Electric Network Reliability as a Public Good

Lynne Kiesling and Michael Giberson

***Abstract*— Many analyses and policies relating to electric network reliability rely on the assumption that grid reliability is a public good. We analyze that claim, applying and expanding economic theory from Buchanan & Stubblebine (1962) and Coase (1960). We argue that network reliability has both public good and private good characteristics. However, as the grid becomes more heavily loaded, continued access to grid services become rivalrous in nature and the public good aspects of reliability are diminished.**

In the process of refining the analysis of network reliability as a public and private good, we derive policy recommendations that enhance transparency and information content in the network. Furthermore, we explore the consequences of our analysis of the private and public good character of grid reliability for the prospect of creating and selling reliability as a differentiated product complementary to bulk power markets. An overall goal of the research is to improve our understanding of network reliability in an increasingly market-driven transmission system.

***Index Terms*—networks, priority insurance, public goods, reliability.**

I. INTRODUCTION

POLICY discussions of electric system reliability often assert that reliability is a public good. The claim is usually followed by the assertion that, therefore, the costs of providing reliability should be shared by all. Increasingly, this claim is used to support the idea of making reliability rules mandatory, i.e., enforceable by regulators. Rarely do the authors of these claims pause to analyze or explain the public good character of reliability on the grid.

Recent market design efforts within regional power market operators have tended to move in a non-public good direction on assignment of costs, toward particularizing the provision of some reliability resources. For example, efforts under way in the Northeastern U.S. markets incorporate locational elements into both reserves and capacity markets.[1] These efforts arise out of practical attempts to address reliability issues on the grid, but these efforts, too, typically do not explicitly address the public- and private-good characteristics of network reliability.

In this paper we take an initial step in that direction, exploring the potential policy benefits that can come from recognizing the private-good characteristics of reliability. An extensive literature in economics is devoted to exploring the nature of public goods, to assessing the problems and opportunities that such goods present, and to devising mechanisms to overcome the problems and exploit the opportunities present in public goods. Applying this literature to issues of reliability on the grid necessitates more careful analysis of the public good character of grid reliability.

This paper will review a few examples of the public good claim for grid reliability to motivate and provide context for the analysis. We then provide a brief primer on public goods, examine reliability issues in the context of the transmission system, and seek out public goods problems in grid reliability. Finally, will examine the policy relevance of the public goods problems identified and consider the potential to address the problems using tools of economic systems design.

An examination of these issues will contribute to addressing one of the critical issues of electric power restructuring: how to ensure economical provision of electric system reliability in a decentralized market environment.

II. PUBLIC GOOD CLAIMS

The North American Electric Reliability Council definition of reliability divides the concept into two separate concerns – "security" and "adequacy." Oren explains the two issues in this manner:

- *Security:* "the ability of the system to withstand sudden disturbances." This aspect concerns short-term operations and is addressed by ancillary services, which include: Voltage support, Congestion relief, Regulation (AGC) capacity, Spinning reserves, Non-spinning reserves, Replacement reserves.

- *Adequacy:* "the ability of the system to supply the aggregate electric power and energy requirements of the consumers at all times". This aspect concerns planning and investment and is addressed by

Manuscript received November 15, 2004.

Lynne Kiesling is Director of the Center for Applied Energy Research at the International Foundation for Research in Experimental Economics, and Senior Lecturer of Economics at Northwestern University (E-mail: lynne@knowledgeproblem.com).

Michael Giberson is a postdoctoral fellow at the Critical Infrastructure Protection Project and the Interdisciplinary Center for Economic Science, both of George Mason University (Corresponding author: E-mail: mgiberso@gmu.edu).

