Efficient and Resilient Electric Power Networks: A Chinese Case Study

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Abstract

Electric power networks are susceptible to cascading failures due to technical and human failures, natural disasters, and terrorist attacks. Power networks consist of generation, transmission and distribution stations, used to transmit and distribute power from centralized generation points to end-users. They have been shown to have a single-scale topology, which makes them vulnerable to targeted attacks on high degree nodes.[1,2] We are interested in comparing the fairly well studied behavior and robustness of networks with this topology, with that of an alternative electric power grid that incorporates small-scale electric power generation close to end-users in communities or clusters. These distributed generation stations could utilize renewable energy technologies, which are ideal for scaled-down generation in the form of residential or commercial on-site installations, or medium-sized wind farms or solar power farms. In this study we build a model of a simplified electric power grid. We investigate the dynamics of this network by allowing demand to fluctuate and electrical energy to be re-routed accordingly. We investigate the robustness of the network by observing increases in operational costs and undersupply as edges are removed to simulate cascading failure. We apply this model to the Chinese electric power network, and compare scenarios in which the network evolves along a business-as-usual path, and an alternative path that incorporates distributed generation.

Introduction

Electricity delivery networks are critical life-lines. An ideal electric power network would be robust to a variety of attacks and failures, minimizing any spikes in operational costs due to power rerouting as well as minimizing the number of underserved nodes. However, there are numerous notorious cases of cascading grid failures induced by natural disasters such as Hurricane Katrina in August 2005, and technical or human failures such as the August 2003 blackout in the North American Power Grid. These large blackouts are life threatening and costly events. Additional risk in the form of terrorist attacks is of increasing concern.

Electric power networks consist of centralized generation and a complex transmission network. The North American power network was shown to be a single-scale network, with cumulative degree distribution following an exponential $P(k > K) \sim \exp(\ 0.5\ K)$, i.e. the probability that a node has more than K edges falls off exponentially as K increases.[2] This distribution makes the network vulnerable to targeted attacks on high degree nodes. Deregulation of the electricity market adds a level of complexity to this system, since power is sold over increasingly large distances by a variety of electricity suppliers. Teasing out all possible areas of vulnerability of real world electric power networks and the measures required to add robustness is not a trivial task.

One way to increase a network's robustness to edge removal may be to add redundancy in the form of extra transmission lines. These could provide alternative paths from centralized sources to end-users so that a small number of disruptions to transmission lines would not cause the entire network to fail. Another option may be to add sources closer to end-users. Decreasing the distance between sources and end-users minimizes the probability that any given end-user loses power when an edge is removed.

Decentralized generation, close to end-users, could be met by renewable generation sources, which are suitable for both large and small-scale operations. They would have the additional benefit of reducing the negative health and environmental effects of conventional energy sources – both local (NO_x, SO_x, particulate pollution, etc.) and global (greenhouse gases). In this paper we compare these two approaches, by exploring two alternate paths for evolution of the Chinese electric power network.

The evolution of the power network is a particularly relevant issue for China, which is currently at an important crossroads in its development. China is the second-largest energy consumer and the second-largest source of greenhouse gas emissions in the world.[3] Air pollution, most of which arises from stationary sources (i.e. power plants), is already a serious problem, killing thousands prematurely each year in large cities.[4] Blackouts due to undersupply are not uncommon. While China had held energy demand increases constant at 60% of GDP for decades, more recent energy demand increases have outstripped GDP growth by as much as one third.[3]

The Chinese government has responded to its country's rapidly increasing energy demand by developing domestic oil and gas resources and by seeking stakes in foreign producers. CNOOC's recent bid for Unocal is one recent manifestation of this trend, but as early as 1997, China had arranged oilfield development deals totaling 5.6 billion USD.[5] Although China has made some investments in renewable technologies, primarily wind, increasing fossil fuel supplies and developing nuclear energy remains one of the government's top priorities. China has significant coal resources, which it relies on for 65% of its primary energy consumption.[6] It is the world's largest coal producer and consumer.

China's increasing energy demand is expected to lead to major investments in infrastructure over the next few decades, making this a crucial time for China to make design choices. The power plants China invests in now will drive its emissions for the next 30-50 years. China has an opportunity to forestall health and environmental problems while development is still occurring and before billions of dollars in investments lock it into certain technologies.[4] In this paper we investigate the aspects of one option, increased use of renewable energy, by comparing the robustness of the electrical grid that might result with and without decentralized generation.

Previous studies on electrical grids appear to fall into three main categories: detailed electrical engineering based studies on system failure[7]; simplified network models in the complex systems literature[2]; and studies of the dynamics of deregulated electricity markets[8]. While some studies address the system at various scales and with an interdisciplinary approach, a comprehensive model linking the detailed physical constraints with the system-level behavior still appears to be missing. In this project we develop a simplified model, with the aim of providing a framework that can subsequently be modified to reflect more of the detailed electrical engineering constraints present in the system.

