Modeling Electric Power and Natural Gas System Interdependencies

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Abstract: To promote the resilience and protection of infrastructure assets from an all-hazards perspective, this paper describes the progress of interdependencies modeling and integration efforts to anticipate cascading failures among critical infrastructure systems. A data-centric architecture is adopted that integrates existing and proven infrastructure models used for impact assessment analyses to aid and enhance the design of resilient infrastructure systems. The assessment framework is applicable to all types of critical infrastructure and permits (1) the integration and automation of the assessment process, including threat and hazard identification and data acquisition; (2) the estimation and projection of impact zones; (3) the simulation of the initial effects on infrastructure assets resulting from an initiating disruptive event; (4) the evaluation of propagating effects within each infrastructure system; and (5) the simulation of the influence of cascading failures across infrastructure systems. The paper presents the application of the framework to integrate two proven energy models—*EPfast*, for electric power, and *NGfast*, for natural gas—to anticipate regional and local cascading failures, and design resilient energy systems. Two state-level case studies illustrate the approach in simulating the propagation of disruptions between the natural gas and electric power systems. **DOI: 10.1061/(ASCE)IS.1943-555X.0000395.**

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Introduction

The United States faces significant challenges in enhancing the protection and resilience of the nation's critical infrastructure systems to various types of natural hazards and manmade threats. This goal is made more challenging by the complexity of infrastructure systems and their inherent interdependencies. Key policy documents—including the Presidential Policy Directive on Critical Infrastructure Security and Resilience (PPD-21), the 2013 National Infrastructure Protection Plan (NIPP), and the Voluntary Private Sector Preparedness Program—PS-Prep and Small Business Preparedness—identify the need to integrate critical infrastructure interdependencies analysis in risk management processes (Executive Order Number 13636 2013; DHS 2013; FEMA 2014).

Furthermore, assessing infrastructure protection and resilience requires consideration of many interconnected socioeconomic, ecological, climatic, and technical elements. These interconnections mean that disruption or failure of one element can lead to cascading failures in others. Interdependencies among infrastructure systems lead to a level of complexity that masks many systemic risks. As a result, an impact to a single node or link—the proverbial *single point of failure* that is often hidden deep within these interconnected systems—can result in important economic and physical damage on a city-wide, regional, or even national or international scale.

Even though the research addressing infrastructure interdependencies started more than 15 years ago with the work of Rinaldi et al. (2001), modeling, simulation, and visualization tools still need to be harnessed to identify infrastructure interdependencies. Too often, as identified during Superstorm Sandy, interdependencies are discovered only after the fact by the direct experience of cascading failures (Flynn 2015). In 2016, the authors participated in a multilaboratory technical exchange in Washington, DC, that reaffirmed the conclusions as Rinaldi, Peerenboom, and Kelly. However, the group defined several recommendations on how to advance the science of modeling infrastructure interdependencies to provide information to decision-makers (Clifford and Macal 2016). During the technical exchange, the participants particularly identified the exploration of an integrated modeling approach that combines multiple models allowing anticipation and simulation of potential cascading failures.

Considering the limited resources for funding infrastructure improvements, security, and resilience enhancement initiatives, it is useful to apply an approach that can examine an infrastructure's operational characteristics and potential failure modes to assist in prioritizing competing engineering projects. One successful approach performs impact assessments of infrastructure components that support critical aspects of infrastructure operations, knowing that those components are vulnerable to various threats

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and hazards. To assist in the evaluation of infrastructure assets from an all-hazards perspective, the authors demonstrate an assessment framework that combines infrastructure simulation models to identify potential cascading failures resulting from natural hazards, and proposes related resilience and protection enhancement measures.

This paper begins with a discussion of the motivation that led to the development of the assessment framework. Next, the authors present the work undertaken to integrate existing electric power and natural gas systems simulation models. The remaining sections of the paper cover the results of the assessment using two case studies and discuss possible future research projects.

Motivation

A primary goal of this research effort was to develop an infrastructure impact analysis tool that integrates and automates the interactions of existing infrastructure simulation tools, which will anticipate cascading and escalating failures (Clifford 2015). Employing integrated models for resiliency assessment of interdependent systems permits the evaluation and visualization of disruptions occurring in one system that could easily cascade to other systems, potentially magnifying the overall societal impact of the event. From a planning perspective, extended situational awareness of the operational aspects of integrated infrastructure systems enables a better understanding of how a failed component in one system can initiate and propagate a disturbance in another system. This essential capability is a necessary outcome of an integrated modeling environment. Furthermore, the use of simulation models to aid in the design of resilient infrastructure is a generally accepted approach in the global engineering community.

The first step is to develop an assessment framework that can apply to all types of critical infrastructure systems and to test the framework by assessing the electric power and natural gas infrastructure systems.

Further steps will address the integration of water, communications, and transportation systems. Electric power and natural gas systems were selected because they are two of society's most important lifeline systems, and are known historically to have strong synergistic interactions.

Both electric power and natural gas systems exhibit a strong interplay or interdependence that is well recognized. For example, the electric grid depends on natural gas for fueling its power plants. In the other direction, the natural gas supply is dependent on electricity to operate natural gas processing plants (NGPPs) and other supporting system assets (such as electric-driven compressor stations in some regions). To further illustrate, preference for natural gas for electric power generation continues and was emphasized during recent training and interaction opportunities with the Midcontinent Independent System Operator (MISO) organization during 2015 (Argonne National Laboratory 2015). Therefore, the motivation to integrate electric power and natural gas simulation models is highly supported and contributes to the initiative to couple the interaction between both infrastructure systems.

Developing integrated electric power and natural gas models has been a subject of numerous studies for many years. Two factors have recently heightened the importance of developing such models:

- Significant decrease in gas prices largely because of availability of new resources (shale plays) and new technologies (fracking) for its extraction; and
- Replacement of retiring and future coal-based generation with gas-fired power plants.

With such significant growth in gas-based generation, the interplay between the two systems has intensified and models that analyze the back-and-forth propagation of disturbances between the two systems have become a subject of utmost interest. Energy system operators usually utilize several models for both sectors that were developed in different time periods. In addition, these system models are generally completely different in both formulation and solution algorithms. The question becomes: How can one directly combine these tools without making major modifications in the internal codes of either?

A number of formulations (Chen and Baldick 2007; Unsihuay-Vila et al. 2007; Zavala and Chiang 2016; Quelhas et al. 2007) characterized the coordination of electric power/natural gas and fall within the deterministic optimization domain, where the objective function minimizes total system cost (or maximizes total benefits).

Most of these models are developed for the coordination of planning and operation between electric power and natural gas systems. Usually, the two systems are integrated in a single simulation model that does not readily allow the developed model to be combined with other simulation models that apply to different types of infrastructure systems. Zavala and Chiang (2016) propose an integrated model within a node-link environment, which focuses on gas-fired power plants as the points of connectivity between the two infrastructures. The natural gas and electric power models are both nonlinear and were developed together from the very start of the research work. The natural gas and electric power components have similar formulations. Arnold and Andersson (2008), Moeini-Aghtaie et al. (2014), and Urbina and Li (2008) show a slight variation of this approach and apply decomposition techniques to optimize the electric power and natural gas systems separately but in a coordinated manner. Other studies, like the work conducted by Unsihuay-Vila et al. (2007), used energy hubs to couple the electric power and natural gas systems. Even with the concept of energy hubs to serve as connectivity points between electric power and natural gas networks, formulation of both the electric power and natural gas problems are nearly identical under the node-link framework. In some cases, however, the gas networks used to illustrate the approaches are synthetic, small, or very simplistic as in An et al. (2003) and Urbina and Li (2008).

Chen and Baldick (2007) addressed the problem of maximizing the market value of the natural gas portfolio of a local electric distribution as it supplies fuel to electric power plants. However, this approach did not explicitly define the physical crossover interface or points of connectivity between the natural gas and electric power infrastructure systems. The interactivity emphasis was on the economic or financial side rather than on the physical transfer of energy. Again, both the electric power and natural gas infrastructure systems were developed simultaneously from the very start of the study with the intent of merging them.

Chertkov et al. (2014) take the approach of characterizing natural gas pressure fluctuations as a function of the variation in natural-gas-fired generation. The study in Chen and Baldick (2007) examines the optimization of the gas supply portfolio to maximize market performance by electric utilities. Quelhas et al. (2007) used a linear model as the foundation for developing a generalized network flow model of the United States' integrated energy system involving electric, gas, coal, and petroleum. The latter approach defined the linkages among the infrastructures.

Most of the methods presented in the scientific literature do not specify impact analysis models that characterize the consequences of disruptions expressed in terms of outage areas or number of customers affected. In general, existing integrated electric power and natural gas models were developed simultaneously by using a similar topological framework. No specific approach seems to coordinate independent simulation models with dissimilar formulations. Current interdependency simulation models embody an intentional fusion of the systems at the very start of the model development process. Thus, if one system is based on a link-node framework, the other shares the same environment. The result is an integrated model with a uniform mathematical formulation and a similar solution methodology applied across both the gas and electric infrastructure models. However, this approach to model development is often relatively more expensive and slower, especially if there are already existing proven models that could be combined. Furthermore, these models do not usually use real-world data representing large topographic regions.

Other studies are not specific to energy systems and address interdependencies among all types of infrastructure (Ouyang 2014; Ouyang and Duenas-Osorio 2011a, b). Ouyang (2014) reviewed infrastructure modeling and simulation studies and groups them in six categories: empirical, agent-based, system-dynamics-based, economic-theory-based, network-based, and others. All these approaches differ by their fundamental principles, research focus, modeling rationale, analysis method, and risk components. The review conducted by Ouyang (2014) identified several existing challenges that should guide the development of future research. Critical infrastructures are not static and interdependencies modeling and simulation require development of an open modeling framework that will be flexible. The framework should allow the integration of different modeling and simulation approaches, allow consideration of different types of critical infrastructure systems, and capture different aspects of interdependencies.

The studies conducted by Ouyang and Duenas-Osorio (2011a, b) are particularly interesting. Their first study (Ouyang and Duenas-Osorio 2011a) proposes an approach to designing or retrofitting interface topologies to minimize cascading failures across urban infrastructure systems. The approach and assessment framework proposed that, like the identification of hazard types, the modeling of initial failures and the modeling of operating mechanisms are important elements to consider in an interdependency assessment framework. The simulation models used abstract networks to simulate the interactions between the electric power and natural gas systems because of the difficulty to access real data. In a later paper, Ouyang and Duenas-Osorio (2011b) complete this work by proposing an approach to explore the generalized interdependent effect of different, simultaneous failure fractions.

When using integrated models that appropriately characterize the energy interplay between the linked systems, engineers can design systems that maximize overall benefits during normal operations, and minimize unforeseen cascading impacts within and across infrastructure systems during major events. In addition, such models, whether employed offline or in real time, increase the situational awareness of system operations during emergencies, leading to informed and appropriate decision-making, timelier mitigation and response measures, and more effective restoration actions.

