ECE 588 – Electricity Resource Planning

17. Reliability Economics

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This topic explicitly discusses the worth and costs of reliability: we take for granted that reliability is important, but, we also need to explicitly evaluate its economic aspects.

The efforts aimed to ensure reliability incur large costs; such expenditures must be commensurate with the value reliability provides to all customers, who pay for electricity services.
INTEREST IN RELIABILITY WORTH

- Example of a utility with a historical peak load of 20,000 MW and total installed capacity of 23,000 MW load:
  - Projected annual growth of 2% entails the addition of more than 400 MW each year to the supply system
  - A 1% surplus – 200 MW – in the reserve margin entails over $12 million/year additional expenditures, which, unless borne by the customers, must be covered by the shareholders
INTEREST IN RELIABILITY WORTH

As the electricity industry finds itself in the increasingly competitive environment, electricity companies must concern themselves with the market value of the services they provide as well as the costs to provide those services.
INTEREST IN RELIABILITY WORTH

- Investments in demand– and supply–side resources to meet the utility’s obligation to serve must, consequently, be valued in terms of their reliability worth, as well as, the incurred costs; such an evaluation requires an explicit cost/benefit analysis to determine the appropriate level of system reliability.
INTEREST IN RELIABILITY WORTH

- The assessment of the cost-effectiveness of resource investments requires the economic evaluation of reliability to permit utilities to plan for levels of reliability commensurate with the customers’ willingness to pay.

- The reliability indices in use – deterministic or probabilistic – fail to account for the costs of providing a given level of service reliability.
Moreover, the criteria fail to consider customer preferences regarding reliability and costs:

- criteria are arbitrary
- criteria cannot evaluate the optimal level of reliability and therefore cannot provide an economic balance of reliability worth and the costs to achieve the reliability

Example: should the LOLP criterion of one day in ten years be considered as the minimum acceptable level of risk or as the maximum acceptable risk level?
RELIABILITY CRITERIA IGNORE ECONOMICS

cannot evaluate the economic impacts of different levels of reliability

criterion not based on economics may tip the scale in an undesired direction
We use a generic reliability measure $\rho$

$\rho$ may be a proxy for any of the following metrics:

- $\text{LOLP, LOLE or LOLH}$
- $\mathcal{U}$ : expected unserved energy
- $C_0$ : outage costs : $MW$ reserves
- $C_N - \ell_{\text{peak}}$
COSTS AND RELIABILITY

\[ \rho^* = \text{value of reliability measure corresponding to the least value of } C_S + C_O \]

Supplementary Costs
- Supply costs: \( C_S \)
- Outage costs: \( C_O \)

Total costs:
\[ C_S + C_O \]

Diagram:
- Lower reliability\( \rho^* \)
- Higher reliability\( \rho \)
- Costs axis
- Reliability axis
THE BASIC OBJECTIVE

the establishment of an economic basis for the selected reliability criterion so as to balance the marginal costs with the marginal benefits of reliability
THE BASIC APPROACH

- Measurement of the **reliability worth** in terms of customer outage costs
- Integration of the reliability worth information into the resource planning framework through the explicit incorporation of customer choices concerning reliability worth and service
- Determination of the **optimal** level of reliability for the utility and customers
THE OPTIMAL INVESTMENT DECISION PROBLEM

- Find the resource mix that minimizes the total costs over the planning horizon subject to the constraints

\[ \mathcal{C}_{\text{total}} = \mathcal{C}_s + \mathcal{C}_o \]

- **Total costs**
  - **Supply costs**: \( \mathcal{C}_s \)
  - **Outage costs**: \( \mathcal{C}_o \)

- **Capital investment and production costs to supply energy**
- **Customer outage costs incurred due to energy not supplied**
THE OPTIMAL INVESTMENT DECISION PROBLEM

The graph shows the relationship between costs and reliability. The costs are plotted on the y-axis, and the reliability metric is plotted on the x-axis. The graph includes three curves:

- $C_{\text{total}}$: Total costs.
- $C_s$: Costs associated with a specific reliability metric.
- $C_o$: Costs associated with another reliability metric.