The approach used in this study could be applied to a broad set of topics, such as supply and demand systems in economics, communication or transportation, all of which can be modelled as networks carrying some type of flow. These human constructed systems are often engineered to minimize capital and operational costs, while maximizing robustness (i.e. they should be cheap to build and run, and simultaneously durable and low maintenance). These networks also form the substrate for a dynamical flow process that introduces a level of complication and unpredictability alongside purely topological considerations such as connectedness and the cost of establishing edges. All of these networks are examples of "frustrated" optimization problems, where optimizing one aspect often requires sacrifices to be made to another.

Exploratory model

In order to simulate the behavior of the electrical grid, we begin by building an exploratory model that includes key characteristics of an electric power grid, but is general enough to apply to any problem in which a dynamic process occurs on a network. In this model we include sources (power-plants) and sinks (end-users) of arbitrary size, transmission lines of limited capacity and transmission stations.

On a network of directed edges, we study the minimum cost flow problem, defined as:

$$\sum_{i \neq j} c_{ij} x_{ij} = \min$$

where c_{ij} is the cost associated with sending one unit of flow along a path from node i to j, and x_{ij} is the amount of flow sent from node i to j. The total cost of sending all flow should be minimal. At the same time, we have to fulfill two constraints:

$$x_{ij} \leq u_{ij},$$

i.e. the flow along an edge must be smaller than the capacity of that edge. Furthermore

$$\sum_{j \neq i} (x_{ji} - x_{ij}) - b_i = 0,$$

i.e. the outflow from every node must match the inflow minus the amount of flow consumed (b_i<0) or produced (b_i>0) at that node. Nodes that have b_i=0 are considered transmission stations. For simplicity, we allow the routing of flow in both directions along every edge. This aspect of the model does not match the real world situation. However, the model's supply and demand structure ensures that bidirectional edges occur only between transmission stations, never at sources or sinks, in any given solution to the flow problem. When power is re-routed after edges are removed, the flow on some edges does reverse its direction.

In our model, we assume the costs c_{ij} of routing flow to be proportional to the physical distance between two nodes i and j, thereby ensuring that energy is routed along the (geographically) shortest paths on which the capacity of the lines is sufficient. In order to calculate the minimum cost flow solution, we used a standard augmenting shortest path algorithm described further elsewhere.[9] One requirement for this linear programming algorithm to give a valid solution is that a solution exists. In order to ensure this, we added one extra (virtual) node v to the network, and gave it connections to sources and sinks only through edges with an associated cost $c_{iv}=\infty$. This ensures that these edges are only used in solutions that would not be feasible otherwise. The bias of node v is set to $b_v = \sum_{i \neq v} b_i$ so that supply and demand will always be balanced when the system is forced to use the virtual node.. Thus, the virtual node ensures that a solution to the minimum cost flow problem always exists, and allows us to measure undersupply in the network as the sum of inflows to sinks from node v. It also ensures that overcapacity on the supply side is effectively "dissipated."

Figure 1 shows an example of the solution of the minimum cost flow problem on a random network. To construct this network, we distributed nodes randomly in a plane, and connected each one to its k nearest neighbors (k=3 in this example). We randomly selected some nodes to be sources and sinks (shown as stars and squares, respectively) and assigned these a random supply capacity or demand. Nodes that are neither sources nor sinks act as transmission stations. The dashed lines represent the edges in the network and the solid lines show the actual flow corresponding to the solution of the minimum cost flow problem.

We use this model to investigate two aspects of robustness: how fluctuating demands are met by the supply side, and how the network responds to cascading edge failure. For the first question, it is understood that the network topology plays an important role in the solution of the minimum cost flow problem. Figure 2 gives an example of how different topologies (in particular, the availability of alternative routing paths) lead to correlations among the fluctuations on the demand or supply side. These correlations may then be amplified or damped by the limited edge capacities. Furthermore, although the fluctuations on a particular node are generally Gaussian, the correlations introduced by topological characteristics mean that global response functions, such as total routing cost, may not exhibit Gaussian fluctuations. This observation is particularly important in systems where routing decisions are made by different operators, as may be the case in power grids owned by multiple companies that trade flow and routing capacity.