In addition to the interactions among infrastructure, it is important to consider the hazards and threats that influence the behavior of the integrated systems. The list of hazards and threats that endanger the normal operations of lifeline infrastructure is lengthy. In general, threats refer to manmade disasters, while hazards refer to natural disruptive events. For electric systems, substations located along coastal regions may be vulnerable to higher water surges during hurricanes. Higher water surges can be influenced by rising sea levels, increased precipitation, and stronger winds. An integrated energy model could simulate the simultaneous loss of substations at risk of flooding prior to landfall of an anticipated hurricane and flooding event. Such studies could determine whether disturbances can propagate inland throughout the electric grid and possibly cause widespread power outages. When power outages are predicted for areas further inland, protective measures can be taken at natural gas infrastructures and other critical assets that rely on electric power. Furthermore, resilience measures such as selective reinforcement and installation of backup generators can be implemented to improve overall system resilience at selected assets.

Extreme temperature rise also introduces an extraordinary threat to electric infrastructure assets. High temperatures reduce transmission line capacity, lower thermal efficiency of natural-gas-fired power plants, shorten the life of transformers, and threaten the sufficiency of the cooling water supply needed for steam generators. Infrastructure owners need to consider adapting infrastructure assets to attain increased levels of resilience beyond originally designed parameters. Learning the cascading impacts from one infrastructure to another can aid in the design of more resilient infrastructure systems.

In summary, modeling infrastructure interdependency requires consideration of several complex elements:

- Integration and automation of the assessment process, including threat and hazard identification and data acquisition;
- Estimation and projection of impact zones;
- Simulation of the initial effects on infrastructure assets;
- Evaluation of propagating effects within each infrastructure system; and
- Simulation of the influence of cascading failures across systems.

To address these elements, the authors have developed a flexible interdependency assessment framework that:

- Complements existing infrastructure interdependency simulation models;
- Considers all types of hazards;
- Uses publicly available and proprietary data for large-scale systems;
- Integrates existing and proven infrastructure models;
- Simulates cascading failure scenarios in short time;
- Defines outage areas resulting from cascading failures at small and large scales;
- Provides results directly usable by infrastructure owners and operators to foster and enhance the design of resilient energy systems; and
- Can operate on stand-alone computers.

The framework was first used to integrate the existing energy simulation tools *EPfast* and *NGfast* (Portante et al. 2009, 2014). Both tools have been subjected to extensive validation procedures. Numerous applications using *EPfast* for U.S. Department of Homeland Security (DHS)-related activities have enabled interactions with regional utilities. Their reviews and comments on modeling results have been favorable and encouraging. In addition, both models are threat agnostic and can be adapted to simulate impacts under various disaster scenarios postulated under an all-hazards approach. Finally, *EPfast* and *NGfast* are linear models and the interdependency linkages between them are, as expected, linear. Such linearity is very useful in supporting simplified analysis of the propagating disturbance across the two infrastructures.

The following section presents the methodology developed and the interdependency assessment framework for combining *EPfast* and *NGfast*.

Methodology

The methodology goal is to develop an assessment framework that easily integrates and automates existing capabilities, which can improve the speed and flexibility of the simulation model. The first phase of development focused on three objectives that improves existing methods:

- Automate the steps needed to define the initial degradation conditions and simulate the cascading failures of energy transportation systems. The automated process will result in faster time to prediction, which will allow more time to consider the best response, and enable quicker overall response. The automated assessment and analysis framework also enables a number of capabilities that would otherwise be too impractical for routine utilization. The proposed methods could enable the user to rapidly test the impact of hypothetical hazard scenarios, establish detailed quantification of the uncertainties associated with the predicted impacts, study combinations of scenarios, execute searches through infrastructure configurations to probe potential weaknesses, and provide analyses to guide infrastructure planning strategies;
- Integrate the dependencies and interdependencies that exist between electric power and natural gas transportation systems. For a given hazard, any of several infrastructure systems may be at risk. Therefore, the interdependency model must be able to seamlessly connect the effect of the hazard on the local environment to the impact of the hazard on a potentially wide range of infrastructure assets; and
- Propose a flexible computing architecture to support the integration of other simulation tools and use of available databases. The software design and development process must be able to support straightforward addition of the necessary data and code to enable the tool to respond to new or improved hazard types. It also needs to support the addition of infrastructure components at low cost, descriptions of the impact of a hazard on component functionality, and even entirely new layers of infrastructure, if required.

The assessment framework integrates three main modules:

- Failure analysis module—Defines the initial conditions resulting from a given hazard;
- Infrastructure interdependency simulation module—Integrates the infrastructure simulation models (i.e., *EPfast* and *NGfast*); and
- Visualization module—Represents the infrastructure service outage areas and other meaningful simulation results.

Fig. 1 shows an overview of the assessment framework.

Failure Analysis Module

The standard process of analyzing and forecasting the impacts of a natural hazard on a critical infrastructure, such as the electric power grid, currently can take several days to complete. Much of this time is invested in manually analyzing the damage to each asset from various hazard scenarios. Accelerating the production of geospatial data that describe the potential damage a hazard can cause to critical infrastructure is a key step to assessing critical infrastructure resilience. The proposed method includes an automated process that models the interaction between hazards, infrastructure assets, and descriptions of asset fragility. This failure analysis approach uses data that describe the four principal aspects of the scenario: disasters, infrastructure layers, asset descriptions, and asset fragility data.

- The disaster data describes each hazard in the scenario. For example, a hurricane description may include a shapefile giving the wind strength and projected inundation profiles over an affected geographical area;
- The infrastructure layer provides a description of the connectivity and geographical layout of the principal components of a critical infrastructure, such as the electric power grid. In this case, a shapefile may provide the locations of generation plants, substations, towers, and other components, as well as the connectivity between them provided by the power lines;
- The asset descriptions include information about the type of asset, its function, and physical characteristics in a logically separate data resource; and
- The asset fragility data provides a quantitative mapping between the local effects of the hazard to the viability of the asset. For example, it may be that wind speeds in excess of 120 mph result

Fig. 1. (Color) Assessment framework overview

in a 50% chance that a building will suffer extensive damage. These data come in many forms depending on available information and common practice. In some cases, fragility is captured in a set of curves describing probability of damage at various levels of severity, while in others, a simple threshold may be sufficient (or all that is available).

Three assessment modules support the failure analysis phase:

- The hazard module is the trigger that initiates the simulation. It gives the users the opportunity to define a hazard scenario of their choice. The hazard module currently allows users to choose between three types of natural hazards (i.e., hurricane, flood, or tornado) and the option to consider manmade threats;
- Following the definition of the simulation scenario, the disaster module automatically mines natural hazard data from web-based sources and then projects the contoured disaster and impact zone given the postulated scenario. For the case of storm or hurricane events, the disaster module utilizes data extracted from the National Oceanic and Atmospheric Administration's (NOAA) website. Data are uploaded from NOAA's Advisory through Hurricane Evacuation Studies (*HURREVAC*). For seismic events, the disaster module utilizes data from the U.S. Geographic Survey's web-based publications. Specific assets targeted by a postulated manmade threat are defined as out of service via a specialized user interface; and
- The damage module uses the impact zones resulting from the disaster module and infrastructure fragility curves to produce a list of infrastructure assets that would be affected given the postulated scenario. Electric outage fragility curves in conjunction with hurricanes and tropical cycles are developed in-house. The fragility curves are based on empirical data derived from recorded weather disturbances over the past several years. For example, fragility curves relate to the probable number of customers that could lose power as a function of wind speed. For seismic events, the fragility curves are defined with the Federal Emergency Management Agency's (FEMA) *HAZUS Multi-hazard User Manual* (FEMA 2016). The damage module returns a list of infrastructures and their states (i.e., functional, degraded, or nonfunctional) that constitutes the input to the infrastructure interdependency simulation module.

Infrastructure Interdependency Simulation Module

The overarching approach aims to neutralize the challenges encountered during model integration by adopting a generalized integration process. The generalized process facilitates the exchange of data among models of different infrastructures with different granularity and network topology complexity, and facilitates integration of these multiple disparate models into one *virtual* infrastructure interdependency simulation tool, without introducing major modifications to the original stand-alone models.

The integration is performed with a data centric modeling/simulation (DCMS) platform that allows current infrastructure models to remain intact, and avoids many code changes. This approach makes it possible to develop an array of interdependency simulations by combining existing and future infrastructure models to better simulate cascading and escalating failures.

Two main principles guided the approach adopted to develop the interdependency simulation module:

- Take advantage of existing functionality that has proven to be effective, has already supported various infrastructure impact and resiliency analyses, and has wide acceptance among customers of those analyses; and
- Combine the models, without major changes in their internal codes, using a mechanism that focuses on managing data exchange between their input-output interfaces.

The initial effort focused on integrating two existing energy system simulation models, *EPfast* and *NGfast*. Prior to this study, *EPfast* and *NGfast* were used independently, and the results were interpreted by an experienced infrastructure analyst. This approach failed to examine the interdependencies between both infrastructures, which is integral to capturing the full impact of a given hazard. A key component to the interdependency simulation model was, therefore, automation of the manual integration process. The automation process also needed to be reproducible with other existing infrastructure simulation models. The following sections succinctly present *EPfast* and *NGfast* and illustrate the methodology used for their integration.

EPfast

EPfast, developed in 2010, estimates the area of an electric power outage caused by the loss of power system components (Portante et al. 2011). The model explores the possibility of uncontrolled islanding caused by successive steady-state line overloads. Such overloads are initially triggered by a major, nonreclosable, line-to-line fault, or simply by the de-energization of a major line due to a natural cause or manmade (deliberate) act. The model estimates the extent (geographic size) and depth (amount of load shed) of the power outage. *EPfast* provides four basic capabilities:

- Standard load flow analysis;
- Contingency analysis;
- Islanding analysis; and
- Power outage estimation.

Given the initial conditions for an event, the model (1) quantifies the amount of load shed, (2) identifies the affected substations, (3) estimates the territorial dispersal of lost demands, and (4) generates a geographic information system (GIS) outage area for the event. Fig. 2 shows the *EPfast* graphical user interface for a 64-bus electric network prior to a load flow run.

EPfast employs a direct current (DC) load flow program to determine line flows through the network when scheduled power injection and node demand values are provided. DC formulation is employed because of its ability to solve large-scale grid problems quickly without the convergence difficulty that often plagues the nonlinear or alternating current (AC) formulations. When a contingency is postulated, *EPfast* has the capability to track down:

- The cascading line outages due to ensuing line overloads; and
- The formation of island grids resulting from such cascading failures.

EPfast uses LINGO, an optimization modeling software for linear, nonlinear, and integer programming (Lindo Systems, Inc. 2017), to characterize and solve the DC load flow problem. The physical behavior of the electric transportation system is described by the following optimization problem:

$$\text{Objective Function} = \min \sum_{j=1}^{G} (a_j y_j + b_j) \tag{1}$$

where y = generator output in per unit of generator j; a and b = coefficient of linearized production cost curve for generator j; j = index for the participating generator; $j = 1, 2, 3, \ldots, G$; and G = total number of participating generators.