The optimal reliability metric, $\rho^*$, is the point where the total costs are minimized. This occurs between the lower and higher reliability levels.
THE OPTIMAL INVESTMENT DECISION PROBLEM

- $\mathcal{C}_{total}$ is optimal at $\rho^*$; then, the necessary condition of optimality is

$$
\frac{\partial \mathcal{C}_{total}}{\partial \rho} \bigg|_{\rho^*} = \frac{\partial \mathcal{C}_s}{\partial \rho} \bigg|_{\rho^*} + \frac{\partial \mathcal{C}_o}{\partial \rho} \bigg|_{\rho^*} = 0
$$

so that

$$
\frac{\partial \mathcal{C}_s}{\partial \rho} \bigg|_{\rho^*} = - \frac{\partial \mathcal{C}_o}{\partial \rho} \bigg|_{\rho^*}
$$
THE OPTIMAL INVESTMENT DECISION PROBLEM

- We interpret \( \frac{\partial c_s}{\partial \rho} \) as the marginal costs of additional reserves and \( - \frac{\partial c_o}{\partial \rho} \) as the marginal benefits of additional reserves; therefore,

\[
\text{marginal costs of additional reserves} \bigg|_{\rho^*} = \text{marginal benefits of additional reserves} \bigg|_{\rho^*}
\]
The control variables are the installed capacity $C_N$ and the load magnitude $\ell$.

The dependence of $\epsilon_o$ and $\epsilon_s$ on $C_N$ is such that

$$C_N \uparrow \Rightarrow \begin{cases} \epsilon_s \uparrow \\ \epsilon_o \uparrow \end{cases} \quad \text{and} \quad C_N \downarrow \Rightarrow \begin{cases} \epsilon_s \downarrow \\ \epsilon_o \downarrow \end{cases}$$

The dependence of $\epsilon_o$ and $\epsilon_s$ on $\ell_{peak}$ is precisely in the opposite direction to that of $C_N$. 
Any additional investment in reliability cannot be made because the reductions in outage costs and operating expenses are exceeded by the investment costs.

Any lesser investment cannot be made because the savings in investment costs are outweighed by the benefits of reduced outage costs and operating expenses.
Recall that

\[ R = A_{\text{total}} - L \]

The IELDC provides the values of the LOLP and
EVALUATION OF MARGINAL TERMS

- $\mathcal{U}$ is a function of $r$, the value of the reserves

- $\mathcal{U}$ has the property that

$$r \uparrow \Rightarrow \mathcal{U}(r) \downarrow \quad \text{and} \quad r \downarrow \Rightarrow \mathcal{U}(r) \uparrow$$

- Let $s$/MW be the *marginal costs of capacity* – typically, these are taken to be the costs of the gas turbines added to improve reliability; we assume in this discussion that such
turbines have very small, if any, impacts on operating costs and so we ignore such impacts.

- At the optimum $r^*$ we require

$$s = d \left( r^* \right) q$$

where

$$d \left( r^* \right) = \left. \frac{\partial \mathcal{U}}{\partial r} \right|_{r^*}$$

and

$$q = \text{marginal outage costs in } \$/\text{MWh}$$
EXPECTED UNSERVED ENERGY

\[ P \{ R \leq r \} \]

original system + \( \Delta r \)

\( \Delta r \) increase in reserves

LOLP

available reserves (MW)

decrease \( \Delta \mathcal{U} \) in \( \mathcal{U} \)
Demand cannot be served whenever reserves fall below zero

LOLP is the probability that the reserves fall below zero

We may view LOLP as the expected fraction of time in a given period that load will not be served
Consider the analytical computation of \( \frac{\partial \mathcal{U}}{\partial r} \) at any value of \( r \)

\[
\frac{\partial \mathcal{U}}{\partial r} = \lim_{\Delta r \to 0} \frac{\mathcal{U}(r + \Delta r) - \mathcal{U}(r)}{\Delta r}
\]

We have shown that

\[
\frac{\partial \mathcal{U}}{\partial r} = \frac{\partial \mathcal{U}}{\partial C_N} = -T \cdot LOLP
\]
EXPECTED UNSERVED ENERGY

- In actual operations, a utility invokes control actions, such as *emergency* or *remedial actions*, prior to the fall to \( \theta \) operating reserves.