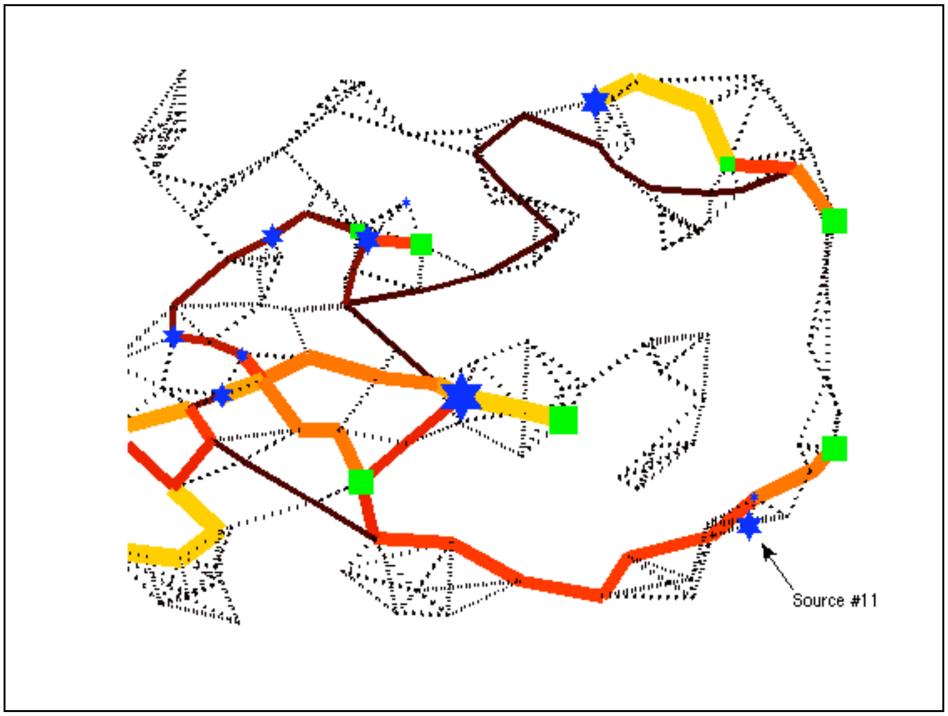

Figure 1. Model of undirected transport network. Nodes are distributed randomly in a plane. They are then connected by linking each one to its k nearest neighbors (k=3 in this case). Supply nodes (stars) and demand nodes (squares) are chosen randomly from the nodes. The dashed lines symbolize possible transport paths and the solid lines represent actual flow along these lines as found after solving the minimum cost flow problem. Line thickness represents amount of flow on one particular line. The cost of transporting flow along one line is proportional to the amount of flow transported and the length of the line.

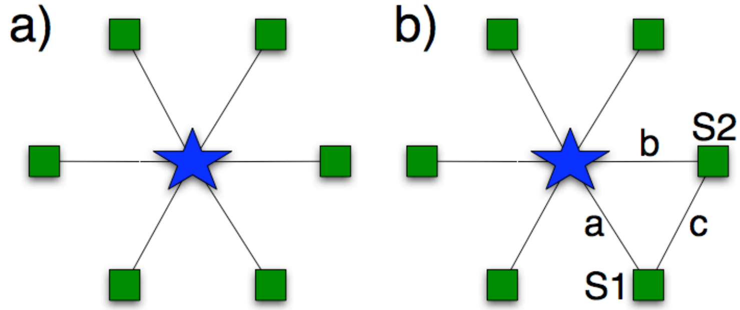

Figure 2. Network topology. An example of how the network topology introduces correlations in the response functions. a) All demand nodes are served by one supply node. The fluctuating demand is summed up at the source and the routing cost is fluctuating in the same way the demand is fluctuating. b) One additional link between S1 and S2 introduces alternative paths. If S1 now shows larger demand than can be served through *a*, there exists backup capacity through *b* and *c*, provided that S2 shows a demand that does not alone make *b* operate at full capacity. Also, suppose *a* is a low capacity, low cost line and *b* is a high capacity, high cost line and the cost of c is smaller than the difference in cost of *a* and *b*, then, whenever possible, that is, whenever demand at S1 is low, flow to S2 is routed via *a-c*. Sink S1 hence acts as a gate for this flow to S2, Though the supply only has to fluctuate as the sum of demands, the total routing cost is now a function of correlated variables and hence will generally show a different pattern of fluctuations.