The objective function uses the following power flow equation:

$$P_i - \sum_{i=1}^{N} P_{ik} = 0 \tag{2}$$

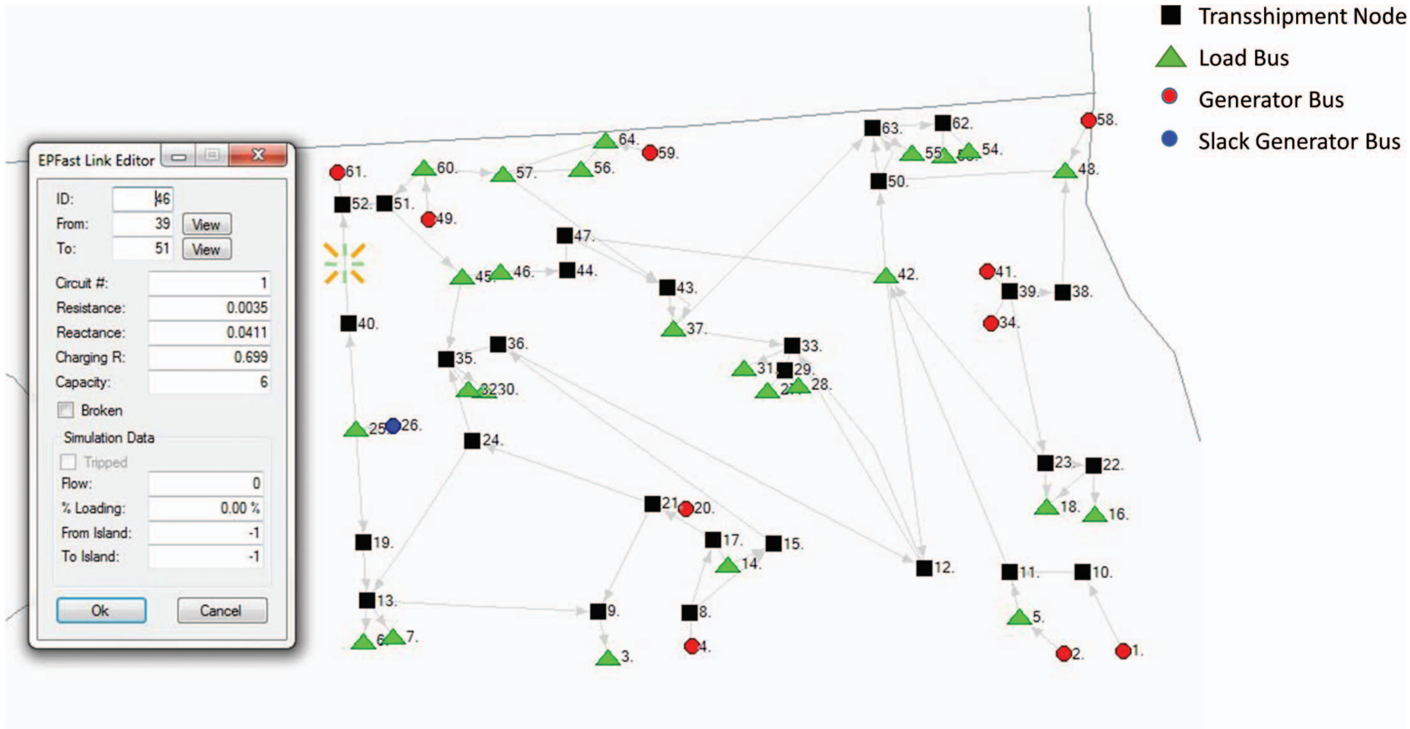

Fig. 2. (Color) *EPfast* depiction of a 64-bus network and associated link data

where P_i = net power injection into bus i (positive for generators and negative for loads); P_{ik} = power flow from bus k to i (flow is zero if bus k is not linked to bus i); and N = total number of buses.

The power flow equation and therefore the objective function are subject to the following constraint:

$$\text{Lower}_j < P_j < \text{Upper}_j \tag{3}$$

where Lower_j = lower bound operating limit for generator j, and Upper_j = upper bound operating limit for generator j.

For steady-state simulation with fixed generator output (i.e., scheduled dispatch), the lower and upper bound values are set equal to the generator output, y. Furthermore, in order to speed up calculation and minimize the number of variables in LINGO, the objective function is modified as follows:

$$\text{Objective Function} = \min \sum Gy_j - \text{total load} = \min y\,\text{slack} \tag{4}$$

where $\sum Gy_j$ = total load supply, and y slack = fixed number equal to the difference between total supply and total demand.

Because the slack generation, y slack, is actually a fixed number equal to the difference between total supply and total demand, effectively no optimization is accomplished. The intent is simply to cause LINGO to solve the equality constraints, Eq. (2), faster. Eq. (1) remains an essential formulation approach as *EPfast* is further upgraded to find optimal generator dispatch solutions.

To complement the optimization algorithm, *EPfast* operates on three main assumptions to define the islands resulting from a disruptive event:

1. Steady-state condition—The effects of transient power swings, transient frequency excursions, and transient voltage variations are incorporated later as part of the heuristics solution;
2. Line condition—Whenever line overloading occurs, the line is assumed to be open and to remain open until a major restoration effort is completed. During the initial and ensuing line trippings, the load levels and generator outputs throughout are assumed to remain constant, until the system breaks into island grids; and
3. Island grid—When the system splinters into several island grids (as a result of cascading overloads), the following assumptions are made:
   - Island grids that do not have power sources are assumed to be under total blackout;
   - Island grids with power sources are assumed to be capable of adjusting either the loads (i.e., via automatic load shedding) or generator outputs (i.e., via output reduction) to settle to a new, balanced operating point. More specifically, when demand exceeds generation, load at all demand buses is shed to maintain supply/demand balance; when generation exceeds demand, generation sources are reduced proportionately to regain balance. The direction of the adjustments is always toward either reducing load levels or reducing generation output to minimize the possibility that further overloading will occur after the system experiences a major breakup (i.e., splintering into many island grids); and
   - The dispatch, as well as balancing of generation and load within the island grids, can be done by invoking an optimal power flow program or employing a heuristics-based methodology. If the load exceeds generation in an island, a load-shedding scheme is assumed in which loads are dropped systematically until load equals generation. In practice, the scheme may be triggered by frequency and voltage relays.

EPfast utilizes publicly available information including Federal Energy Regulatory Commission (FERC) 715 data sets for transmission system and generation dispatch information, Energy Information Administration (EIA) 860 data set for power plant characterization, as well as commercial data available via Energy Visuals (FERC 2017; EIA 2017a; Energy Visuals 2014).

Fig. 3 shows the substation outages, cascading line failures, and associated island grids resulting from a disruptive event on the 64-bus network example.

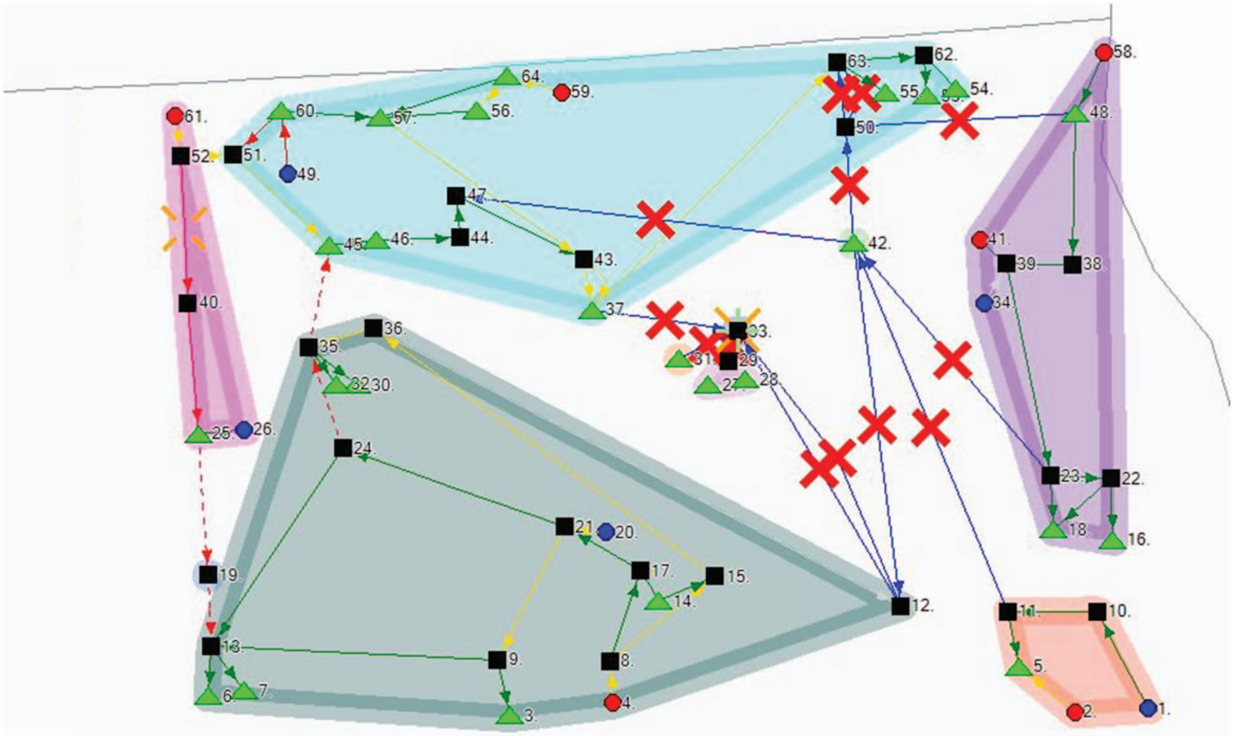

Fig. 3. (Color) *EPfast* depiction of island grids resulting from a multiple-line outage event

EPfast generates power outage area GIS shapefiles that form the basis for subsequent interdependency analysis tasks. For each island identified, *EPfast* also generates tables defining the loss of initial load and identifying the different nodes (substations) impacted and their geographic coordinates. This information (i.e., nodes and outage areas, and load loss) can be used to identify other system infrastructure assets located in the area that would potentially be impacted by a loss of electric power supply. For example, if there is an electric-dependent gas asset within the outage area such as a NGPP, then that asset can be considered at risk of being disrupted. The gas sector then would need to adjust its supply-side configuration and assess the impacts of such disruption. Such assessment is conducted by running *NGfast*.