---

[1] Proposals for locational reserves, locational ICAP, and arguments for participant funding of grid upgrades are examples of such initiatives. If these resources were *pure* public goods, then the location of the reliability resources would not matter. Of course, they are not pure public goods, but these efforts provide evidence that reliability resources are not even pure network goods. Depending on the location of a reliability resource, some networked load will benefit and others may not. Note also efforts to develop "participant funding" mechanisms to pay for transmission system improvements, which reveal a belief in the non-public nature of some system improvements.

> Planning reserves, Installed capacity, Operable capacity or Available capacity. [2]

Oren observes, "Security and Adequacy are clearly related since it is easier to keep a system secure when there is ample excess generation capacity."[3] In a more recent article, Oren says:

> "From an economic point of view security and adequacy are quite distinct in the sense that the former is a public good while the latter can potentially be treated as a private good. Security is a system wide phenomenon with inherent externality and free ridership problems. For instance, it is not possible to exclude customers who refuse to pay for spinning reserves from enjoying the benefits of a secure system. Hence, like in the case of other public goods such as fire protection or military defense, security must be centrally managed and funded through some mandatory charges or self-provision rules. …. Adequacy provision on the other hand … amounts to no more than insurance against shortages, which in a competitive environment with no barriers to entry translate into temporary price hikes. Such insurance can, at least in principle be treated as a private good by allowing customers to choose the level of protection they desire."[4]

The assertion that at least some aspects of network quality are shared by all network users, and that each user's actions on the grid have "external" effects, is common. However, public goods, as the term is understood in economics, require more that the presence of an externality, and the presence of an externality is insufficient in itself to justify regulatory action. To devise a consistent conceptual framework for understanding reliability in networks, we need to examine the precise kinds of externalities and public goods are involved.

III. Externalities and Public Goods

According to the now-standard approach to public goods in economics, a pure public good is characterized by nonexclusiveness and nonrivalry.[5] A good is nonexclusive if others cannot be excluded from the effects of the good, or can only be excluded at great expense. A good is nonrival in consumption if the use or enjoyment of the good by one person does not diminish the ability of others to also use the good.[6] In consequence, once a pure public good is provided by anyone, it is available to everyone.

Clearly the production of pure public goods unavoidably has external effects, or effects on "third parties." Following Pigou, an externality arises when one agent's action affects another agent's value, positively or negatively.[7] The concepts of externalities and public goods are closely related, but strictly speaking a public good is a subset of the more general category of externality in economics. A pure public good is a particular type of externality in which excluding non-payers is not feasible, and all third-party agents are affected.

The existence of public goods could create problems with market processes because of the possibility of free riding. A free rider is an agent that does not contribute to a public good, but intends to enjoy the benefits of other agents' efforts to provide the public good. An example in an electric power network would be a load-serving entity (LSE) that does not make any investments in network reliability, but instead relies on the contributions of other LSEs to keep the grid stable and power flowing to its customers.

For example, consider a model of a network of load-serving entities (LSEs) that treats reliability as a pure public good. Suppose that this network has n agents/LSEs operating and benefiting from the uniform level of reliability provided on the network.

Suppose that each of these n LSEs has a value function, V. This value function can either represent value from consumption (utility) or from production (revenue). Keeping the value function general allows for the possibility that agents can both consume and produce reliability. Suppose further, without loss of generality, that each LSE's value function is defined over the consumption of a rivalrous numeraire good, X, and over the total amount of reliability, Y. Recall that under the standard public good model Y is a function of the investment choices of all n LSEs. Formally,

$V_i = V_i(X_i,Y)$ where $Y = Y(y_1,Y_j)$, $X_i >=0$, $Y >=0$, $y_i >=0$ for all $i \in \{1,\ldots,n\}$, $Y_j=\Sigma_{j\neq i}y_j$

Assume that each LSE acts to maximize V subject to the cost of X_i and of y_i, and subject to the reliability investment decisions of the other $j\neq i$ agents.

At the margin, an externality exists when

$$\partial V_i/\partial y_j \neq 0 \tag{1}$$

In other words, when some LSE_j's choice of y_j affects LSE_i's value at the margin, a marginal externality exists. Note that this externality can be either positive or negative.