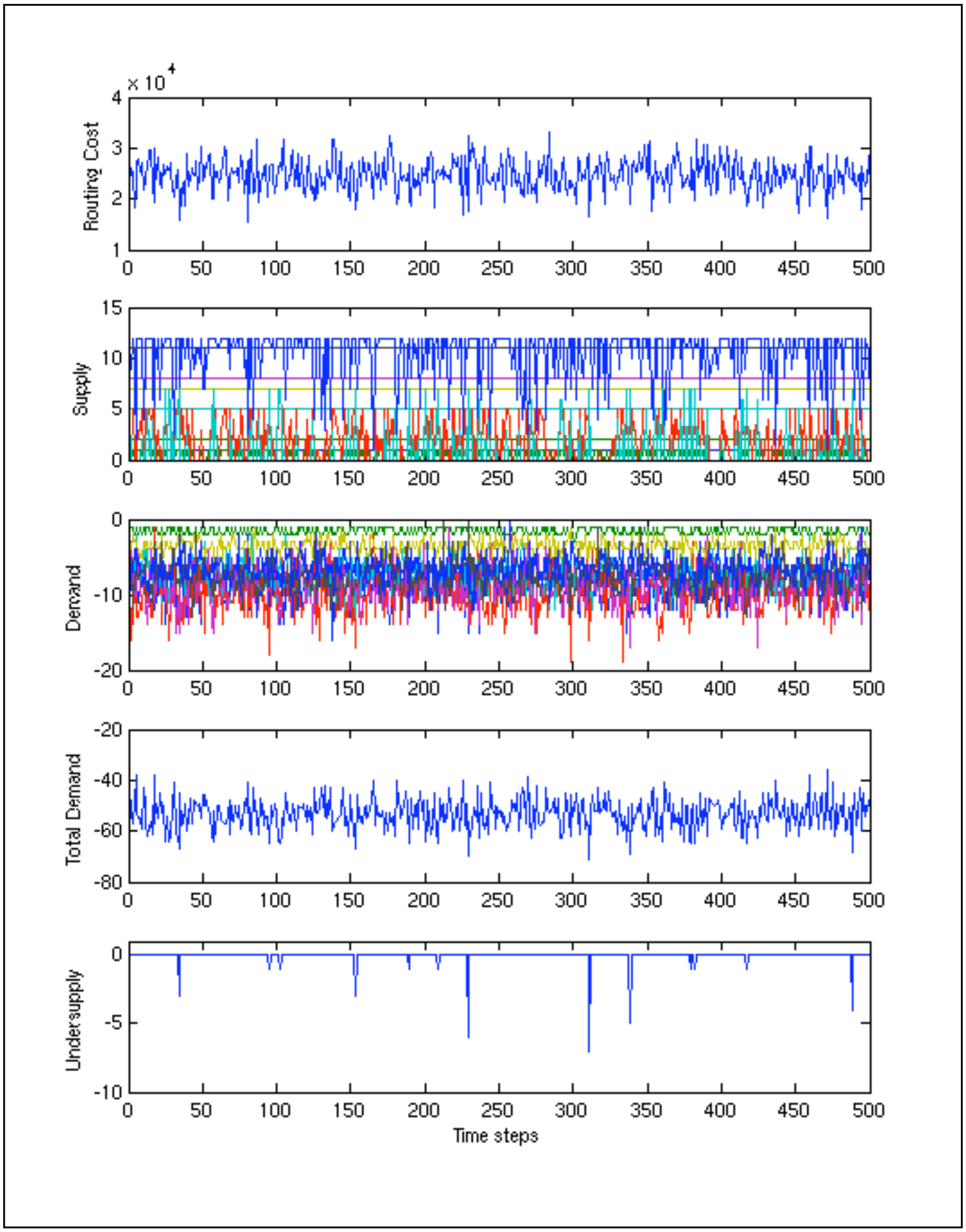

Figure 3. Demand fluctuation and undersupply. Uncorrelated Gaussian fluctuations of the individual nodes on the demand side and various response functions for the network of figure 1.From top to bottom: Fluctuation of the total routing cost, fluctuation of all individual supply nodes (note how some supply nodes operate at constant capacity, while others fluctuate), fluctuations of all individual demand nodes, fluctuations of total demand, and fluctuations of total undersupply. The particular connectivity pattern of the network introduces correlations on how demand is satisfied by the supply side under the condition of minimum cost flow. This leads to non-trivial response functions including occasional shortages of power.

Figure 3 shows a number of possible response functions under Gaussian fluctuating demand. These functions were calculated for the network topology corresponding to that shown in figure 1. Each demand node fluctuates around a mean value, so the total demand fluctuates around the same mean. However, the individual supply nodes show a completely different behavior. Almost all supply nodes in the middle of the network operate at full capacity, while those at the periphery operate only to supply peak demand. Figure 4 demonstrates this phenomenon on the network shown in figure 1. Compare the histogram of fluctuations of total demand with the fluctuations of the power output at source number 11. Also, the total routing cost shows a histogram of fluctuations that is not Gaussian, but has rather fat tails, since some demands can only be met by routing exceptionally long detours. Overall, the network structure greatly influences the response functions to fluctuations in supply and demand. Studying this interdependence and then measuring global response functions as the total routing cost from day to day may lead to some understanding and insight into the network structure without actually mapping it out.