- We define a control action to be a load reduction measure deployed in operations in an attempt to forestall the system from a transition into a deficiency state (loss of load or *l.o.l.* event).
The rationale for control actions is to alleviate the system deficiency problems via the provision of certain load relief measures with the objective to avert a l.o.l. condition.

The deployment of control actions is operator controlled with the triggering dependent on the operating reserve levels.
TYPICAL CONTROL ACTIONS

- Disconnection of interruptible loads
- Appeals for load curtailment by large industrial customers
- Public appeals for curtailment by residential, commercial and agricultural customers
- Voltage reduction
- Load shedding
CONTROL ACTIONS

- We associate with each control action a load relief capacity $c_i$ whose dispatch results in lessening the $\mathcal{U}$ by an amount $\mathcal{E}_i$, where we define

  $$\mathcal{E}_i = \text{energy "supplied" by the control action } i$$

- An example of such a control action is the disconnection of the interruptible loads whenever the operating reserves fall below the 5% level.
ENERGY RELIEF FROM CONTROL ACTIONS

$P \{ R \leq r \}$

capacity of control action $i$

$\frac{\mathcal{E}_i}{T}$

available reserves (MW)

0

decrease of the expected unserved energy by $\mathcal{E}_i$

results from invoking the control action $i$
ENERGY RELIEF FROM A SEQUENCE OF CONTROL ACTIONS

\[ P \{ R \leq r \} \]

expected unserved energy

stage 3 energy relief

\begin{align*}
&0 \quad 1.5\% \text{ of peak} \\
&5\% \text{ of peak} \\
&7.5\% \text{ of peak} \\
\end{align*}

available reserves \((MW)\)

stage 1 & 2 energy relief

\{ PR r \leq ! \}
ENERGY RELIEF

For each control action $i$, we associate a load relief capacity $c_i$ and energy “supplied” $\mathcal{E}_i$, $i = 1, 2, \ldots, I - 1$; we denote by $I$ the control action for the implementation of rotating outages – the last resort control action before a blackout.

Then, we represent by

$$\mathcal{U}^\text{dec} = \sum_{i=1}^{I} \mathcal{E}_i$$

the decrease in $\mathcal{U}$ and so the rate is

$$d(r) = \frac{\partial \mathcal{U}^\text{dec}}{\partial r} = \sum_{i=1}^{I} \frac{\partial \mathcal{E}_i}{\partial r} = \sum_{i=1}^{I} d_i(r)$$
We can evaluate the partials \( \frac{\partial \mathcal{E}_i}{\partial r} \) either analytically or by block differencing.

To evaluate the costs involved in the dispatch of the control actions, we require the costs/unit \( q_i \) expressed in \$/MWh of energy “supplied” by the control action \( i \) and those of the expected unserved energy during rotating outages.
ENERGY RELIEF

- At the optimum $r^*$,

$$s = \sum_{i=1}^{I} q_i d_i (r^*)$$

where the $d_i (r^*)$ are evaluated in a straightforward way using either probabilistic production costing or reliability analysis approach.
\( \Delta \varepsilon_i \) is the decrease in control action relief due to an increase \( \Delta r \) in the reserves.
IMPACTS OF AN OUTAGE

- Disruption
- Inconvenience
- Discomfort
- Annoyance
- Health and safety effects
- Out-of-pocket costs
- Damage and spoilage
We deduce the “worth” of reliability from the customer costs incurred due to the unavailability of electric service.