The standard externality argument holds that for goods with positive externalities that we consume collectively, the optimality conditions differ from those for private, rivalrous goods. For private goods, a necessary condition for optimality is that the marginal rate of substitution (MRS) between

---

[2] Shmuel S. Oren [13].

[3] Oren, [13] p. 7.

[4] Shmuel S. Oren [12], p. 5. The Oren discussion was the clearest explanation of the public good aspects of reliability that we uncovered. See also Joskow [9] and Cowart *et. al*. [5].

[5] This section draws upon Cornes and Sandler [4]. Also helpful is Cowen [6], which reprints the key Samuelson article [15]. Another discussion of the pure public good argument is in Musgrave [11].

[6] A congestible good is one that is not perfectly nonrival, but that becomes increasingly rivalrous as consumption approaches some upper bound. Any good with a limited capacity is congestible, including highways, swimming pools, and electricity transmission networks.

[7] Pigou [14], pp. 166-168. Pigou argued that remedying the allocative inefficiency arising from this interdependence requires the use of "bounties and taxes" to realign the incentives of the offending agent to address "uncompensated services and uncharged disservices."

pairwise sets of goods is equal across all agents, and that it is also equal to the marginal rate of transformation (MRT) that reflects the production technology for each good. However, with joint production and consumption of reliability, the optimality condition changes to

$$\sum_i MRS_{YX}^{i} = MRT_{YX} \qquad (2)$$

This condition suggests that LSE_i's additional investment in Y makes LSE_j better off, and that if LSE_j is maximizing her own value function, if she can enjoy Y while LSE_i pays for the investment in it, then she has a clear incentive to free ride. Note one condition that makes this situation more likely and one implicit assumption that leads to the free riding conclusion. First, the condition under which LSE_i's investment is small relative to the sum of y_j ($j \neq i$) increases the probability that free riding and underprovision can be a likely outcome. Second, this model implicitly assumes that all n agents have identical value functions. In such a case, LSE_i's and LSE_j's investments are perfect substitutes, and the equilibrium condition described in equation (2) treats them as such.

IV. RELEVANT AND IRRELEVANT EXTERNALITY

Both the general theoretical framework and the application to electricity that relies on public good theory overstate the public good characteristics of network reliability. That overstatement overlooks the crucial ways that reliability is a private good, and policies overlooking the private good characteristics of reliability are also likely to lead to inefficient outcomes. Reliability is both a public good and a private good, a composite good with dimensions involving both system security and commodity delivery.

The primary fallacy in the traditional public good/externality argument is that it ignores the direct comparison that an individual supplier makes between the marginal private benefit he or she gains and the marginal private cost of the additional unit of the public good. Regardless of whether others contribute or free ride, if that supplier's marginal benefit is at least as great as the marginal cost, then the supplier *will* provide that additional unit, unless the supplier chooses to behave strategically to try to induce payment by others to reduce his or her own private costs.

Unlike the traditional treatment of public good market failure, we are unlikely to see the infinite reversion of public good provision to zero if enough providers are willing to incur the costs to receive the benefits, or if a few providers have intense enough preferences that they will provide the good regardless of the actions of others. The remaining important policy question is whether or not the marginal benefits that are not reflected in the supplier's choice would change the supplier's decision. Only in the cases where they would change that decision should the effect be considered potentially policy relevant.

The standard public good argument fails to make this distinction between relevant and irrelevant externalities.[8] Take an example of an environmental amenity – the view of a forest on an island by passing ships.[9] The view is a public good, so the standard conclusion is that the island's owner would underprovide forest relative to other uses of the land, such as pasture for beef cattle (an economic commodity). Thus to achieve the optimal level of forest to reflect the benefits to bypassing ships, the island's owner should be subject to land use regulation that increases the amount of forest beyond what she would choose independently, and the passing ships should be taxed to pay for the increase in forest acreage.

