Lessons from the 2010 Chilean earthquake and its impact on electricity supply

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Where is Chile?
Presentation Overview

- Chilean electricity market
- Earthquake in Chile
- Effects on generation and transmission
- Distribution damages and supply recovery
- Final remarks
## Chilean electricity market (1/5)

### Northern Interconnected System (SING)

<table>
<thead>
<tr>
<th>Max Demand (MW)</th>
<th>1,900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales (GWh)</td>
<td>13,656</td>
</tr>
<tr>
<td>Installed Capacity (MW)</td>
<td>3,573</td>
</tr>
<tr>
<td>Coverage</td>
<td>Region I - II</td>
</tr>
<tr>
<td>Population</td>
<td>5.7%</td>
</tr>
</tbody>
</table>

### Aysen System

<table>
<thead>
<tr>
<th>Max Demand (MW)</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales (GWh)</td>
<td>106</td>
</tr>
<tr>
<td>Installed Capacity (MW)</td>
<td>48</td>
</tr>
<tr>
<td>Coverage</td>
<td>XI Región</td>
</tr>
<tr>
<td>Population</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

### Central Interconnected System (SIC)

<table>
<thead>
<tr>
<th>Max Demand (MW)</th>
<th>6,139</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales (GWh)</td>
<td>39,964</td>
</tr>
<tr>
<td>Installed Capacity (MW)</td>
<td>11,147</td>
</tr>
<tr>
<td>Coverage</td>
<td>Region III - X</td>
</tr>
<tr>
<td>Population</td>
<td>92.6%</td>
</tr>
</tbody>
</table>

### Magallanes System

<table>
<thead>
<tr>
<th>Max Demand (MW)</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales (GWh)</td>
<td>218</td>
</tr>
<tr>
<td>Installed Capacity (MW)</td>
<td>80</td>
</tr>
<tr>
<td>Coverage</td>
<td>XII Región</td>
</tr>
<tr>
<td>Population</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
Chilean electricity market (2/5)

- Installed capacity and peak demand in Central System

- Projected demand growth of 5% per year 2010-2020

Arrival of natural gas imported from Argentina
Load contraction:
- high energy prices
- global financial crisis
Chilean electricity market (3/5)

- Electricity sector based on a competitive market
  - Private competitive investment in generation
  - Regulated private investment in T&D

- Energy
  - Prices set in contract auctions (financial)
    - Large consumers (> 2MW) privately auctioned supply contracts
    - Distribution companies auction long term supply contracts in an observed process for regulated consumers (≤ 2 MW)
  - Spot market with marginal pricing
    - Wholesale market with exclusive access to generators

- Capacity payment
  - Price regulated: investment cost of supplying the marginal peak demand
Chilean electricity market (4/5)

- Generation by technology and marginal costs (2007-2010)
  - Dependence on hydro and imported fuels
  - High volatility of marginal cost
  - Highest energy price in the region
Chilean electricity market (5/5)

- Installed capacity in the central system
  - Low non conventional renewables participation
  - High participation of large hydro, both run of river and reservoirs/dam
  - Natural gas is being replaced by coal fired plants and hydro
## Major earthquakes in Chile

<table>
<thead>
<tr>
<th>Year</th>
<th>City</th>
<th>Mag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1575</td>
<td>Valdivia</td>
<td>8.5</td>
</tr>
<tr>
<td>1730</td>
<td>Valdivia</td>
<td>8.7</td>
</tr>
<tr>
<td>1751</td>
<td>Concepcion</td>
<td>8.5</td>
</tr>
<tr>
<td>1835</td>
<td>Concepcion</td>
<td>8.5</td>
</tr>
<tr>
<td>1868</td>
<td>Arica</td>
<td>9.0</td>
</tr>
<tr>
<td>1906</td>
<td>Valparaiso</td>
<td>8.2</td>
</tr>
<tr>
<td>1922</td>
<td>Vallenar</td>
<td>8.5</td>
</tr>
<tr>
<td>1943</td>
<td>Coquimbo</td>
<td>8.2</td>
</tr>
<tr>
<td>1960</td>
<td>Valdivia</td>
<td>9.5</td>
</tr>
<tr>
<td>1985</td>
<td>Santiago</td>
<td>8.0</td>
</tr>
<tr>
<td>1995</td>
<td>Antofagasta</td>
<td>8.0</td>
</tr>
<tr>
<td>2010</td>
<td>Concepcion</td>
<td>8.8</td>
</tr>
</tbody>
</table>
Building codes and technical standards

- High standards for seismic requirements regarding civil works.
  - Building codes in Chile are substantially the same as US codes (ACI 318, American Concrete Institute).

