the needs for simplicity and complexity in system representation.

Conclusion

The sections above have elaborated on a framework for supporting the development of energy infrastructures that balance the demands of climate change mitigation and adaptation. The complexity of infrastructure systems and the uncertainties inherent in their environment complicate the process of effectively preparing infrastructures to deal with the multiple challenges of climate change. The key building blocks of the proposed framework – agent-based modeling and exploratory modeling – provide a basis for navigating these complexities and uncertainties. The structure of the framework furthermore seeks to capture the multiple timescales and the multiple societal domains over which the interactions between climate change and energy infrastructures play out. A preliminary implementation of the framework in the form of a “proof-of-concept” model proved a fruitful test of its feasibility and suitability, and helped reveal several key challenges to more comprehensive implementation.

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