However, consider the fact that the island's owner has preferences over both the financial and the non-financial benefits of the land use. She may place high (marginal and total) value on the view (and smell and sound and fauna habitat) of the forest. How likely is it that the preferences (marginal benefits) of those on the passing ship will be higher than the owner's? Only if the marginal benefit of an additional acre of forest is higher for the ship passengers than for the owner, and the transaction costs are high enough to prevent them from negotiating with the owner, will Samuelson's argument hold. That special case is the only case in which free riding is economically relevant.

The crucial distinction between policy-relevant and policy-irrelevant externalities rests on the difference between total benefit and marginal benefit. In order for an externality to be relevant, or to influence the optimal amount of the public good, the marginal benefit of the party not being considered in the decision has to be positive. In other words, just because LSE_A benefits from LSE_B's investments in reliability, that positive externality is not sufficient reason for LSE_A to pay toward LSE_B's investment. LSE_A's *marginal benefit*, not total benefit, has to be positive at the reliability level that LSE_B provides in order for LSE_A's preferences to make a difference. The crucial question is: at the level of reliability that LSE_B has provided (where, presumably, LSE_B's marginal benefit is nonnegative), is LSE_A's marginal benefit positive? If not, then LSE_B's reliability provision is enough for LSE_A, and if LSE_A is required to pay LSE_B it is simply a transfer of surplus from LSE_A to LSE_B.

Thus the policy-relevant case is one in which LSE_A's marginal benefit is still positive at the level of reliability that LSE_B's investments have provided. Now suppose that LSE_A's marginal benefit is small, smaller than the incremental cost of providing additional reliability through a centrally planned regulatory framework. Then the least-cost way for LSE_A to get the reliability it wants is to enable LSE_A to take small actions on its own that will satisfy its preferences for additional reliability, such as offering interruptible contracts and/or installing decentralized voltage management technology. But the transaction costs of increasing reliability through a centralized institution, such as long-term capacity auctions, may be high enough to leave LSE_A dissatisfied and unable to get that small, incremental amount of reliability benefit.

Now suppose that LSE_A's marginal benefit after LSE_B's actions is positive and large. Then LSE_A would benefit from investing in reliability, and would do so up to the point that

---

[8] This crucial distinction, long overlooked in public policy, was first articulated by Buchanan and Stubblebine [1].

[9] Haddock [8].

equalizes LSE_A's marginal benefit and marginal cost from the incremental investment. In other words, incremental investments in reliability need not be subject to underprovision simply because others are simultaneously investing.

The preceding analysis relies on two assumptions that differ from the assumptions that typically underlie simple public goods analysis – that agents have homogeneous preferences, and that agents necessarily consume the same amount and quality of the public good. Instead, we have assumed that agents have a variety of preferences for the public good and we have assumed that reliability levels can differ across the grid. It is worth examining these two points more explicitly.

An LSE's demand for grid reliability, like its demand for power, are derived demands that arise from the end-use demands of the LSE's customers. Some of these customers will be very tolerant of variations in power quality and power supply interruptions, and some customers will be less accepting of power problems. At the retail residential level the difference may be as simple as one customer has gas heater rather than electric, and a wind-up alarm clock, while another is all-electric for both heater and alarm clocks. A mid-winter power interruption might only mildly inconvenience the first customer, while the second customer's life could be seriously disrupted. At the commercial and industrial levels, the financial stakes will be much higher and the range of risk exposure much greater. Variation among end-use consumer exposure to risks from network-based disruptions will lead to variation among LSE preferences for the public good.

The second assumption – that reliability can differ across the grid – is in some respects saying no more than grid reliability is not a pure public good. While at first glace it may appear that all network users are in the same boat, metaphorically speaking – after all, the network is either working or it is not – turns out to be an oversimplified approach. Consider the August 14, 2003 blackout in the Midwestern and northeastern United States and parts of Canada. Despite being the largest such network failure in history, the network failure was in some respects contained. While service was out for many millions of customers, several million more customers continued to receive service.