NGfast

NGfast is an impact analysis simulation model developed in 2008 for natural gas systems. The tool allows for rapid first-stage assessment of the impacts of major natural gas pipeline disruptions at state border points and reductions in flow from import points and production fields. Within minutes of a postulated pipeline break or disruption, *NGfast* can generate HTML-formatted graphics and tabular reports to supplement briefing materials for state and federal emergency responders. The model provides summaries, as well as detailed reports (i.e., pre- and postdisruption conditions), on impacts down to the local distribution company (LDC) level. Impacts are measured in terms of extent of gas volume disrupted, states affected, utilities affected, number and type of customers affected, and amount of natural-gas-based capacity affected (Portante et al. 2007).

NGfast is a linear model that uses a progressive forward pipeline ownership identification and flow quantification process to track lost flow volumes due to a pipeline break or curtailment in production. The calculation starts at the upstream state, most affected by the break, and proceeds progressively toward the terminal, downstream, states. The special structure of its core data set, which is the state border database (i.e., *from-state* and *to-state* fields), allows the calculation method to proceed following the flow of gas along the pipeline, analyzing each state in sequence as it is traversed by the pipeline. The forward quantification logic operates by repeatedly applying a recursive flow balance equation to each affected state. The recursive equation simply states

$$\text{State Delivery} = \text{Inflow} - \text{Outflow} \tag{5}$$

The process that *NGfast* uses to determine natural gas impacts caused by an event begins with the identification of the disruption points in the state border data set by identifying the delivering (i.e., disrupted) pipeline and defining the magnitude of flow. A series of relational database calculations are launched to determine the states affected, the LDCs affected in each state, and the corresponding demands at risk of curtailment in each LDC. After *NGfast* determines the magnitude of the demands at risk of curtailment for each state, it triggers the mitigating measures logic and examines corrective actions from underground storage (UGS), liquefied natural gas (LNG), production wells, and interconnecting pipelines.

Because the states traversed by the affected pipeline are in series, the output of the upstream state becomes the input into the immediate downstream state. Fig. 4 illustrates the forward flow quantification process for a simple single-pipeline system traversing several states.

As shown in Fig. 4, the flow in the different interstate pipeline segments s can be defined by the difference between the inflow load and the outflow load at each node

$$x_1\,(\text{In-state Delivery}) = \text{Inflow at Node 1} - \text{Out flow at Node 2} \tag{6}$$

$$x_2\,(\text{In-state Delivery}) = \text{Inflow at Node 2} - \text{Out flow at Node 3} \tag{7}$$

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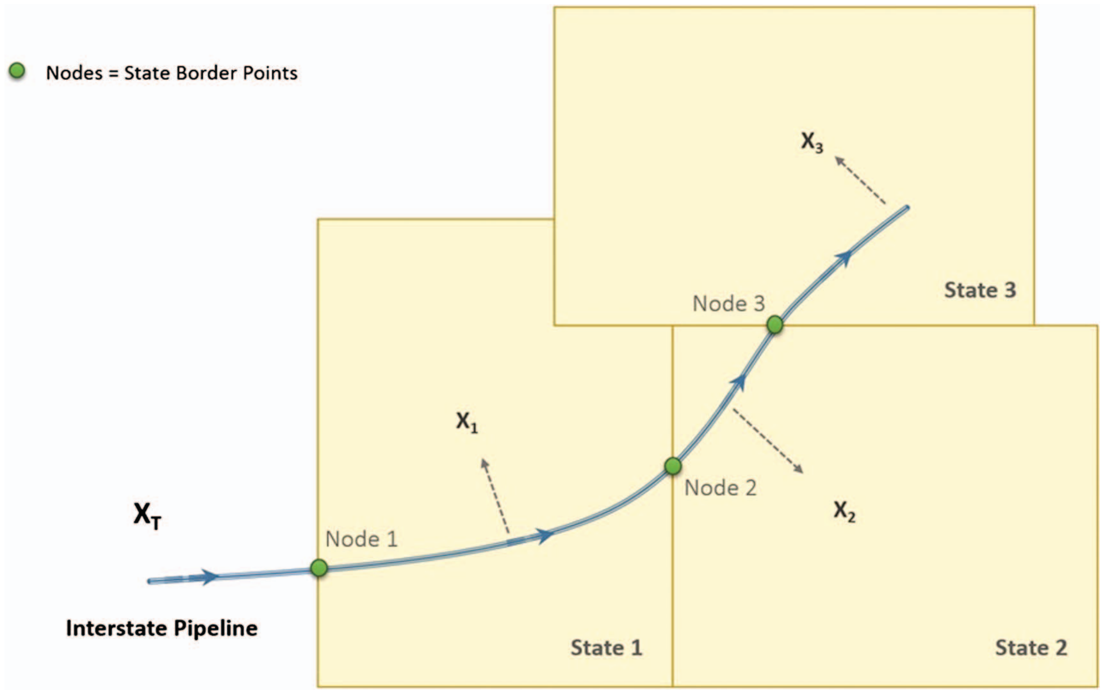

Fig. 4. (Color) *NGfast* forward flow quantification process

$$x_3 \text{ (In-state Delivery)} = \text{Inflow at Node 3} \tag{8}$$

The variable x_i (In-state Delivery) represents the net delivery to the State i. The total flow can then be determined by the sum of in-state delivery defined at each node

$$x_t = x_1 + x_2 + x_3 \tag{9}$$

Alternative pipeline configurations require some dynamic modifications on the basic recursive equation. Furthermore, this disruption propagation model relies heavily on a set of interrelated databases and an efficient data management engine. In particular, the EIA 860 data set provides information on pipeline connections to gas-fired power plants (EIA 2017a). EIA 191 (EIA 2015b) and EIA 176 (EIA 2015a) data sets are also used to describe UGS monthly operations and LDC-level customer mix, respectively. Finally, *NGfast* uses the U.S. Department of Transportation's National Pipeline Mapping System (NPMS) used to describe the pipeline routing layout through various states (NPMS 2015). Fig. 5 shows the original data sets and their linkages that constitute the core elements of the model.

Fig. 6 shows a sample graphic output from a simulation run involving breaks in a two-legged gas pipeline system.

NGfast generates state-level and LDC-level flow curtailment reports per customer type that form the basis for subsequent interdependency analysis tasks. Further, for each state or LDC identified, *NGfast* generates tables identifying specific gas-fired power plants that would be affected by the postulated pipeline breaks.

The integration of *EPfast* and *NGfast* requires coordination, with attention to the exchange of data between the two models because the output of one becomes input for the other.

Infrastructure Simulation Models Integration

The infrastructure interdependency simulation module uses a DCMS manager that facilitates the integration of multiple disparate models into one *virtual* model without introducing major modifications to the original stand-alone simulation models (Joshi 2011). The DCMS manager facilitates the synchronization between simulation models (Fig. 7).

The list of disrupted infrastructure assets generated by the failure analysis module constitutes the first input to the infrastructure interdependency simulation module; its generation triggers the DCMS manager. The DCMS manager operates all infrastructure simulation models (i.e., *EPfast* and *NGfast*) and translator models. Translator models convert outputs from one infrastructure simulation model to inputs to another infrastructure simulation model. When all required information is present, the DCMS logic is triggered. The logic determines whether to perform some translations or to run some simulation models. The output of each model (i.e., simulation or translator) is then sent back to the DCMS manager. Each model is triggered when new inputs are available. If there is no change (no new input), then no additional model or translator is triggered and the simulation stops. The DCMS manager processes output files from one model as it receives them, so the input files of other simulation models reflect pertinent information. The DCMS manager continually performs these operations until all module interactions cease (i.e., when no new input is available). The pseudo code for the DCMS manager is therefore elementary:

- Listen for inputs;
- Wait for all required inputs;
- Run appropriate logic; and
- Send any output.

The infrastructure interdependency simulation module design is based on event-driven programming. It is not procedural; the different models (i.e., simulation and translation) are launched automatically when new inputs are available. The process ends when no new or modified outputs are generated. Driven by outputs, the models will cycle until the system stabilizes, until no additional outages occur, or until stopped by the user. The event-based simulation emphasizes the logical unfolding of the events and implies the notion of time. In the current phase of development, the emphasis of the simulation is on the anticipation and determination of cascading

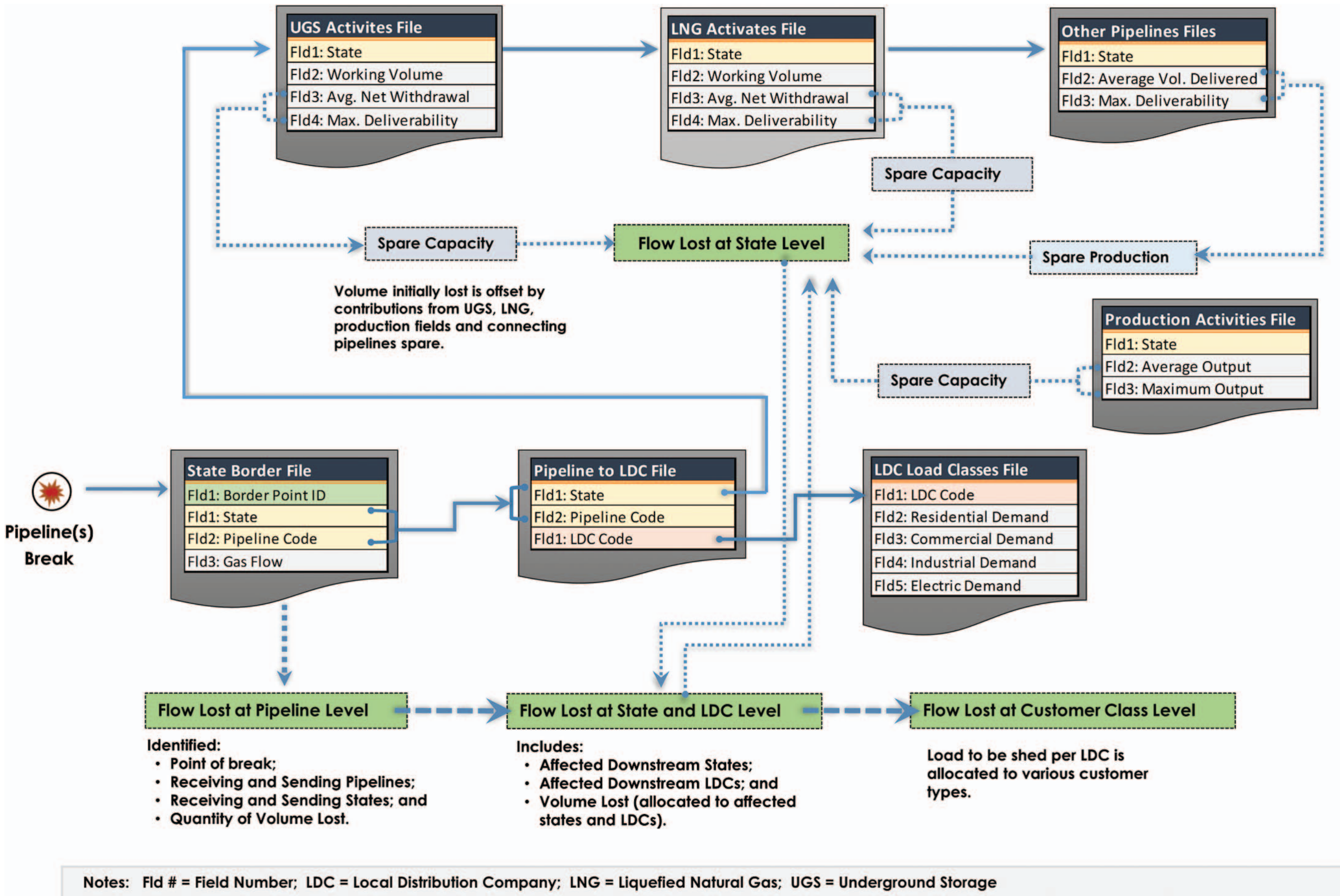

Fig. 5. (Color) *NGfast* relational data supporting disruption propagation approach