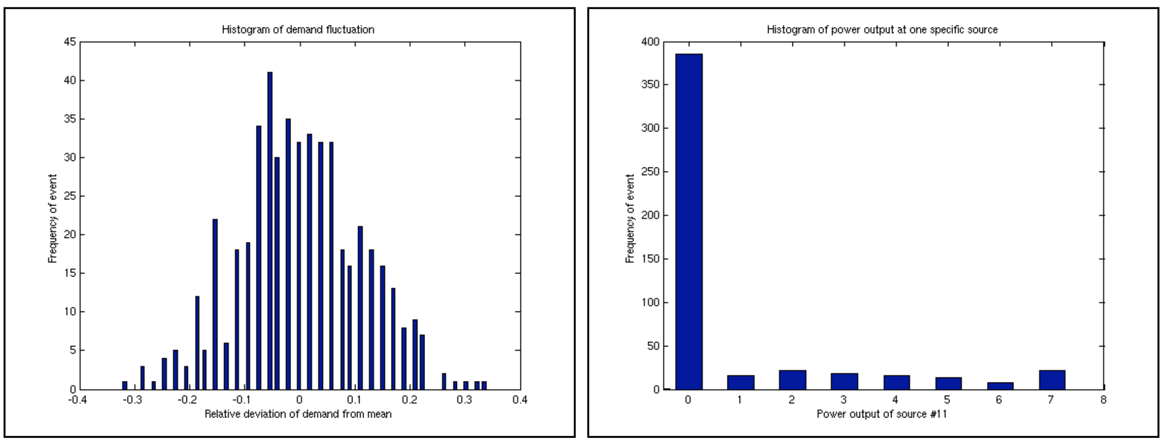

Figure 4. Global demand and local supply. Gaussian fluctuation of the total demand is shown at left and non-Gaussian fluctuation of the power produced by a particular node (node number 11 in figure 1) is shown at right. This source is apparently only needed to back up peak demand. Its location at the periphery of the network suggests this operation mode. Sources in the center of the network generally operate at full power, as their centrality allows a broad and cost-efficient distribution of energy.

A second measure of robustness is that of robustness against edge removal. We model this situation as follows. After solving the minimum cost flow problem on the original network, we select the edge that is closest to its capacity limit and delete it from the network. Then, we recalculate the minimum cost flow for the new network and repeat the procedure. This algorithm mimics a cascading failure. The edges that are removed at each stage can be thought of as those closest to their operational limits or as those most vulnerable to targeted attacks. Figure 5 shows a typical course of events for a network similar to the one shown in figure 1. As the first edges are removed, the redundancy in the network allows rerouting of the flow such that the total demand can still be met. At some point, this is no longer possible, so a set of nodes is cut off from the network. A balance of demand and supply can be re-established in the smaller network, and can also be maintained for a number of steps due to redundancy in the network, but eventually it is also disrupted, and the pattern repeats itself. This process leads to a step-like increase in the percentage of demand that cannot be met.

It is also interesting to note that edges with high load are also those with high shortest path betweenness (i.e., many of the shortest paths form sources to sinks in the network include these edges). The deletion of such edges quickly isolates clusters of sources and sinks from the rest of the network. Therefore, it seems advisable to mix generation and production as much as possible in order to decrease the number of high betweenness edges and to make targeted attacks more difficult.

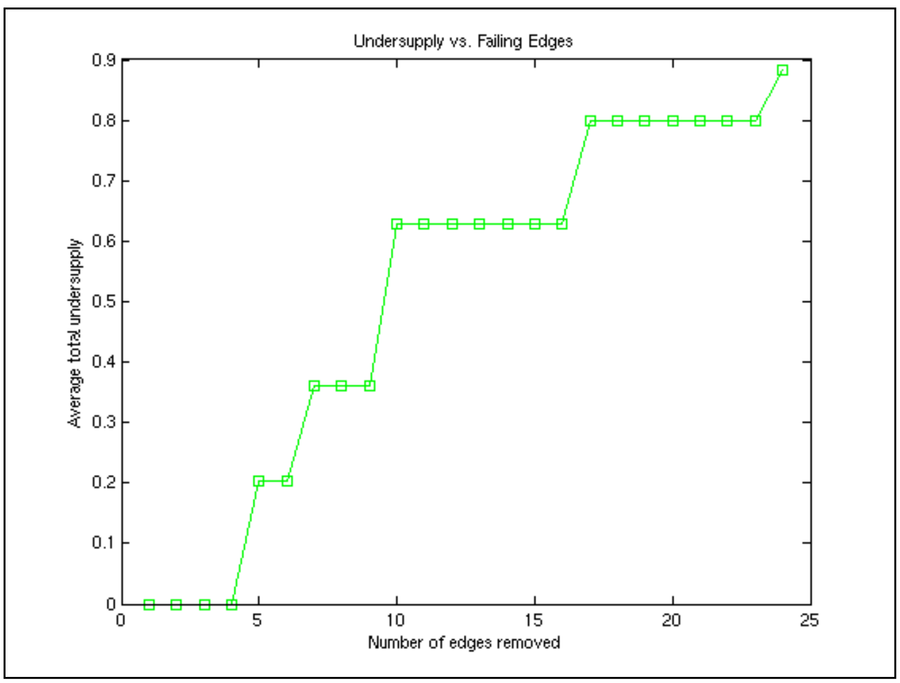

Figure 5. Undersupply. Edges with high load will form the critical backbone of any network carrying flow. Hence, tolerance to their failure is essential. We study the rise of undersupplied demand as we remove more and more of those edges that operate closest to their capacity limit. For this model, we observe a step-like increase of undersupply as modules of the network are disconnected from all suppliers. Decreasing the modularity of the network might prove a valuable strategy to increase the robustness of the grid.