Much of the impetus for our work arises from the realization that network reliability does differ across the grid. Such a realization opens up the analysis such that we can look at policies that contribute to more or less network reliability at particular places, we can examine how actions taken by producers and consumers connected to the grid add to or subtract from reliability (both for themselves and for their neighbors on the network), and we can compare efforts to improve grid reliability to a fuller range of alternatives that consumers face in making trade-offs between power consumption, need for reliable service, and overall expense.

Of course, our "realization" that network reliability differs across the grid is not news to the engineers and managers working with the grid on a day-to-day business, nor likely to anyone else. The point has been underemphasized in policy discussions. We are making this connection in order to develop the implications of this difference in demand for reliability, and to better apply the economics of public goods and externalities to understanding reliability policy.

V. MODELING NETWORK RELIABILITY

If the n agents have heterogeneous preferences over reliability, then some will prefer more reliability, some will prefer less reliability, and those who prefer less will be satiated at lower levels. Thus their free riding on the incremental investments of the high-value agents is economically irrelevant to the optimal level of provision.

The concepts of irrelevant externalities and heterogeneous agents have implications for the models used to analyze externality and public good problems. Recall the standard specification used above for an agent's value function, $V_i = V_i(X_i,Y)$. This model assumes that the agent has preferences only over individual consumption of the private good and aggregate provision of the public good. However, if reliability has private good characteristics as well as public good characteristics, that specification assumes away the agent's preference over his or her own provision of the public good. In other words, if reliability is both a private and a public good, then an agent will care about both her own provision and the aggregate provision:

We model this distinction by applying a state-contingent model of grid reliability, following Joskow and Tirole (2004) [10]. Suppose n load-serving entities (LSEs) are agents on a shared electric power network. Each LSE has a (net) value function V_i, where

$V_i = V_i(X_i,Y)$

X_i is the private (numeraire) good

Y is the network good, $Y=Y(y_i,Y_j)$, where $Y_j = \Sigma_j y_j$, $j \neq i$

Furthermore, Y is a variable that can take on two states: with probability α it is in a good state, Y*, and with probability $(1-\alpha)$ it is in a bad state, _. Notice that the risk exposure of the agent to network failure can be seen as the difference between Y* and _.

Suppose also that LSEs are legally responsible for both components of the composite good, reliability; they are responsible for both delivery of the commodity to the end user and maintenance of the voltage, frequency and stability of the network.

Given this general setup we can consider several cases for modeling the interaction of agent choices and reliability on the network.

A. *Case 1: The pure public good model*

$V_i = V_i(X_i,Y)$

$Y = \alpha Y^* + (1-\alpha)\_$

Think of α as exogenously determined and common to all LSEs on the network. While regulators (and power system engineers) might see this as the ideal state, and the underpinning of the move toward mandatory uniform standards, it is physically unrealistic and ignores the very real fact that each agent can have some effect on the probability of a network outage.

First order conditions for y_i, Y_j:

$$\partial V_i/y_i = \alpha\partial Y^*/\partial y_i + (1-\alpha)\partial\_/\partial y_i$$

$$\partial V_i/\partial Y_j = \alpha\partial Y^*/\partial Y_j + (1-\alpha)\partial\_/\partial Y_j$$

Interpretation: given exogenous α, if y_i and Y_j have symmetric effects on Y, they are perfect substitutes, which then leads to incentives to free ride and underprovision of reliability

B. *Case 2: Agents experience different values of Y and can affect outage probability*

At the other extreme from the pure public good assumption and homogeneous agents, we can assume that the probability of network failure varies across agents, and that agents can have differing rates of exposure to network failure. In this formulation, agents can explicitly influence the level of local reliability and degree of exposure to the risk of network failure.

