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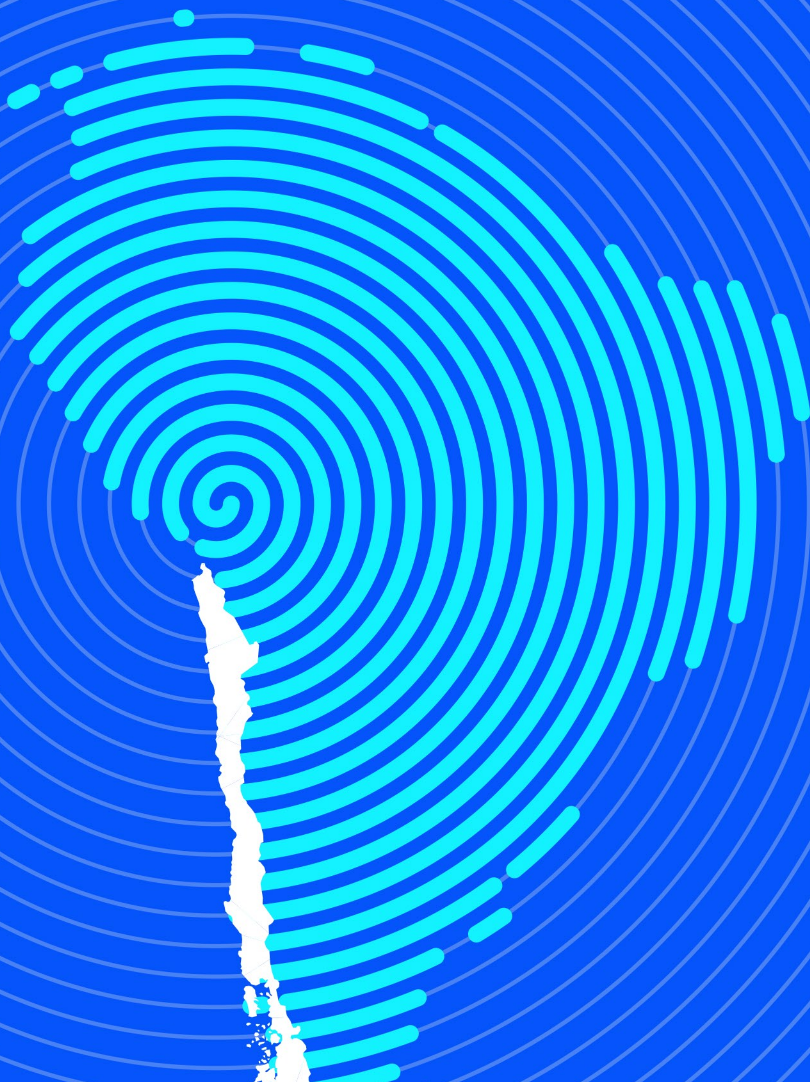
ISCI INSTITUTO SISTEMAS COMPLEJOS DE INGENIERÍA

ESTIMATING THE IMPACTS OF BLACKOUTS IN CHILE

EXECUTIVE SUMMARY



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Executive Summary

Electricity system reliability and resilience are central to economic development, social welfare and energy security. The increasing complexity of modern power systems, driven by a higher share of variable renewable generation and stronger regional interdependencies, has heightened their exposure to climatic, technical and operational contingencies. In this context, large-scale interruptions of supply, such as national blackouts, are no longer rare anomalies, but critical stress tests for the robustness of energy systems and regulatory frameworks.

In Chile, the nationwide blackout of 25 February 2025 exposed structural vulnerabilities of the National Electric System (SEN) and underscored the urgency of having robust tools to quantify the economic and social cost of electricity supply interruptions. The concept of Value of Lost Load (VoLL), or cost of unserved energy, is a central instrument for this purpose. It provides a monetary measure of the social cost of each kilowatt-hour that is not delivered, and thus informs planning, operation, regulatory design and investment decisions.

This executive summary synthesises the main topics and conclusion of the report "Estimating the Impact of Blackouts in Chile". It is structured in eight sections, moving from context to policy implications. It begins by situating the VoLL within the Chilean regulatory framework, then summarizes international practice, presents the proposed methodological innovation, describes its application to the Chilean economy, reports the results for the 25 February 2025 blackout, discusses the broader indirect impacts of recurrent outages and concludes with recommendations for regulators, policymakers and system operators.

Context

The blackout of 25 February 2025 revealed the fragility of key components of the power system. It affected over 70% of SEN electricity consumption in the first four seconds and the whole system after a few minutes. The center–south of the country experienced a deficit of around 25% of demand, while the northern area operated with surplus generation, leading to instability in both frequency and voltage. Automatic defense schemes did not perform as expected, and additional generation losses prevented the system from stabilizing, ultimately resulting in a widespread system collapse. During restoration, loss of telecontrol, communication and SCADA systems significantly delayed the service recovery plan. These operational failures were compounded by regulatory non-compliance and deficiencies in the actions of some electricity firms.