Chinese case study

In our model of the Chinese electric power network we include demand and supply of electricity to China's 40 largest cities. Total electricity supply in China is projected to be 462 GW by the end of 2005.[6] Based on city-by-city population growth projections, the 40 cities modeled will require ca. 150 GW of that supply.[10,11] We assume this will be met by 30 existing thermal and hydroelectric sources (figure 6). Using a similar procedure to that described for the exploratory model, we simulate cascading failure on the network. The results are shown in figure 7.

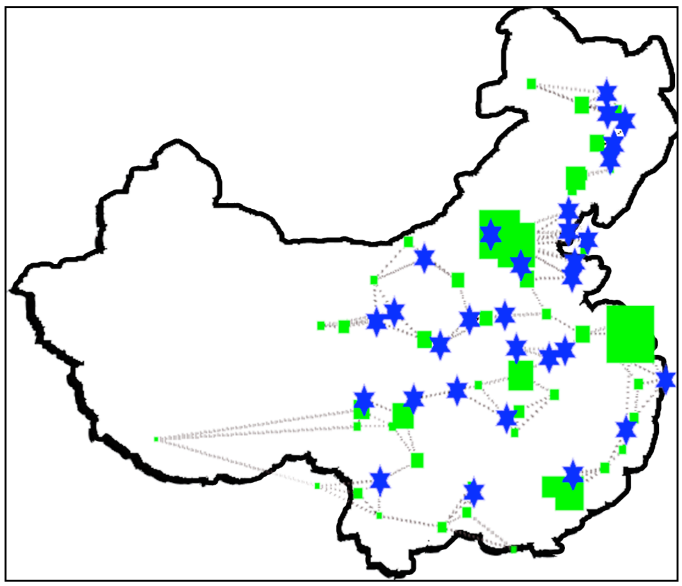

Figure 6. China's electric power network. A map of China's supply (power plants) and demand (cities) nodes. Stars indicate supply nodes. Connections are made from each node to its three nearest neighbors. Additional edges are added from sources to Beijing, Tianjin and Shanghai in order to supply their large demand.

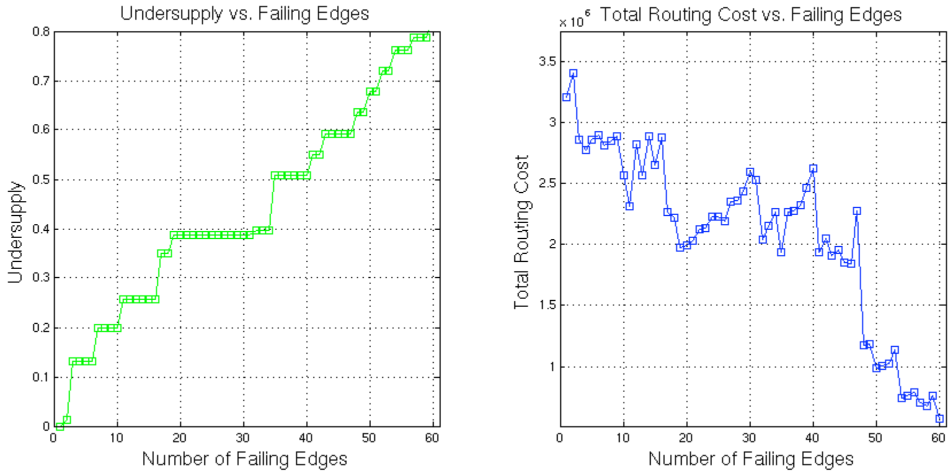

Figure 7. Undersupply and operational costs for the 2005 baseline. Much like in the exploratory model, targeted attacks on edges with the highest load result in a step-wise increase of undersupply as sets of nodes are disconnected from all sources. The shorter average distance from sources to sinks leads to smaller steps along the failure cascade. Discontinuities also appear in operational cost. Cost displays a large drop each time a set of nodes is disconnected. Between the steps down, cost increases as power is re-routed through less and less efficient paths to supply the same demand.