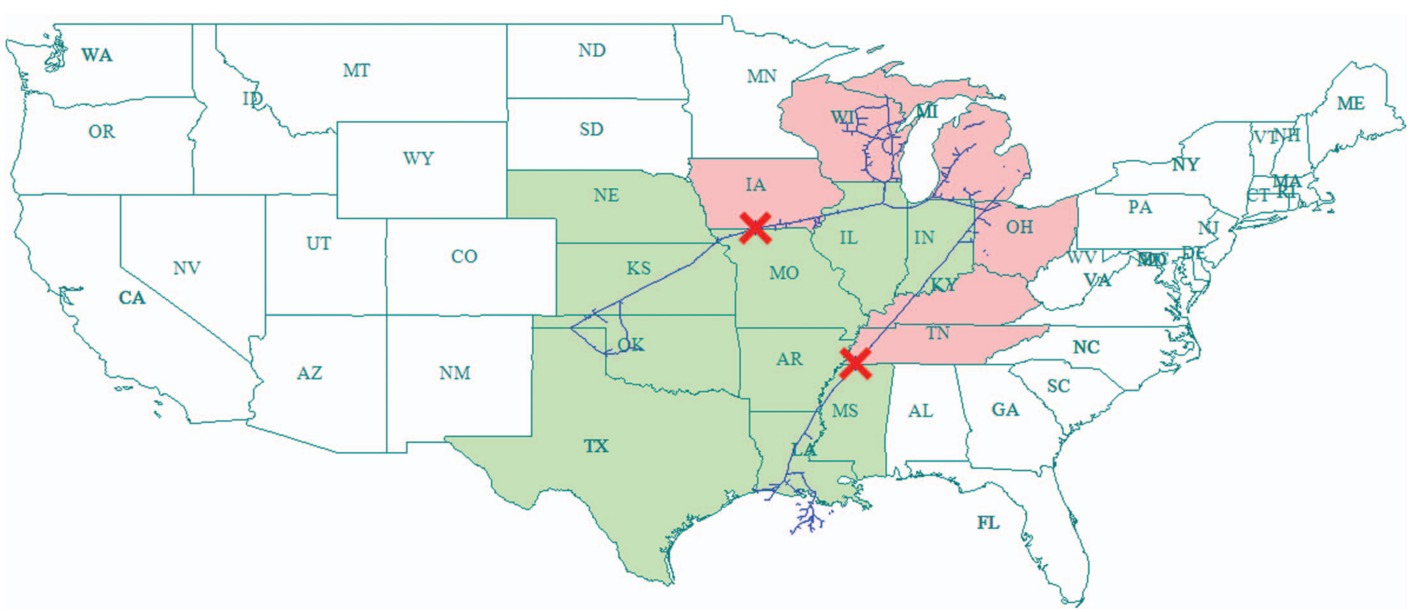

Fig. 6. (Color) *NGfast* graphical output for two notional pipeline breaks

failures across the electric power and natural gas systems instead of specifically defining the exact timeline for these events to occur.

The DCMS manager remains the same regardless of the type of infrastructure simulation model to be integrated. Integration of additional simulation models requires only the development of their corresponding translator models; the translator models transform the output of the new simulation model to inputs for other simulation models that constitute the infrastructure interdependency simulation module.

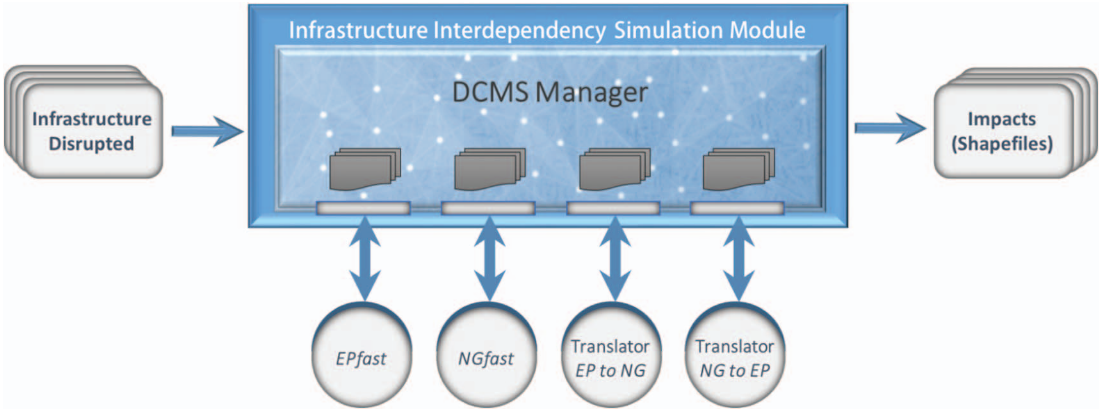

Fig. 7. (Color) Infrastructure interdependency simulation module

Integrating multiple systems developed independently can be a challenge because of the complexity of tracking the bidirectional interactions among interdependent infrastructures. The simulation models (i.e., *EPfast* and *NGfast*) simulate the cascading failures, respectively, within the electric power and natural gas infrastructure systems. The DCMS architecture provides the required mechanism to facilitate the exchange of data between *EPfast* and *NGfast*. Such iterative exchange terminates when either *EPfast* or *NGfast* does not generate additional changes in the outage areas or results.

Integration of *EPfast* and *NGfast* also requires using two translator models characterizing the directional interdependencies that exist between the electric power and natural gas infrastructure systems. The first translator model [i.e., electric power (EP) to natural gas (NG) translator] characterizes the assets of the natural gas infrastructure system that would be affected by the disruption of the electric power infrastructure system. The first translator applies the electric outage area footprint defined by *EPfast* and determines the affected natural gas assets. It also characterizes the level of electric power curtailment, and, therefore, projects the operational state of affected natural gas assets that are at risk of being de-energized and removed from service.

The second translator model (i.e., NG to EP translator) characterizes the assets of the electric power infrastructure system affected by the disruption of the natural gas infrastructure system. This second translator applies the natural gas supply curtailments defined by *NGfast* and determines the gas-fired power plants affected by the gas disturbance with electric generation buses in the electric sector.

Fig. 8 shows a simplified depiction of interdependencies between the electric power and natural gas infrastructure that supports the development of the two translator models required for integrating *EPfast* and *NGfast*.

The connection points from the natural gas infrastructure system to the electric power infrastructure system occur in gas-fired power plants. The scientific rule that governs the energy flow is identified by the conversion of the gas flow rate in $\mathrm{Mm^3/d}$ (mega cubic meters per day) to electric megawatts (MW) by each gas-fired power plant. The conversion depends on the type of gas-fired power plant:

- For simple-cycle gas turbines with an average net conversion efficiency of 25%, one $\mathrm{Mm^3/d}$ produces about 105.3 MW; and
- For combined-cycle gas turbines with an average net conversion efficiency of 65%, one $\mathrm{Mm^3/d}$ produces about 253.3 MW.

Stated another way, a flow reduction of 100 $\mathrm{Mm^3/d}$ along a natural gas pipeline could potentially affect about 10,530–25,330 MW of aggregate gas-fired capacity, assuming all 100 $\mathrm{Mm^3/d}$ is allocated for electric power production without knowing the exact composition of the interconnected power plants. In general, the load-shedding prioritization hierarchy for the NG system is as follows: electric production, industrial, commercial, and residential. Furthermore, active gas-fired plants with an interruptible service contract are shed first, followed by the largest gas-fired plants in the firm service contract (noninterruptible contract) category. The empirical natural gas monthly consumption of individual gas-fired power plants is publicly accessible information and can be obtained from Form EIA-923 (EIA 2017b). This data set is used to refine generator output shaving for the individual at-risk gas-fired plants.

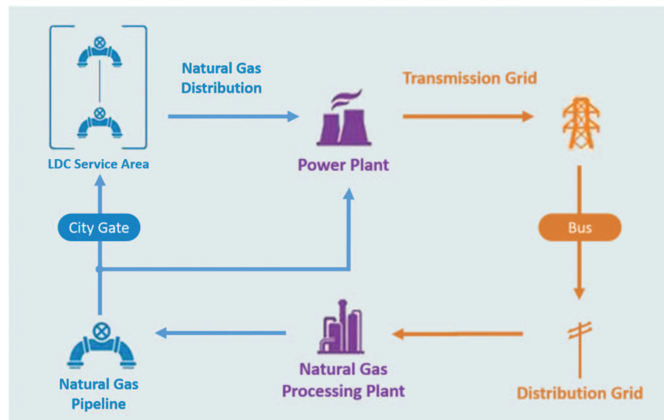

Fig. 8. (Color) Example of interdependencies between the electric power and natural gas infrastructure

The connection points from the electric power infrastructure system to the natural gas infrastructure system occur in NGPPs. NGPPs are critical to the natural gas supply because unprocessed natural gas contains corrosive impurities that would contaminate and corrode natural gas pipeline infrastructure components and damage customer equipment. NGPPs are highly dependent on electricity for their operation and typically have no backup power. The disruption propagation is therefore relatively simple. When electric power supply is lost, an NGPP stops operating. A rule of thumb is used to determine whether an NGPP should lose power whenever there is partial load curtailment (i.e., not a total blackout). If the formed island grid has a load curtailment of more than a preset threshold value, then the logic assumes that the NGPPs within the island grid are disrupted or shed; otherwise, it is assumed the NGPPs are unaffected. The logic assumes that the shedding priority for the electric system is industrial, commercial, and residential.

The identification and characterization of all connecting points between the electric power and natural gas infrastructure systems is the prerequisite for the development of the two translators realizing the integration of *EPfast* and *NGfast*. Developing the translator models present two main challenges:

- Mapping electric power and natural gas infrastructure assets to define the electric power infrastructure dependent on natural gas and the natural gas infrastructure dependent on electric power; and
- Defining how the loss of natural gas supply affects the operations of these electric power infrastructure assets, and, inversely, how the loss of electric power supply affects the operations of these natural gas infrastructure assets.