The magnitude and operational complexity of this event illustrate why economic quantification of blackout impacts is indispensable. A well-designed VoLL framework translates the technical fact of unsupplied energy into a measure of social cost. This provides an explicit benchmark for evaluating resilience investments, calibrating security standards, designing compensation mechanisms and prioritizing infrastructure projects. In other words, VoLL operates as a bridge between engineering reliability metrics and economic policy objectives.

The Value of Lost Load in Chile

Chile has developed a formal framework for cost of failure[1] estimation, in which VoLL underpins several regulatory instruments. The official cost of short-duration failure (*Costo de Falla de Corta Duración*, CFCD) and long-duration failure (*Costo de Falla de Larga Duración*, CFLD) are calculated every four years for use in transmission planning, security analyses, procurement of ancillary services and compensation schemes for customers affected by unplanned interruptions.

In transmission planning, the National Energy Commission (CNE) simulates system operation over a horizon of up to twenty years, minimizing operating and failure costs. The long-duration cost of failure is used to identify transmission expansion needs, while the CFCD is applied to value energy not supplied in security studies and to quantify the economic benefits of expansion projects justified by security reasons. This integrates VoLL directly into cost–benefit analyses of network investments.

The evolution of the CFCD, presented in **Figure E1**, reflects methodological changes rather than a trend in risk or damage in the Chilean power system. Earlier studies, such as SYNEX (2015), produced a national VoLL of about 11.03 USD/kWh, while the more recent E2BIZ (2021) exercise reports a lower value of 5.69 USD/kWh. The preliminary report presented by SYNEX+ (2025) in late November, sets the new value of VoLL at 10.75 USD/kWh.

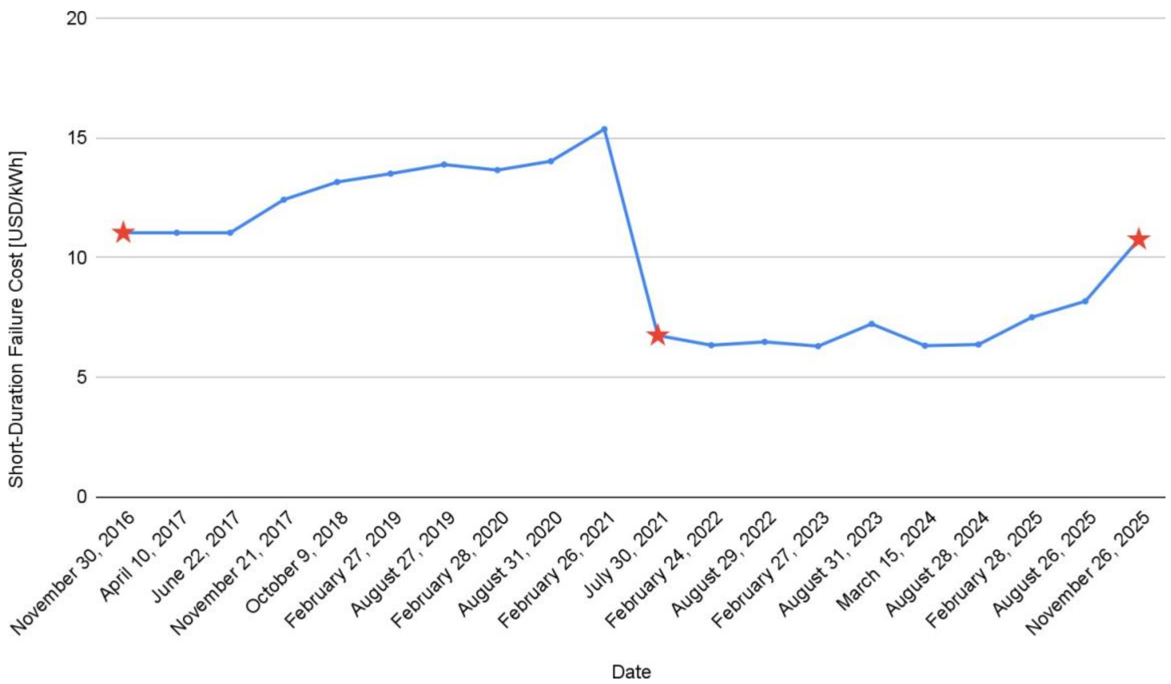

Figure E1. Evolution of the Cost of Short-Duration Failures in the National Electric System, 2017 to 2024.