By 2015, China's electricity supply is expected to increase to ca. 750 GW.[6] Based on city level population growth predictions, the 40 cities modeled here will require a 260 GW supply capacity. Our first growth scenario follows a business-as-usual path, where centralized sources increase in size and transmission lines are strengthened accordingly. Production capacity is added evenly across all sources to match increased demand; edge capacity along the 2.37 million kilometers of transmission lines is strengthened accordingly (by a factor of 1.73). Robustness is added into the system in the form of edge redundancy (shortcuts) along paths that are particularly vulnerable to targeted attacks. In the 2005 baseline, all but seven sinks were directly connected to a source. In this 2015 scenario, a shortcut was added from each of these seven sinks to its geographically nearest source.

Capital costs arise from the expansion of sources (1 USD/W) and addition of high voltage transmission lines (175,000 USD/km). The scenario requires the addition of 91.25 GW of production and 3,380 kilometers of transmission lines, bringing the total capital costs for these system modifications amount to 91.8 billion USD. Note that the additional cost associated with increasing the line capacity of existing transmission paths has not been included here. However, This additional cost is likely to be small in comparison with the total. The undersupply and routing costs for this scenario, with increasing numbers of removed edges, are shown in figure 8. The robustness of the network was improved as compared to the baseline scenario.

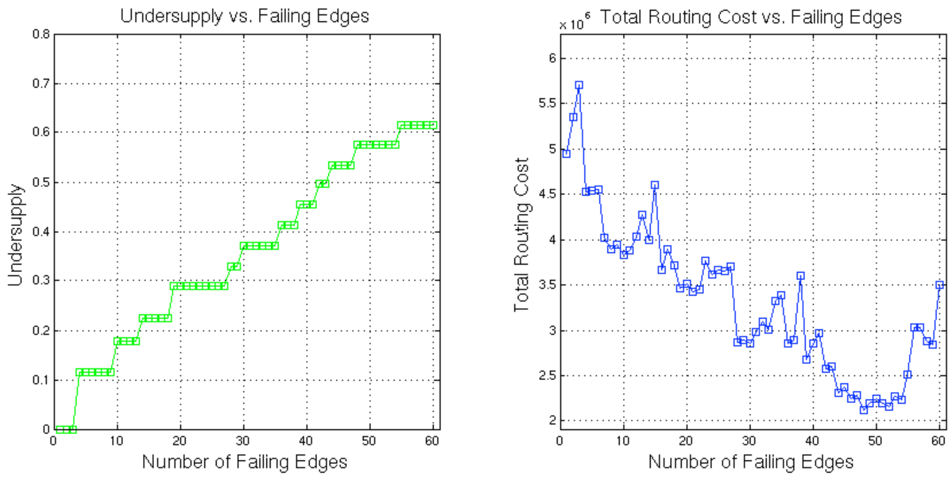

Figure 8. Robustness in scenario 1. Growth in demand is met by centralized sources, and redundancy is added through extra transmission lines. As in the baseline model, undersupply increases step-wise as sets of nodes are cut off from all sources. Operational cost corresponds to undersupply with the same pattern as in the baseline. Due to the topological changes made, the network displays increased robustness (visible as longer and lower steps) compared to the baseline situation, even at increased demand. Shorter paths from sources to sinks increased the failure tolerance of the network.

In the second scenario, growth in demand by 2015 is supplied by distributed sources situated close to end-users. This is represented in the model by adding sources within sinks in each of the 40 cities, so that in the model it appears as if they have no increase in demand. These cities are then connected via lower-cost, lower-voltage lines to the two cities geographically nearest to them. This requires 31 new lines totaling 13,720 kilometers in length. Capital costs arise from the addition of sources (1 USD/W) and low-voltage transmission (75,000 USD/km). This scenario adds 91.25 GW of distributed production. Combined with the additional low-voltage transmission lines, the total capital cost is 92.3 billion USD. Figure 9 shows the undersupply and routing costs for this scenario as edge removal progresses. This second scenario shows an improvement over both the baseline and the first growth scenario. The onset of undersupply occurs later than in the first scenario, and the total amount of undersupply increases much more slowly with subsequent edge removal. In figure 10 one can compare the robustness, in terms of undersupply, for each of the three scenarios to see that the distributed scenario outperforms the others.