Defining these connection points can be complex because their complete spatial information is not always identified in publicly available data sets. Spatial and connectivity information are generally available in proprietary data sets. The simulation and translator models utilize several data sets (i.e., FERC, EIA, and Energy Visuals) and the infrastructure asset identification can vary from one data set to another. The identification of infrastructure system connection points requires mapping existing data sets. The mapping algorithm is automated and is programmed using *Julia*. The method associates cross-infrastructure nodes that are nearest to one another based on either *spatial distance* (i.e., geographic proximity based on longitude and latitude) or *string distance* (i.e., substation names compared with power plant names). The closer the string distance is between two node names, the higher the confidence that the nodes constitute a matching pair. The degree of mismatch in comparing strings for closeness of semblance is called the *Levelshtein distance*.

The natural gas to electric power translator also utilizes a snapping algorithm based on spatial distance queries to associate natural-gas-fired power plants with specific gas pipelines. The snapping algorithm establishes a threshold distance based on which natural-gas-fired power plants are deemed to be directly connected to a particular gas pipeline. This algorithm, in combination with publicly available data, ensures that the fuel supply source (i.e., pipeline name) for most natural-gas-fired power plants is identified. Natural-gas-fired power plants not directly connected to a pipeline, but indirectly supplied through a LDC, are linked to pipelines using other available data.

The DCMS manager provides the required mechanism to facilitate the cyclic exchange of data across the simulation and translator models. Such iterative exchange is terminated when the magnitude of the impact-related data is within a predetermined criterion—when no new model inputs are available.

To summarize the overall process, either the *EPfast* or the *NGfast* models can be launched first, depending on which infrastructure is identified as disturbed by the failure analysis module. If the electric sector is the initiating party, *EPfast* is launched first, and then estimates electric power system impacts, and generates GIS outage areas that could potentially affect natural gas assets. The EP to NG translator is then launched to identify natural gas infrastructure assets that are affected. If this is the case, *NGfast* is launched to propagate the disturbance within the gas system. Next, the NG to EP translator launches to identify any electric power infrastructure assets that are affected. Simulation and translator models run in an iterative process until simulation results converge or settle to a new operating point, which represents the worst-case assessment.

If the disruption is initiated in the natural gas sector, *NGfast* launches first and simulation results identify gas-fired power plants that could be affected. The process remains the same with the alternate use of translator and simulation models until both natural gas and electric power outage areas reach a stable state.

The process is currently sequential because only two infrastructure simulation models are integrated. If more models were integrated, the collection of different models will not automatically be triggered in alternation. Based on the succession of events, the DCMS manager would trigger the models (i.e., simulation or translator) for which new inputs would be available.

At the end of the simulation, the Infrastructure Interdependency Simulation Tool generates electric power and natural gas outage shapefiles that are used by the visualization module.

Visualization Module

The visualization module utilizes the output of the failure analysis and infrastructure interdependency simulation modules to generate a GIS map in the form of Environmental Systems Research Institute (ESRI) shapefiles. These shapefiles show the combined consequences of the natural gas and electric power outages, including the characteristics of load shed and infrastructure disruptions.

Application

The interdependency assessment framework was applied to two state-level case studies. The interdependency simulation model is threat agnostic and scenarios involving various hazards and threats are candidates for case study applications. However, representative and notional threat examples were selected for each case study to illustrate the application of the modeling environment. Florida and North Dakota were selected to demonstrate the use of the tool and, in particular, the logic of propagating disruptions between electric power and natural gas infrastructure systems.

State of Florida Case Study

Florida represents the simplest electric power-natural gas interactions because it is a terminal state—it has no complex downstream system that could further propagate the disruption to other states.

As of early 2017, Florida's natural gas system is relatively simple, with only two major high-pressure transmission pipelines serving the state: Florida gas transmission (FGT) and Gulfstream natural gas pipeline (Gulfstream). FGT supplies most of the natural gas (67%), and Gulfstream supplies the remaining (33%). In addition, FGT supplies natural gas to about 50 natural-gas-fired power plants that support Florida's 500- and 230-kV electric transmission system. The natural-gas-fired power plants represent an equivalent of 35,000 MW of the total installed capacity (61,000 MW), or about 57% of the in-state generation capacity, indicating that Florida is dependent on natural gas for its electric production. Fig. 9 shows the natural gas and electric power infrastructure in Florida.

The Florida scenario postulates the occurrence of lightning strikes on a major natural gas compressor station near the Florida-Alabama border along the FTG pipeline system resulting in the shutdown of main transportation pipelines. As a direct consequence of the reduced natural gas flow in the pipelines, fuel delivery to a large number of natural-gas-fired power plants in the state is disrupted. The model simulates the outage of these power plants, which causes a blackout within the state. The blackout, in turn, disrupts the delivery of electric power to NGPPs, thus further decreasing the natural gas production capabilities within the state and exacerbating the loss of natural gas delivery to customers in Florida.

Overall, the majority of the natural-gas-fired power plants within the state cease operation, leading to a statewide blackout

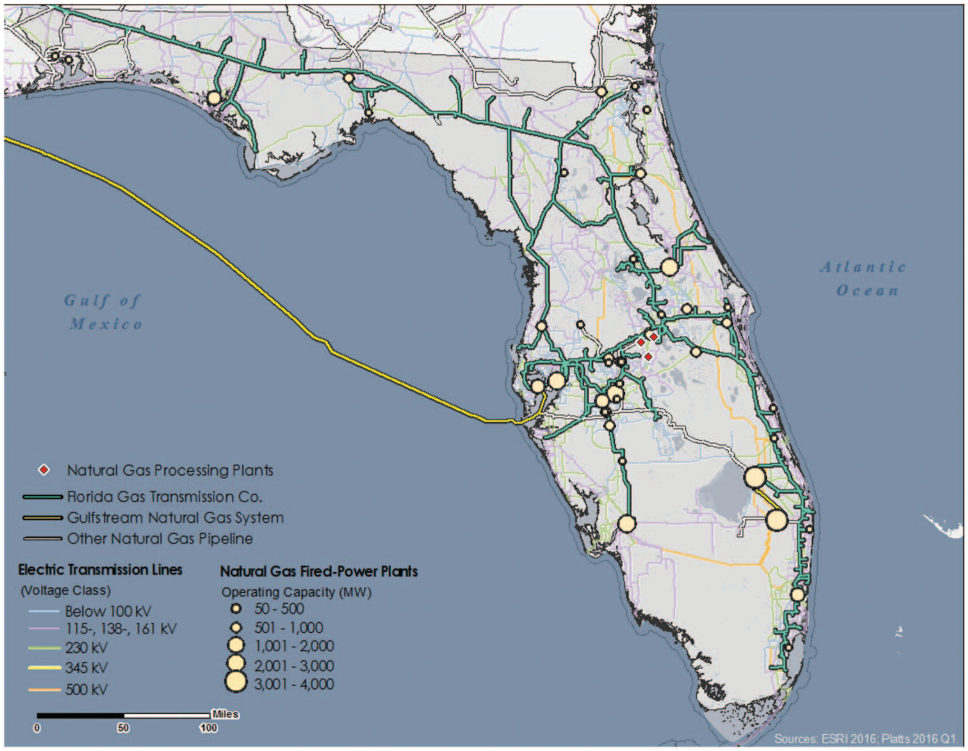

Fig. 9. (Color) Natural gas and electric power infrastructure in Florida (map data from Platts 2016 Q1)

with varying load curtailment intensity ranging from 10 to 100%. The electric power system is fractured into nine major island grids and experiences a total load loss of about 22,600 MW (about half of the state's peak summer load), impacting practically the entire population of the state. In-state NGPPs lose electric power supply as their service grid experiences a 40% load curtailment. As such, the NGPPs are assumed to be de-energized and out of service. However, because the combined output from these NGPPs is small relative to the total statewide natural gas load, the associated gas curtailment from these plants has no additional effect on gas customers in Florida. Fig. 10 shows the results of the simulation for the Florida case study.

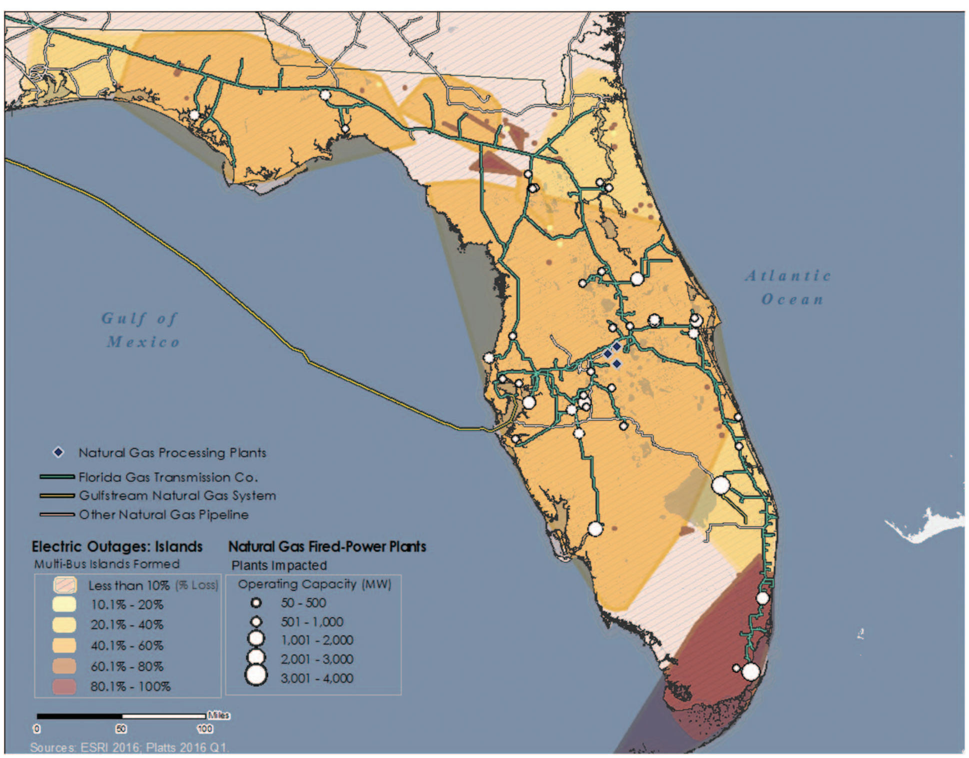

Fig. 10. (Color) Simulation results for the Florida case study (map data from ESRI 2016; Platts 2016 Q1)

It is important to note that the simulation of the Florida electric grid is conducted as part of the entire U.S. Eastern Interconnection. As such, connectivity of the Florida grid to nearby states (e.g., Georgia) is fully represented. Although Florida is interconnected with Georgia, the capacity of these tie lines is limited; therefore, these transmission lines are unable to provide relief given the postulated scenario. Restoring the Florida electric power system after an area-wide blackout may require the strategic use of black start units within the formed island grids as well as reactivation of tripped tie lines.