Examples of these costs include:

- lost industrial production
- lost sales revenue
- food spoilage
- loss of leisure time; inconvenience
OUTAGE ATTRIBUTES

- Frequency
- Duration
- Magnitude
- Timing
- Warning [advance notice]
- Cause
- Geographic spread

Outage experience has major impact on the results obtained for customer outage costs.
## ESTIMATES OF OUTAGE COSTS ($/kWh)

<table>
<thead>
<tr>
<th>Type</th>
<th>Typical Range</th>
<th>Median Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>0.50 – 5</td>
<td>1.00</td>
</tr>
<tr>
<td>Industrial</td>
<td>2 – 20</td>
<td>5</td>
</tr>
<tr>
<td>Commercial</td>
<td>5 – 35</td>
<td>10.00</td>
</tr>
</tbody>
</table>

Source: EPRI, PG&E and Ontario Hydro
IMPACTS OF SERVICE INTERRUPTIONS
DETERMINE OUTAGE COSTS

- Idle/underutilized productive resources in terms of
  - labor
  - capital
  - enterprise
- Spoilage and damage
- Restart costs
- Social costs
Residential customers perceive the value of electric service reliability according to the importance they attach to having electricity available for meeting their temporal requirements for lighting, space conditioning, washing, meal preparation, cleaning, safety and relaxation.
MEASUREMENT TECHNIQUES FOR OUTAGE COSTS

- Proxy methods
- Market-based methods
- After-the-fact measurements
- Survey methods
PROXY METHODS

- Use some measure of electricity service or the impacts of such service to indirectly measure outage costs; results provide an upper and/or lower bound for outage costs.

- Examples of typical measurements include:
  - the ratio of area output to electricity consumption
  - the value of lost leisure evaluated at wage rates
  - the costs of backup generation
STUDY OF ITEMS PURCHASED TO RESPOND TO OUTAGES

- **backup generators**: 2%
- **surge protector/power conditioners**: 15.7%
- **battery backup**: 34.1%
- **candles and flashlights**: 92.5%
- **no items**: 3.6%

Source: Florida Power & Light for EPRI RP2878-1

Percent of respondents (total sample of 1065)
MARKET–BASED METHODS

- Examine actual customer behavior in response to various service options or investments in reliability to infer customer outage costs.
- A good example is the use of historical data that provide price elasticity of demand to derive a demand function for electricity: an outage reduces the quantity supplied without a corresponding price increase so that an estimate of the outage costs is obtained from the consumer surplus.
MARKET–BASED METHODS

price
$/MWh

ρ'
ρ

outage maintains
price at ρ
and does not
raise it to ρ'

lost consumer
surplus

ρ

outage causes
demand to
decrease

Q'
Q

MWh demanded

ρ

reduction in
consumer
surplus when
demand Q – Q'
is not served

lost consumer
surplus = reduction in
consumer surplus when
demand Q – Q’ is not served

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Another example is the use of historical data on customers who sign up for non-firm service to infer the costs of differentially reliable service.
MARGET–BASED METHODS

use the parametric results of the plots of price vs. quantity at different reliability levels to plot the price vs. reliability index
AFTER-THE-FACT MEASUREMENT METHODS

- Measure the impacts of outages that have actually occurred: for example after the second New York blackout, a study was commissioned by the government and performed by a consultant whose detailed report, “Impact Assessment of the 1977 New York City Blackout” gave a large list of such impacts.

- *Ex post* analysis may be very thorough and detailed; however, such analysis has a greater lack of generality than other techniques.
SURVEY METHODS

- Use customer responses to postulated outage scenarios to measure outage costs; basic approach is described in detail in the paper by R. Billinton and G. Wacker, *Proceedings of the IEEE*, Vol. 77, No. 6, June 1989

- Aim to find answers to some basic types of questions such as:
SURVEY METHODS

- **direct costs:** what costs would the customer incur due to an outage of a specified duration with a specified warning time?

- **willingness to pay:** how much would the customer pay to avoid an outage of a specified duration with a specified warning time?
SURVEY METHODS

- Willingness: How much would the service provider have to pay the customer to accept an outage of a specified duration with a specified warning time?
SURVEY METHODS

° revealed would the customer prefer a preference: given level of service of reliability of, say, \( n \) outages/\( \text{year} \) at a given price or a higher level of reliability of, say, \( n - k \) outages/\( \text{year} \) at a higher price?
SURVEY METHODS

- Surveys have gained favor because they allow the service providers to focus on the particular needs of their customers and the unique outage and operating characteristics of their particular systems.