This reduction is explained primarily by a shift from time-value assumptions towards methods based on consumer surveys and surplus for the residential sector, which aim to capture more realistic perceptions

[1] In Chile, the VoLL is also referred to as the "cost of failure" and is divided into two categories: short- and long-duration costs of failure.

of damage in a context of high supply reliability. It is important to bear in mind that changes in the VoLL influence both operational and investment decisions. A lower VoLL tends to weaken incentives for reliability- and resilience-enhancing operational strategies and investment choices, whereas a higher VoLL strengthens them. In this context, it is pertinent to question whether a reduction in VoLL genuinely reflects a structural change in the societal valuation of reliability and resilience. Methodological revisions that produce a substantial effect, such as, in this case, nearly halving the VoL, should therefore be examined with particular care, given their potentially far-reaching implications for system planning and operation.

The latest regulatory study (SYNEX+, 2025) introduces a refined segmentation of customers, as seen in **Table E1**. It distinguishes regulated residential and non-residential customers from free customers (industrial, mining and commercial), and for several of these groups relies on direct survey methods in which users report their own valuation of electricity service continuity. This approach improves the alignment between perceived damage and VoLL but introduces subjectivity and makes it harder to compare figures across methodologies.

Table E1. Short-Duration Failure Cost by sector presented in the Preliminary Failure Cost Report of Nov. 2025, prepared by SYNEX+. The value used to obtain the national value is highlighted in light blue[2].

Sector	CFCD SEN [USD/kWh]								Weighted by Sectoral Energy Withdrawals
	Indirect			Direct (Surveys)					
	Consumer Surplus	Value of Time	Value Added	Interruption up to 20 min	Interruption up to 1 hour	Interruption up to 4 hours	Interruption longer than 4 hours	Weighted by Probability of Occurrence	
Residential	-	**14.44**	-	-	-	-	-	-	-
Non-Residential	**0.60**	-	-	-	-	-	-	-	-
Industry	-	-	2.15	33.42	21.25	7.84	5.48	**16.78**	-
Mining	-	-	1.53	19.12	10.01	4.23	4.15	**9.76**	-
Commerce and Services	-	-	14.04	43.45	16.46	8.62	6.43	**13.76**	-
Transport	-	-	**13.68**	-	-	-	-	-	-
Others	-	-	**4.59**	-	-	-	-	-	-
National	-	-	4.23	-	13.34	5.39	4.59	-	**10.75**

Overall, Chile already uses VoLL as a central parameter in planning and compensation, but current estimates are heterogeneous in origin, vary across sectors and rely on a mix of survey-based and macroeconomic approaches that are not fully consistent with one another. This limits their effectiveness as a unified tool for resilience analysis and for evaluating the systemic cost of large-scale blackouts.

[2] National Energy Commission (CNE), Preliminary Technical Report: "Study of Short- and Long-Term Failure Costs for SEN and SSMM," Santiago, Chile, Nov. 2025.

International Experience in VoLL Estimation

The report reviews international practice in VoLL estimation with detailed case studies for Australia, Brazil, Spain and Italy, each including a major blackout event and the methods used to value associated damages.

- In Australia, regulation distinguishes between the Value of Customer Reliability (VCR), broadly equivalent to VoLL, and the Value of Network Resilience (VNR), associated with longer-duration disruptions. Both indicators are used in cost–benefit analysis, reliability standards and incentive schemes. The VCR is estimated using contingent valuation surveys for residential and standard industrial customers, complemented by direct-cost surveys for large industrial users. The methodology also segments results by climate zones and regions, reflecting the importance of geographic and sectoral heterogeneity.
- Brazil employs an approach centered on the cost of interruption (CI), with values differentiated by sector and region. The national regulator (ANEEL) combines direct and indirect methods, and importantly uses the cost of backup generation as an empirical proxy for revealed preferences: rational firms invest in self-generation until the marginal benefit of consumption equals the marginal cost of backup, so the cost of autogeneration approximates the VoLL for these users.
- Spain defines the VoLL and a reliability standard in line with European regulation. The VoLL represents the social cost of unserved energy, and the Loss of Load Expectation represents the standard limits tolerated. Estimation relies on revealed preferences from demand response auctions for industrial consumers, under the assumption that load shedding will first target industrial circuits and that the marginal social cost of interruption is best represented at that point.
- Like Spain, Italy defines its VoLL and reliability standards in correspondence with the European regulation. It estimates the VoLL by segmenting consumers into residential, tertiary, and industrial groups and applying contingent valuation surveys for households and services, and cost surveys for industry, across standardized outage scenarios. VoLL is calculated as the ratio between the reported value or cost of an interruption and the energy not supplied, based on declared or contracted power. An alternative approach proposed by OpenEconomics uses a value-added framework, deriving VoLL from the direct and system-wide economic benefits of avoiding outages relative to non-residential electricity consumption.

Finally, an international comparison, presented in **Table E2**, shows that there is no single universal benchmark; rather, each country selects its VoLL methodology according to its specific needs and national priorities National average VoLL values range widely, from around 5–11 USD/kWh in Chilean studies to much higher figures exceeding 25 USD/kWh or more in some European cases, with strong sectoral variation.