The value function then becomes

$$V_i = V_i(X_i,Y_i)$$

$$Y = \alpha_i Y^*_i + (1-\alpha_i)\_{}_i$$

First order conditions:

$$\partial V_i/\partial y_i = [\alpha_i(\partial V_i/\partial Y^*_i)(\partial Y^*_i/\partial y_i) + Y^*_i(\partial\alpha_i/\partial y_i)] + [(1-\alpha_i)(\partial V_i/\partial\_{}_i)(\partial\_{}_i/\partial y_i) + \_{}_i - \_{}_i(\partial\alpha_i/\partial y_i)] \qquad (3)$$

$$\partial V_i/\partial Y_j = [\alpha_i(\partial V_i/\partial Y^*_i)(\partial Y^*_i/\partial Y_j) + Y^*_i(\partial\alpha_i/\partial Y_j)] + [(1-\alpha_i)(\partial V_i/\partial\_{}_i)(\partial\_{}_i/\partial Y_j) + \_{}_i - \_{}_i(\partial\alpha_i/\partial Y_j) \qquad (4)$$

In equilibrium, (3)=(4):

$$(1-\alpha_i)(\partial V_i/\partial\_{}_i)[\partial\_{}_i/\partial Y_j - \partial\_{}_i/\partial y_i] - \alpha_i(\partial V_i/\partial Y^*_i)[\partial Y^*_i/\partial y_i - \partial Y^*_i/\partial Y_j] = (Y^*i - \_i)(\partial\alpha_i/\partial y_i - \partial\alpha_i/\partial Y_j)$$

Rewrite this expression as

$$\alpha_i(\partial V_i/\partial Y^*_i)(\partial Y^*_i/\partial y_i - \partial Y^*_i/\partial Y_j) + (1-\alpha_i)[(\partial V_i/\partial\_{}_i)[\partial\_{}_i/\partial y_i - \partial\_{}_i/\partial Y_j] = -(Y^*i - \_i)(\partial\alpha_i/\partial y_i - \partial\alpha_i/\partial Y_j) \quad (5)$$

Ideas about signs:

1. It's reasonable to think that $\partial V_i/\partial Y^*_i < \partial V_i/\partial\_{}_i$, based on diminishing marginal utility as noted above.

Note that if the ratio of the marginal values is >1 by assumption, then the ratio of the relative effects of LSE_i's contribution to the network in the two states is less than the ratio of the probabilities of the two states.

In standard price theory we would say that the inframarginal agents have captured consumer surplus. Why, then, when modeling the inframarginal agents in the market for network reliability, do we model these same agents as free riders? We should only consider their free riding to be a problem if the incremental preferences of those agents over the public good are decision-relevant. Only then, and only in the presence of sufficient transaction costs to prevent negotiation, will a lack of reflection of their preferences in the ultimate choice lead to underprovision.

If it is possible, or even highly likely, that there are enough risk-averse agents in an electricity network to ensure optimal reliability without central planning, then enshrining a central planning mandate in federal policy can be inefficient, or even counterproductive. A more robust and flexible approach may be to hold all network agents jointly and severally legally liable for any lapses in reliability. Technology has made it easier and cheaper to discern whose actions, or inactions, have contributed in what way to a reliability failure. Such decentralized liability and responsibility would deter network agents from free riding. Legal liability would make network agents more risk averse, thus making network reliability less prone to free riding. Legal liability rules governing risk-averse agents are a decentralized institutional alternative to an inflexible central planning framework that is prone to creating costly excess reliability.

Agents with high marginal values will invest, agents with low marginal values will not and will free ride, but so what? At the margin, these are the efficient responses. Taking into account transaction costs and information costs, a bureaucratic response mandating a single level of reliability and using centralized institutions to bring it about is likely to result in an inefficient level of reliability and more costly provision than using decentralized incentives and contractual approaches to enable high marginal value agents to invest in network reliability.