- Random samples are picked for each customer class to conduct separate surveys.
A direct costing procedure was used for this sector.

Firms were asked about various interrelated cost impacts caused by an outage, such as:

- lost sales, services or production
- energy, material and labor costs saved as a result of an outage
COMMERCIAL AND INDUSTRIAL SECTOR MEASUREMENT APPROACH

- energy, material, labor and other costs incurred due to idling that would result from an outage

- backup power costs

- restart costs

- extraordinary costs such as damage to plant or equipment due to an outage
### TYPICAL OUTAGE SCENARIOS IN THE COMMERCIAL & INDUSTRIAL SURVEYS

<table>
<thead>
<tr>
<th>scenario</th>
<th>season and day of the week</th>
<th>starting</th>
<th>duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>summer weekday</td>
<td>morning (9 a.m.)</td>
<td>under 1 minute</td>
</tr>
<tr>
<td>2</td>
<td>summer weekday</td>
<td>morning (9 – 9:15 a.m.)</td>
<td>15 minutes</td>
</tr>
<tr>
<td>3</td>
<td>summer weekday</td>
<td>morning (9 – 10 a.m.)</td>
<td>1 hour</td>
</tr>
<tr>
<td>4</td>
<td>summer weekday</td>
<td>morning and afternoon (9 a.m. – 1 p.m.)</td>
<td>4 hours</td>
</tr>
<tr>
<td>5</td>
<td>summer weekday</td>
<td>evening (5 p.m. – 9 p.m.)</td>
<td>4 hours</td>
</tr>
</tbody>
</table>

All scenarios involve total loss of load without advance notification.
## PG&E VALUE OF SERVICE SURVEY RESULTS

<table>
<thead>
<tr>
<th>customer class</th>
<th>partial outage costs (1990 $/kWh)</th>
<th>full outage costs (1990 $/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>residential</td>
<td>0.58</td>
<td>4.64</td>
</tr>
<tr>
<td>small and medium light and power</td>
<td>4.45</td>
<td>31.63</td>
</tr>
<tr>
<td>large light and power</td>
<td>1.55</td>
<td>10.77</td>
</tr>
<tr>
<td>agricultural</td>
<td>0.61</td>
<td>3.67</td>
</tr>
<tr>
<td>system weighted average</td>
<td>2.37</td>
<td>16.93</td>
</tr>
</tbody>
</table>
HOURLY INTERRUPTION COSTS ARE VARIABLE

<table>
<thead>
<tr>
<th>Industry Customer</th>
<th>Average Costs ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>brokerage operations</td>
<td>6,480,000</td>
</tr>
<tr>
<td>credit card operations</td>
<td>2,580,000</td>
</tr>
<tr>
<td>semiconductor manufacturer</td>
<td>2,000,000</td>
</tr>
<tr>
<td>airline reservation system</td>
<td>90,000</td>
</tr>
<tr>
<td>telephone ticket sales</td>
<td>72,000</td>
</tr>
<tr>
<td>cellular communications</td>
<td>41,000</td>
</tr>
</tbody>
</table>
PG&E LONG – TERM PLANNING RESERVE REQUIREMENTS

% of peak load

VOS

LOLP with hourly loads

LOLP with daily loads

16.2

18.2

22.5
SENSITIVITY OF OUTAGE COSTS

reserve requirements (% of peak load)

multiples of customer outage costs
SENSITIVITY OF THE OPTIMUM TO INCREASE IN THE SUPPLY COST

- marginal benefits of capacity
- new marginal costs of supply
- reference marginal costs of supply
- optimal reserve margin
- decrease in reserve margin at optimum
SENSITIVITY OF THE OPTIMUM TO INCREASE IN OUTAGE COSTS

- Marginal benefits of capacity increase in reserve margin at optimum
- New marginal costs of capacity
- Increase per unit customer outage costs
- Optimal reserve margin
- Increase in optimal reserve margin

Marginal costs vs. Reserve margin graph.
REFERENCES


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