- High voltage electrical facilities must obligatorily fulfill the ETG 1.015 Chilean standard or the IEEE 693 standard in the condition of High Performance Level.
  - It specifies a maximum 0.50 g acceleration
  - Maximum horizontal displacement of 25 cm.

- Specific electrical requirements for construction and maintenance of high voltage facilities
  - Technical Norm for Security and Quality of Service
  - Defines technical and economic evaluations to determine the reliability level for the planning and operation of the power system.
2010 earthquake in Chile

- 03:34 hrs. February 27 2010:
  - 8.8 Richter shakes 6 regions of Chile (80 % of population)
  - Tsunami hits the cost minutes after
- Death toll: 521
- Missing: 56
- Injured: 12,000
- Displaced: 800,000
- Infrastructure affected:
  - 370,000 houses
  - 4,013 schools
  - 79 hospitals
  - 4,200 boats damaged
- Economic loss: 30 billion US dollars
- GDP per capita: 14,340 US$
- Population: 17,000,000
Strong acceleration for a long period of time

- Peak acceleration of 0.65 g for one of the horizontal records
- 70 seconds duration
- Continental plaque was displaced 10 m in average
Earthquake effects: infrastructure collapse
Earthquake effects: large industrial fires
Earthquake effects: structural damage and collapse
Tsunami effects: larger cities
Tsunami effects: floodings smaller towns (Constitución)
Tsunami effects: large coastal areas
Tsunami effects: floodings smaller towns (Constitucion)
Immediate effects of the earthquake

- Immediate complete blackout for a 4,522 MW load
- Island scheme for grid supply recovery
  - Five Islands at first
  - Subsequently two islands
- Severe damage to distribution networks
Supply evolution before and after earthquake
Hourly load evolution after the earthquake

- Blackout with a load loss of 3,000 MW
- Slow recuperation of load over subsequent hours and days
Generation on the day of the earthquake

- 4,522 MW where dispatched at the moment the earthquake struck
Impact on operation

- Severe impacts on country’s communication systems.
  - Basic systems (mobile networks, emergency alert schemes, public order control) did not operate at all or as desired and caused additional harm.
- Difficulties also arose in the communications and telecontrol schemes of most transmission substations and power plants, complicating system recovery and operation.
  - No alternative backup radio systems.
- System operator (CDEC-SIC) had additional difficulties throughout the emergency
  - SCADA system in use (for over ten years), was not able to provide information required for system recovery (alarms could not be trusted as they were often incorrect).
- Land line phone calls had to be used to learn on local conditions and supervise actions for equipment and system restoration.
## Availability of generation facilities

<table>
<thead>
<tr>
<th>MW</th>
<th>Availability of generation facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,000</td>
<td>Unavailable immediately after the earthquake</td>
</tr>
<tr>
<td>2,257</td>
<td>Available within the next 30 days</td>
</tr>
<tr>
<td>693</td>
<td>Required major repairs</td>
</tr>
<tr>
<td>950</td>
<td>Under construction were also damaged</td>
</tr>
</tbody>
</table>

### Unavailability of generation units (MW)

![Graph showing unavailability of generation units (MW)](image-url)
Damage to generation plants

- Mainly thermal generation plants sustained damages
- Also important plants under construction suffered damages, delaying their commissioning
- Most common problems:
  - Cooling systems, transformers, communications, lines, etc

Coal plant chimney fractured
Transmission damages

- Damages concentrated in one transmission line
  - 3 towers from 154 KV line

- At substation level the damages were mainly focused at:
  - 500 kV bushings (high failure rate)
  - 500 kV pantograph disconnector switches
  - 220 kV circuit breakers (live tank type)
  - 154 kV circuit breakers (air compressed type)

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Damaged</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substations</td>
<td>46</td>
<td>12</td>
<td>26%</td>
</tr>
<tr>
<td>Transmission lines (km)</td>
<td>7,280</td>
<td>1.6</td>
<td>0.02%</td>
</tr>
</tbody>
</table>
Transmission damages

- Damage to transmission lines

Hualpen-Bocamina line (3 towers)

www.systep.cl
Transmission damages

- Substation damages
Transmission damages

➤ Substation damages
Transmission damages

- But most remained available

- Capacitor bank without damage
- Circuit breakers with sufficient damping
System recovery process