VI. POLICY EXAMPLE: PRIORITY INSURANCE

While we have discussed why agents on the grid may have differing preferences for network reliability, we have said little about how such preferences can be expressed by consumers and integrated into grid reliability decision-making. Priority insurance is one approach that has been proposed to make the connection between preferences and reliability choices on the grid.[10] A distribution level example will be provided, but with the appropriate changes that approach can be employed at the wholesale level as well.

Typical retail rate regulation provides consumers with a relatively flat rate, and little ability for consumers to influence the level of reliability provided on the system beyond calling the electric distributor when there is an outage. In particular,

---

[10] See, for example, Chao and Wilson [2]; Chao and Peck [3]; and Fumagalli *et. al.* [7]. As compared to the first two listed articles, the Fumagalli, *et al.* article places relatively more emphasis on both the practical value of a priority insurance program and a number of obstacles that would have to be addressed prior to implementing such a system.

there is little ability for a consumer to provide an incentive to the distributor to improve reliability, if the consumer wants more reliability at the present embedded cost of provision, or to reduce reliability if the consumer feels it is costing too much. In addition, many of the costs of system outages are incurred by the end-use consumer, even though they have little direct influence over reliability decisions.

The essence of priority insurance is to have the distribution company pay consumers when the lights go out. A simple idea, but they add a twist: the electric company offers different qualities of service. For a higher price, you get a lower probability of being cut off when the system is short of power (and a higher payment from the electric company when the lights go out); pay a lower price, get a higher probability of being cut off (and a lower payment). Customers would be able to choose between price and reliability. When the embedded premiums are set appropriately, as discussed in the cited articles, each customer class can be assured of being no worse off than before, and they can be better off than before.[11]

While one benefit of Priority Insurance approach is that allows the electric company to allocate a shortage efficiently, a bigger payoff comes from the information created through consumer actions. Because the choices of consumers provide information about values for energy and service reliability, the company can target investments where the can provide the most value. Because of the differing payoff and premiums paid by consumers, the company would also face incentives to invest in the grid where it would provide the most value.

VII. POLICY CONCLUSION

The electric power network is a complex interaction of human agents and physical interconnections, with many real-time characteristics and constraints. It is precisely this interaction of the human and the physical that makes the integration of markets into networks so crucial. Markets are a key human institution for making this complex system into a complex adaptive system. The rules governing the use of such a network can exploit these decentralized, distributed resources and incentives to enhance the stability and reliability of the grid. However, mandatory uniform reliability standards and legacy reserve margin requirements do nothing to take advantage of the very real fact that human agents on the network have diverse preferences over their use of the network.

Our analysis suggests that even network reliability (the portion of reliability capturing the voltage, frequency and stability conditions of the network) is both a congestible public good and a private good. The importance of locational interaction and the increasing ability to use technology to manage voltage in a decentralized manner reinforces this conclusion. Furthermore, the public good characteristics of network reliability may not necessitate cost sharing or some other centralized approach, because the heterogeneity of agent preferences and the private good aspects of reliability may make the public good characteristics an irrelevant externality. In fact, attempts to mandate cost sharing can themselves lead to inefficient outcomes in complex dynamic systems, particularly where the boundary between the public good aspects and the private good aspects differs across agents and shifts dynamically over time.

A more contractual approach to the electric power network, rather than the legacy regulatory approach of uniform standards and reserve margins, can take advantage of agent heterogeneity, and can also increase the transparency of property rights assignment. One particular application of a contractual approach, namely priority insurance, holds great promise for harnessing the decentralized preferences and incentives of network agents to enhance network stability and reliability.

Given these conclusions, a more dynamic and constructive policy approach to network reliability is to use the heterogeneous and locational characteristics of reliability to bolster system and grid security and stability. A system of priority insurance (or reliability insurance) would do just that, recognizing reliability as a differentiated product from the point of view of end-use customers and the load-serving entities selling services to them.