The Florida case study illustrates natural gas supply limitations along the FGT system that could affect the electric power infrastructure and lead to potential electric power outages across the state. Understanding the extent that Florida relies on natural gas for in-state electric generation, this allows options for consideration that include the construction of alternate fuel supply lines to at-risk natural gas power plants that only receive natural gas from one of the two pipelines that serve the state. The simulation also provides information that is helpful for emergency response planning during a potential large-scale blackout in Florida.

The simulation results provided by the integrated tool reveal a number of specific system weaknesses that span both energy subsectors. First, reinforcing the 345- and 230-kV tie lines linking Georgia and Florida emerges as an option to mitigate the limited transfer capability between the two states. Without those transmission reinforcements, the standard mitigation measure of local companies is to shed loads to maintain supply-demand balance. Second, equipping the existing gas-fired power plants with dual-fuel capability (i.e., ability to burn either natural gas or an alternative fuel like fuel oil) appears to be an appealing resilience option. However, pertinent local electric utilities must substantiate decisions to make such improvements. In the absence of empirical quantifiable information to justify such retrofit work, demonstrating the need via simulation may be the only option. Third, the simulation highlights the electric sector's reliance on natural gas as fuel. Florida utilities well understand this reliance, and they have proactively constructed two additional pipelines to serve Florida's northern region, the Florida Southeast Connection, and the Sabal Trail Transmission.

State of North Dakota Case Study

Characterizing the interdependencies between electric power and natural gas systems within North Dakota is more complex. Unlike Florida, North Dakota is an originating state, meaning pipelines traverse the state to deliver natural gas to several downstream states as far away as Illinois. Furthermore, North Dakota includes a number of major oil and natural gas production fields, indicating a large number of essential NGPPs.

North Dakota has three major pipeline systems: Alliance Pipeline Company, Northern Border Pipeline Company (NBPC), and Williston Basin Interstate Pipeline. NBPC receives gas injections, either directly or indirectly, from the 16 NGPPs within the state. NBPC provides service to a large number of customers in the Midwest, with direct connections to at least six natural-gas-fired power plants having an aggregate installed capacity of about 2,500 MW. Each NGPP within North Dakota has a dedicated electric substation that supplies electric power. A failure of the North Dakota electric power grid would disrupt electric service to all 16 NGPPs and reduce the natural gas supply into the NBPC system. Fig. 11 shows the natural gas system in North Dakota, including NGPPs, the major pipelines, and the natural-gas-fired power plants in states downstream of North Dakota.

The North Dakota scenario simulates the occurrence of simultaneous tornadoes affecting six major electric substations in western North Dakota near the location of in-state NGPPs. The tornadoes cause an extended power outage over a broad geographic region that encompasses all 16 NGPPs. A disruption of the NGPPs

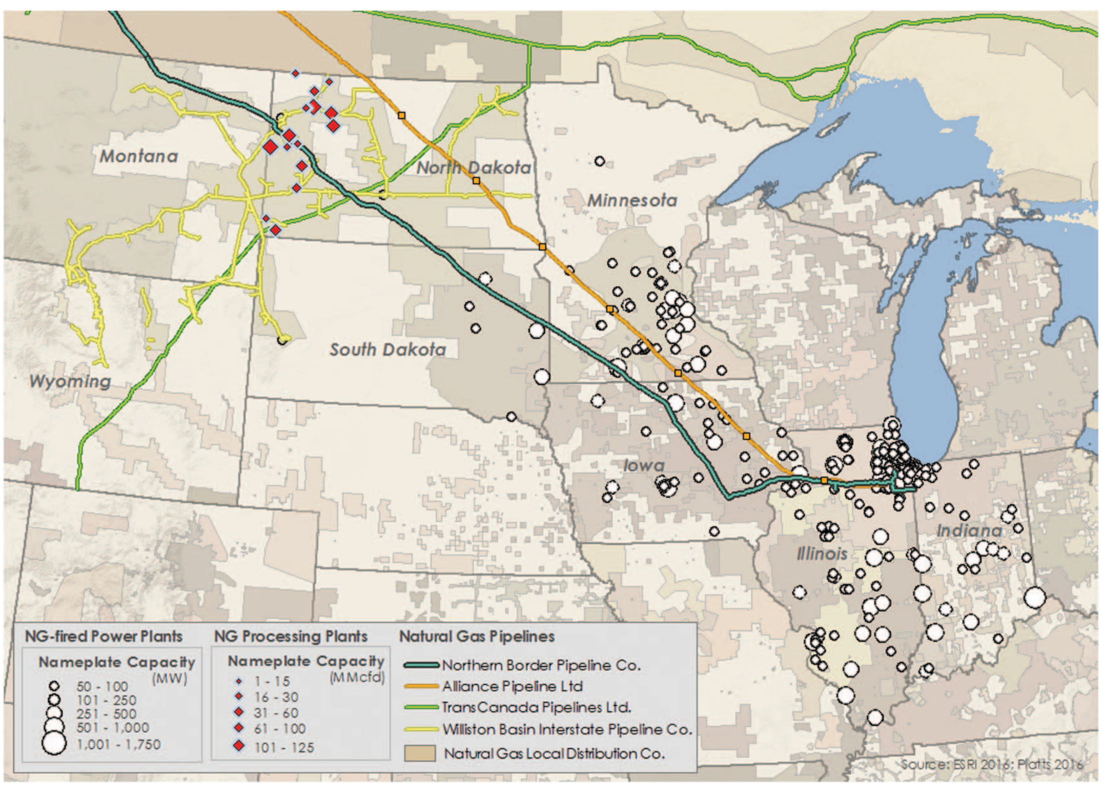

Fig. 11. (Color) Natural gas system in North Dakota and related electric power infrastructure (map data from ESRI 2016; Platts 2016 Q1)

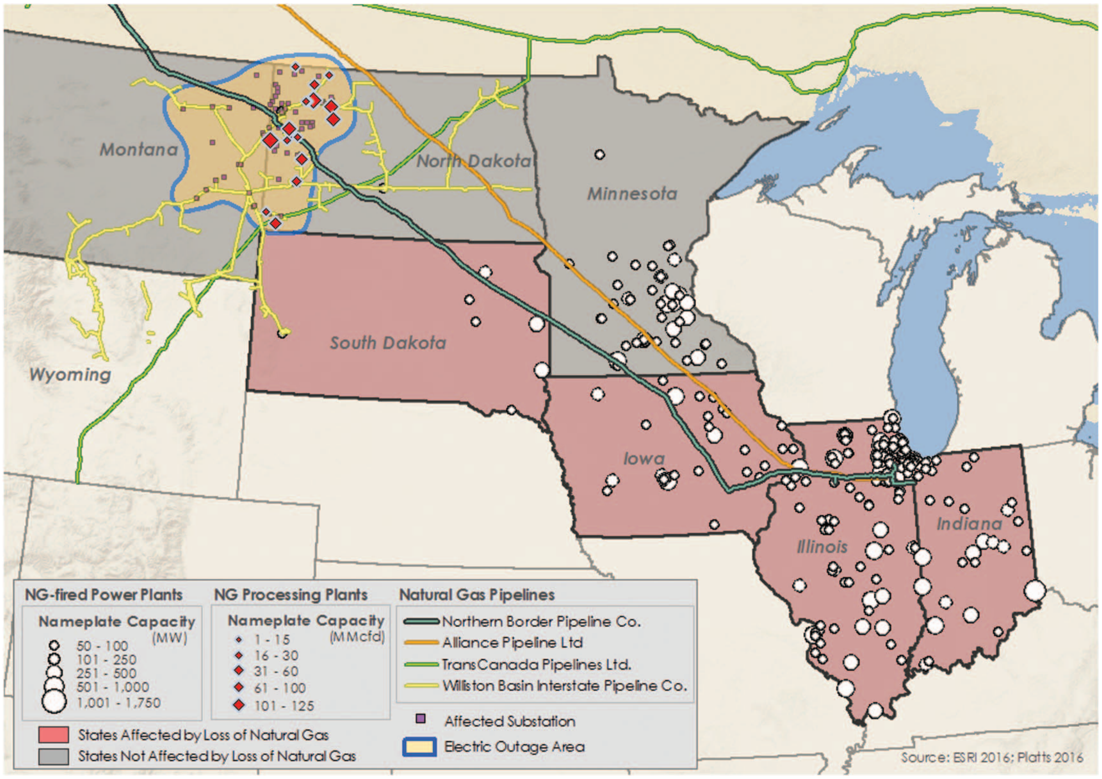

Fig. 12. (Color) Simulation results for the North Dakota case study (map data from ESRI 2016; Platts 2016 Q1)

curtails all in-state gas production. The reduced gas production manifests into reduced gas flows southeast along the NBPC system as the natural gas leaves North Dakota. The reduction in the natural gas supply impacts natural-gas-fired power plants located downstream of North Dakota. Fig. 12 shows the results of the simulation.

The simulation shows an electric outage area disrupting all in-state natural gas production and resulting in a 28% reduction in the natural gas supply flows along NBPC into South Dakota and other downstream states. The power outage area resulting from the simultaneous tornadoes encompasses most of the western portion of North Dakota, including service to all NGPPs located in the area. The reduced natural gas flows have an impact on electric production. In practice, power plant operators are given 4–6 h of advance notice prior to being forced to shut down plant operations in the event of a natural gas curtailment. Because the total amount of electric capacity curtailed (estimated at 336 MW) is small relative to the regional on-line capacity and can be readily mitigated by either the spinning reserves deployment or demand side management, no further impact to the electric power system is noted.

The North Dakota case study illustrates that a disruption in one state can have multistate impacts, especially when the initially affected state is located upstream with facilities supporting natural gas gathering operations. The case study also illustrates the fragility of an electric power grid even during periods of low demand (winter peak demand is usually only 75% of summer peak demand). The case study also underscores that electric power disruptions could have a profound impact on the natural gas supply, especially in a region containing a large number of NGPPs.

The simulation results provided by the integrated tool reveal a number of specific system weaknesses that span both energy subsectors in the Midwest. Understanding these impacts enables consideration of some potential resilience enhancement measures. First, equipping NGPPs with emergency generators fueled by either natural gas from the same production field, or by distillate oil fuel, and able to sustain a 24-h power outage. Such generators would limit the effect of an electric power supply outage. Second, ensuring that multiple sources of treated natural gas are available to the pipeline under consideration, in addition to the NGPPs, would limit cross-state cascading failures. Finally, downstream multistate impacts would be minimized further by improving communications and situational awareness of natural-gas-fired power plant operators, who may need to respond to curtailed natural gas supplies.

Discussion

Characterizing and understanding the interdependent interactions among various infrastructure assets are foundational for resilient infrastructure system designs. Because interdependent systems (such as natural gas and electric power) combine to form one closely coupled system of systems, the complexities of system characterization and design increases. Yet, the benefits of modeling interactions between the different systems improve. Essentially, the designer has a broader view of system interactions and behaviors to improve the characterization of the integrated infrastructure. MISO currently uses the assessment framework and the simulation model integrating *EPfast* and *NGfast* for preparedness and training purposes. By simulating energy interdependencies, the participants in both the electric and natural gas subsectors are aware of coordination issues and can actively work to resolve them.