Recovery process of the interconnected system

<table>
<thead>
<tr>
<th>City</th>
<th>Event</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Earthquake</td>
<td>February 27</td>
<td>03:34</td>
</tr>
<tr>
<td>Santiago</td>
<td>Supply recovered</td>
<td>February 27</td>
<td>03:58</td>
</tr>
<tr>
<td>Temuco</td>
<td>Supply recovered</td>
<td>February 27</td>
<td>04:05</td>
</tr>
<tr>
<td>Copiapo</td>
<td>Supply recovered</td>
<td>February 27</td>
<td>05:05</td>
</tr>
<tr>
<td>La Serena</td>
<td>Supply recovered</td>
<td>February 27</td>
<td>06:35</td>
</tr>
<tr>
<td>Puerto Montt</td>
<td>Supply recovered</td>
<td>February 27</td>
<td>10:31</td>
</tr>
<tr>
<td>Rancagua</td>
<td>Supply recovered</td>
<td>February 27</td>
<td>14:46</td>
</tr>
<tr>
<td></td>
<td>Two islands interconnected</td>
<td>February 27</td>
<td>18:46</td>
</tr>
<tr>
<td>Concepción</td>
<td>Supply recovered</td>
<td>February 28</td>
<td>10:24</td>
</tr>
<tr>
<td>Talca</td>
<td>Supply recovered</td>
<td>February 28</td>
<td>11:38</td>
</tr>
</tbody>
</table>
Hourly spot price at bus bar close to epicenter (Charrua 220 kV)
Effects in distribution networks

- 4.5 million people were initially affected by the extended blackout.
- 80% of clients were without supply the day after the earthquake and this reduced to 0.4% two weeks after
  - Mainly in Concepcion and Talcahuano, next to the earthquake epicenter and tsunami.
- Some distribution networks were destroyed by the effects of the earthquake
  - Houses fell over street lines
  - Lines were washed away by the tsunamis
  - For example 40,000 houses were destroyed out of 1.5 million supplied by CGE).
- Besides those distribution installations directly damaged, there was little damage elsewhere.
Distribution: Evolution of clients without supply
Distribution: effects of earthquake

- Extended damage in distribution networks
Distribution: effects of earthquake

- Extended damage in distribution networks
Distribution: effects of earthquake

- Extended damage in distribution networks
Distribution: effects of earthquake

- Extended damage in distribution networks
Distribution infrastructure

Distribution poles in Chile are mainly compressed pre-stressed concrete poles, which are well founded, and support important mechanical stresses.

- Exceptions in overloaded poles in cities (telephone, cable TV, etc)

Distribution aerial transformers are often placed between two poles and a steel support, thus they also withstand well an earthquake.
Distribution infrastructure

- Distribution infrastructure still standing after earthquake and tsunami
Distribution infrastructure

- Heavily loaded poles in main cities
Main challenges restoring supply

- Main difficulties in restoring supply to houses took place at the connection point between the low voltage lines and the buildings.
- Companies have equipment and human resources to repair normal failures
  - But in an earthquake, the problem is quite different. Communication problems, difficult physical access to locations, no resources to manage the huge number of needed repairs. Companies involved human resources brought from other regions, even other countries.
- Mobile generating units brought to support recovery of supply, particularly in more isolated areas.
- Challenges for distribution companies lasted months after the earthquake
  - Many latent faults, caused by the quake, that could not be detected when repairs were been made days after the event, or if detected, were secondary to the objective of supplying consumers as fast as possible.
  - Arrival of winter, with rain and wind, started igniting these faults in a a massive way, demanding the companies to comply.
Equipment damage at distribution level

- Small proportion of distribution equipment was damaged

- 760,000 poles in CGE
- 300,000 poles in Chillectra
- 50,000 transformers in CGE
- 20,000 transformers in Chillectra.
Final remarks

- International experience confirms greater damage expected at transmission and distribution levels
- Generation and transmission infrastructure had an excellent response, confirming effectiveness of high technical standards
- Serious issues in communication made response phase very difficult
- Operational procedures must reviewed not to prevent blackout in case of a major earthquake, but to speed up system recovery.
- Must be careful to not overreact to low occurrence frequency events
- Economical analysis must be performed to assess preventive versus corrective investments
  - Failure cost
Further reading

- More information of the Chilean electricity market:
  - Publications
  - Monthly reports
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