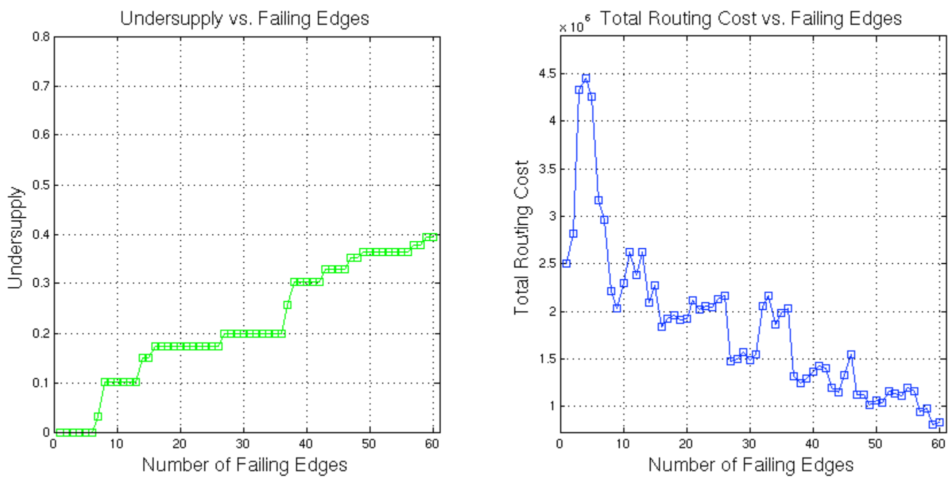

Figure 9. Robustness in scenario 2. The undersupply and operational cost graphs show the same patterns as in the baseline model and scenario 1. However, total undersupply is much lower at all stages and the number of edges that can be removed before undersupply jumps up is higher. Routing cost is also lower in most stages. The network in scenario 2 is more robust than both the baseline case and scenario 1.

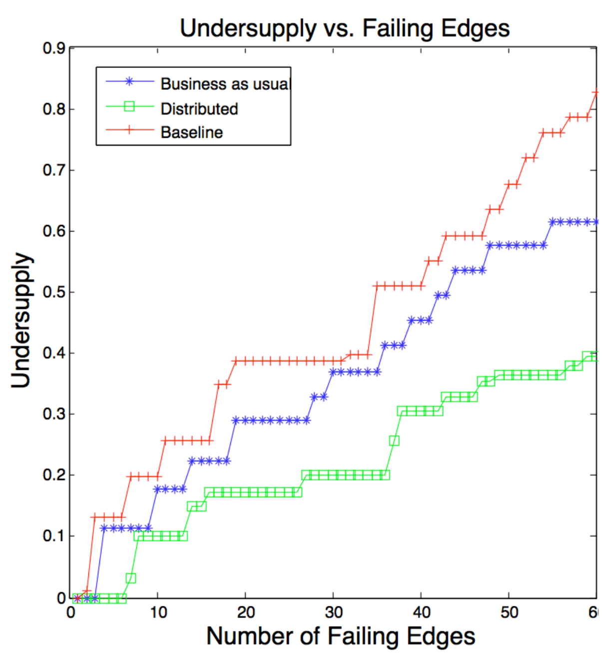

Figure 10. Comparison of base-line and scenarios 1 and 2. Scenario 2 (with distributed generation meeting increased demand by 2015) can be seen here to outperform scenario 1 (with centralized generation meeting increased demand by 2015) and the baseline (2005). The percentage of undersupply is one measure of robustness.

Conclusions and discussion

Understanding how to increase the resiliency of electric power networks is extremely important to mitigate the effects of technical and human failure in routine operation, natural disasters and terrorist attacks. Power failures due to any of these events can lead to debilitating economic setbacks and significant loss of life. The purpose of this project was to begin investigating whether robustness could be increased by adding supply close to end-users via distributed generation. This question is especially important because a distributed generation scheme is compatible with renewable energy technologies (such as solar and wind), which have huge environmental and health benefits on the global scale (slowing climate change) and on the local scale (minimizing pollutants that threaten health and the environment).

China provides a particularly interesting case study. Its energy demand is projected to grow significantly; it is a major contributor to global greenhouse gas emissions; pollution in its major cities is substantial; and the current electric power network has undersupply problems and routine technical failures. In addition, as outlined above, China has reached a stage of development at which it must make crucial infrastructure design decisions..

Our results suggest that distributed generation close to end-users may significantly increase the robustness of electric power grids. This is true in terms of decreasing spikes in operational costs due to system failure, delaying the onset of undersupply to cities, and slowing the progression of undersupply as edges are removed. While other authors have speculated that this would be the case[2], it has not previously been demonstrated.

Ours is a simplified model, and a real world network would be subject to a variety of constraints not discussed here. One gap in the literature is of studies that combine the detailed electrical engineering models with the simplified network models; a model that manages to achieve this could be extremely helpful. Our project goal was to make some advances in understanding how to use network modeling to produce policy relevant results describing the relationship between distributed generation and the robustness of the electrical grid. Potential next steps include incorporating distribution stations and directionality into the network, and improving the cost estimates given here. Also, we have not taken into account fluctuating supply and the potential need for storage when using renewable energy technologies; nor have we considered the dynamics that could be expected to result from sector deregulation. Nonetheless, our approach appears promising for studying the robustness of the electric power network, and perhaps also of other physical or social networks.

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