Additionally, the use of this integrated tool can further educate staff in both subsectors on how the reliability of operations in one sector can materially affect operations in the other sector. The integrated model can also predict, evaluate, and mitigate the potential cascading impacts across both sectors. Furthermore, individuals in the electric power and natural gas subsectors would have an improved method to evaluate and coordinate restoration and prevention efforts across both subsectors. The integrated model allows quantification of the consequences of not providing emergency backup generators at NGPP locations during a power blackout. Understanding these effects may provide an incentive to install emergency power supply systems for NGPPs, or, for natural gas pipeline companies, to actively seek multiple sources of treated natural gas to ensure gas supply.

The current version of the interdependency assessment framework presents several benefits and some limitations, presented in the following sections.

Benefits

The development of the proposed assessment framework generates several immediate gains:

- Development of an interdependency simulation module allowing integration of existing and future infrastructure simulation models;
- Development of automated and improved mapping algorithms to match point-of-connectivity nodes between infrastructure systems to form the cross-infrastructure interface for very large systems;
- Creation of new real-life, regional scale data sets for the United States that define the nodal correspondence between infrastructure and related gas pipelines to various types of physically connected nodes (e.g., natural-gas-fired power plants and NGPPs);
- Development of logic to accommodate the implication of the disruptions of in-state assets such as NGPPs; and
- Development of a coupling mechanism that enables the propagation of disruption across linked infrastructures.

Interdependency Simulation Module

The interdependency simulation module utilizes a DCMS manager to combine existing and future infrastructure simulation models without requiring modification of original simulation algorithms. Simulating additional infrastructure system interdependencies would require development of unique translator models for the simulation models used. The DCMS manager will remain the same. Therefore, the DCMS logic allows rapid integration of all types of infrastructure simulation models and faster automatic simulation of a succession of large-scale events.

Automated and Improved Mapping Algorithms

The problem of matching intersystem nodes to establish interdependent, interconnectivity points between coupled systems emerges from the different identification schemes employed by each system. Furthermore, because the scale of modeling problems handled by the current integrated model is very large (e.g., 70,000 nodes and thousands of power plants), matching the electric power grid nodes with power plants fueled by the natural gas system has become a challenge. In most cases, generator buses (e.g., substations) have the same name as the power plants to which they connect, but some cases have no *common link* or reference. In some instances, proximity may be the only basis for associating buses with power plants, but even this method has practical limitations. The net effect is that about 80% of the gas-fired power plants can be matched accurately with their associated grid buses or substations. For the remaining 20–25%, manual inspection using a GIS viewer is required.

Prior to this effort, finding the points of connectivity between the natural gas and electric power infrastructure systems was a manual task. Mapping corresponding nodes between infrastructures is tedious and takes an unreasonable amount of time. For example, the effort needed to characterize Florida, which has hundreds of natural-gas-fired generation buses, took one analyst about 36 h with a matching success rate of about 80%. The remaining 20% required additional manual inspection using a GIS viewer. An analyst can match nodes using the combined computer-based approach and complete the Florida case in less than 0.5 s. However, the matching success rate is similar to the manual method—about 75–80%.

The algorithms utilized for mapping electric power and natural gas databases can be used for all available infrastructure databases. The simulation would be limited only by access to the databases that apply to the infrastructure systems under consideration.

Creation of New Data Sets

The creation of new national-level data sets that define the crossover interface (composed of points of connectivity) between electric power and natural gas infrastructure systems is another important element. The application of mapping methods makes this effort manageable and feasible. Using currently available information, no database exists characterizing the U.S. electric and national gas pipeline networks. The availability of such a database makes large-scale energy interdependency studies possible.

Development of Logic to Accommodate Natural Gas Processing Plant Disruption

Because NGPPs are the most affected natural gas assets during blackouts, a disruption of these assets has significant implications on the sufficiency of gas supply both in-state and in downstream states. To capture the system effects of NGPP curtailments, additional capabilities were added to *NGfast* to reflect the implications of reduced production (both during compensated and uncompensated simulation modes). The approach developed for this study is applicable to terminal states and flow-through states.

Development of Coupling Mechanism That Enables the Propagation of Disruptions

When a pipeline experiences flow reduction, either via disruption of NGPP operations or through a break, there are implications to both gas and electric customers downstream. Reduced flow could disrupt many natural-gas-fired power plants located in downstream states. Logic for estimating the effect on natural-gas-fired power plants given a flow reduction or a pipeline break provides the following primary benefits:

- Identification of all natural-gas-fired power plants that are directly or indirectly connected to the pipeline under consideration using the crossover interface;
- Prioritization of the curtailment of natural-gas-fired power plants based on the level of use, type of connection, and transportation contract (i.e., either interruptible or uninterruptible); and
- Removal of prioritized natural-gas-fired power plants from the list of participating plants (i.e., generation buses) in subsequent *EPfast* input files to determine resulting electric impacts and outage areas.

The implementation of the assessment framework to the Florida and North Dakota case studies pointed to additional direct benefits:

- Identification of critical infrastructure assets, which, when disrupted, can affect the operations of another infrastructure. Appropriate resiliency enhancement options can be identified and implemented to mitigate effects;
- Increase of situational awareness of system operations during emergencies, further enabling informed and appropriate decision-making. Improved decisions regarding mitigation and

response measures can lead to more timely and effective restoration actions; and
- Ability to provide meaningful information regarding possible intra- and intersystem impacts following disastrous events to enable consideration of hardening of critical assets.

Although the development and implementation of the interdependency assessment framework presents numerous benefits, some limitations exist that need to be addressed.

Limitations

The hazard module does not include all types of natural hazards or human threats, which restricts its usefulness. The visualization module still lacks the features needed to convey the results in clear, decision-aiding graphics. Lastly, the model does not consider the stochastic nature of some events and therefore, falls short in fully supporting a risk-based decision making process.

The interdependency assessment framework puts emphasis on sequence of events, from the initiation of the disturbance to the arrival at the final new steady state operating point. As such, it provides the notion of time but does not define the time lapses between events as well as the overall timeline during which the entire scenario unfolded.

The current models, *EPfast* and *NGfast*, operate in the realm of linear approximation and, although very useful for specific purposes, they do not address the detailed behavior of energy systems the way nonlinear models do. The effects of voltage and pressure variations, for instance, are not captured in the linear model. However, for simplified screening level analysis, linear approximation plus the application of some heuristics may be sufficient to arrive at a reasonable conclusion.

In general, the granularity of the results, especially for the electric side, does not include distribution-level impacts. This is primarily due to the unavailability of distribution-level data from publicly accessible sources. On the natural gas side, the identification of gas-fired power plants behind the LDCs is not very precise and may need support from LDCs in terms of providing more accurate connectivity data.

Future Work

Future research includes constructing case studies of the integrated *EPfast-NGfast* model that go beyond the Florida and North Dakota regions and represent a larger geographic scope, like MISO or our national energy infrastructure. Expanding data sets that relate electric substations to natural-gas-fired power plants and NGPPs is an essential part of this process. Expansion of the database relating natural gas pipeline companies with natural-gas-fired power plants and NGPPs is also needed to characterize the natural gas infrastructure that covers broad regions of the country. Selecting a larger region like MISO as a case study would advantageously leverage previous studies and collaboration with MISO staff that could lead to substantial model validation opportunities. The conditions leading to the polar vortex event in the Midwest are currently applied to the model to assess and compare modeled results with historical values.

Future versions of the failure analysis module will consider other natural, accidental, and made-by-human events, including earthquakes, extreme temperature and weather changes, winter storms, improvised explosive devices, or cyber events. Related to this effort, the assessment framework will also require consideration of regional resilience measures (i.e., preparedness, mitigation, response, and recovery) to simulate the behavior of critical infrastructure systems when an event occurs. Similarly, application of the interdependency simulation module to the integration of other lifeline infrastructure models, such as petroleum, communications, transportation, and water is expected.

In the future, uncertainties can be treated by applying stochastic simulation methods, probably through Monte Carlo techniques. Treatment of uncertainties can potentially be realized by encapsulating the DCMS integration framework within an iterative logic (i.e., Monte Carlo method) to generate varying consequence points based on a probability curve that define specific uncertainties. A time module could be added to the generalized framework to capture varying system dynamics (e.g., pipeline packing, protection device response, time lags, etc.) that are dependent and sensitive to time. For example, *EPfast* and *NGfast* could run simultaneously in multiple windows to simulate scenarios that transpire as a function of time. The construction of the time module, however, requires time-varying load data over the period of occurrence of the disturbance for both the natural gas and electric systems. That specific type of time-dependent load data is currently unavailable for large-scale networks, making development of the time module untenable at this stage.

Interdependency simulation and visualization capabilities could be enhanced. Without a clear portrayal of the succession of events, users and decision-makers may not appreciate interim interdependency simulation results and may miss opportunities to address resilience concerns.

Finally, the assessment framework can be enhanced by future research activities to:
- Facilitate integrated system design that maximizes the performance of both infrastructure systems during normal operations, while minimizing unforeseen cascading impacts within and across infrastructure systems during major events;
- Support loss avoidance calculations needed to justify investment decisions that could improve overall system resilience and harden the system against disastrous threats and hazards;
- Allow for the optimal siting of critical facilities to increase system resilience; and
- Identify cross-sector vulnerabilities to determine which specific assets receive resilience enhancement funding.

Conclusion

The research efforts presented in this paper recognize the increased usefulness of integrated infrastructure simulation models in aiding modeling infrastructure interdependencies. The proposed assessment framework provides a viable approach to combine disparate infrastructure simulation models into one seamless cohesive model. The assessment framework combines two main modules (i.e., failure analysis and interdependency simulation) allowing the simulation of infrastructure interdependencies from hazards identification to cascading failures visualization. The process, entirely automated, identifies hazards, estimates impact zones, simulates the initial effects on infrastructure, evaluates propagating effects within each infrastructure, and simulates cascading effects on interdependent infrastructure. The interdependency simulation module utilizes a DCMS manager to conveniently and economically combine dissimilar infrastructure simulation models. The DCMS manager handles inputs and outputs of infrastructure simulation models to simulate cascading failures occurring among infrastructure systems. As a test, the assessment framework was given two models to combine, *EPfast* and *NGfast*. *EPfast* and *NGfast* independently model cascading failures within the electric power and natural gas infrastructure systems, respectively. The new, combined model was applied to two case studies, in Florida and North Dakota, to model interdependencies existing among electric power and natural gas infrastructure systems and identify potential cascading failures resulting from natural hazard disruptions. Because of its successful application to integration of energy models, the assessment framework is expected to easily accommodate other infrastructure models representing petroleum, communications, transportation, and water infrastructure.

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