VIII. DIRECTIONS FOR FUTURE RESEARCH

The analysis we present is largely preliminary, and based on a general understanding of power system operations. The necessary next steps for this line of research include:

- Developing the theoretical treatment of our transactional approach to understanding network reliability by working through examples in the context of an optimal power flow system;
- Exploring the theory further through simulations and economic experiments conducted in networked systems; and,
- Complementing the theoretical and experimental work through empirical studies of power systems reliability that focus on the underlying economic incentives governing contributions to system reliability.

In priority insurance, empirical studies can help us understand whether and how much better off consumers would be when such a system is implemented. Beyond the priority insurance concept, empirical research will be needed to give a deeper understanding of how the actions of many agents on the grid interact to produce system reliability. One prepatory step necessary for such research is getting beyond the oversimplified view of reliability as a public good that seems to underlie many policy discussions.

REFERENCES

[1] Buchanan, James and Craig Stubblebine, "Externality" *Economica* 29 (1962), pp. 371-384.

[2] Chao, Hung-Po and Robert Wilson, "Priority Service: Pricing, Investment, and Market Organization," *American Economic Review*, Vol. 77, No. 5 (Dec. 1987), 899-916.

[3] Chao, Hung-Po and Stephen Peck, "Reliability Management in Competitive Electricity Markets," *Journal of Regulatory Economics*, 13:189-200 (1998).

[4] Cornes, Richard and Todd Sandler, *The Theory of Externalities, Public Goods, and Club* Good, 2nd Edition (Cambridge University Press: 1996).

---

[11] The significant question is empirical: How much better off can consumer become, and how certain can we be that consumers will be sufficiently better off. As noted in the last section below, this is among the areas in which added research is needed.

[5] Richard Cowart, et al., "Efficient Reliability: The Critical Role Of Demand-Side Resources In Power Systems And Markets," Regulatory Assistance Project, June 2001.

[6] Cowen, Tyler, ed., *Public Goods & Market Failures: A Critical Examination*, (Transaction Publisher: 1992)

[7] Fumagalli, Elena, Jason W. Black, Marija Ilic, and Ingo Vogelsang; "Quality of Service Provision in Electric Power Distribution Systems Through Reliability Insurance," *IEEE Transactions on Power Systems*, Volume 19, No. 3 (August 2004) Pages: 1286 – 1293.

[8] Haddock, David, "Irrelevant Internalities, Irrelevant Externalities, and Irrelevant Anxieties" Law & Economics Research Paper 03-16, Northwestern University Law School, 2003. Available through SSRN at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=437221.

[9] Joskow, Paul, "Restructuring, Competition and Regulatory Reform in the US Electricity Sector," *Journal of Economic Perspectives*, Vol. 11, No. 3. (Summer, 1997).

[10] Joskow, Paul, and Jean Tirole, "Reliability and Competitive Electricity Markets," October 2004. Available at http://econ-www.mit.edu/faculty/download_pdf.php?id=917.

[11] Musgrave, Richard, "Cost-Benefit Analysis and the Theory of Public Finance," *Journal of Economic Literature* 7 (1969), pp. 797-806.

[12] Oren, Shmuel S., "Ensuring Generation Adequacy in Competitive Electricity Markets" (June 3, 2003). University of California Energy Institute. Working Paper EPE-007.

[13] Oren, Shmuel S., "Market Based Risk Mitigation: Risk Management vs. Risk Avoidance", Proceedings of a White House OSTP/NSF Workshop on Critical Infrastructure Interdependencies held in Washington DC, June 14-15, 2001.

[14] Pigou, A. C., *The Economics of Welfare*. London: Macmillan, 1920.

[15] Samuelson, Paul A., "The Pure Theory of Public Expenditure," *Review of Economics and Statistics* 36 (1954), pp. 387-398.