Table E2. Comparison of international VoLL in USD/kWh[3].

VoLL [USD/kWh]	Chile (SYNEX, 2015)	Chile (CNE, 2021)	Chile (SYNEX+, 2025)	Australia	Brazil	Spain	Italy
National Value	11.3	5.69	10.75	19.5	-	25.17	31.24 68.16
Large Industrial Value	–	–	–	3.50 - 7.94	-	-	-
Industrial Value	–	–	–	14.46 - 21.77	2.5	-	-
Services Value	–	–	–	21.52	-	-	-
Residential Value	–	–	–	16.16 - 35.82	3.55	-	-

Differences reflect not only underlying economic structures and reliability levels but also methodological choices: dependence on surveys versus macroeconomic ratios, the degree of sectoral disaggregation, and whether inter-sectoral linkages are incorporated. **The study concludes that VoLL values must be interpreted within their specific methodological and institutional context, rather than treated as directly comparable numbers.**

This international evidence motivates the development of a Chilean methodology that is both internally consistent and capable of capturing sectoral heterogeneity and system-wide effects.

Proposed Methodology for VoLL Estimation

This report proposes a two-tier VoLL framework designed to reconcile the tractability of traditional macroeconomic approaches with a richer representation of indirect and systemic effects. The methodology is summarized in the scheme presented in **Figure E2**.

[3] Prepared internally based on the methodological review of each country and the CNE failure study (2021).

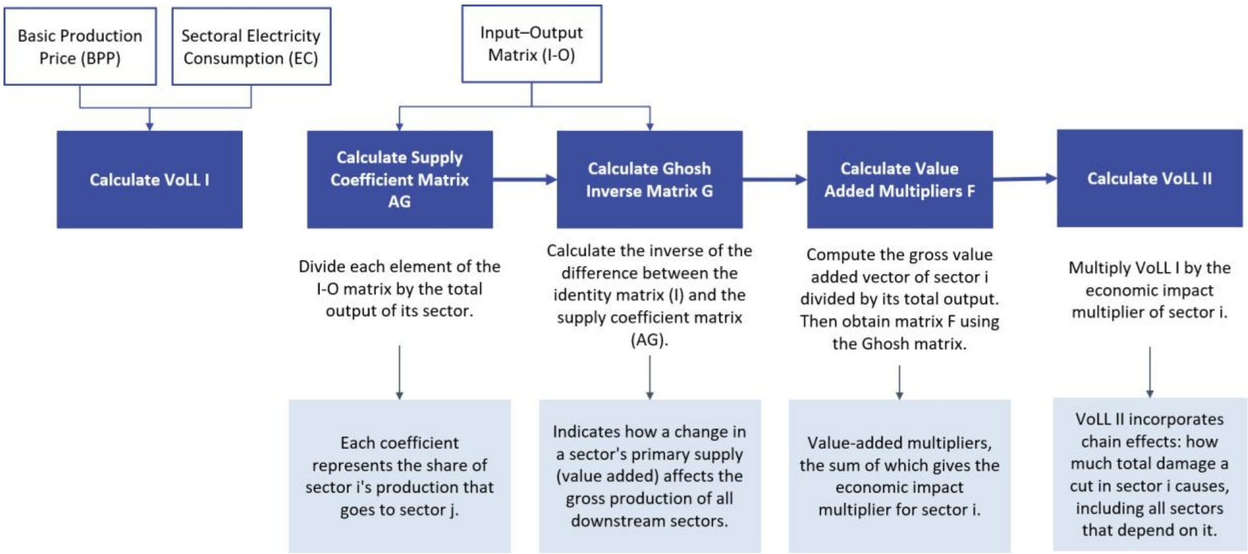

Figure E2. Outline for Determining the Value of Lost Load in the Proposed Methodology.

The first stage reproduces the standard macroeconomic approach (VoLL I), in which the VoLL for each sector is calculated as the ratio between its gross value added and its electricity consumption. This measure assumes a proportional relationship between energy use and output, and that a given percentage loss of electricity leads to an equivalent percentage loss in value added. It captures only direct, sector-specific losses, ignoring substitution possibilities and inter-sectoral linkages. As such, VoLL I is conservative and static but offers a transparent starting point for quantification.

The second stage extends this framework to VoLL II by incorporating economic interdependencies using an input–output (IO) representation of the Chilean economy. Through the I-O matrix and its associated inverse, the methodology captures how an interruption in one sector propagates downstream via its role as a supplier of intermediate goods and services. VoLL II includes both a systemic effect, the impact on national GDP, and a transmission effect that quantifies the macroeconomic consequences of a failure in the electricity, gas, water and waste sector, treated as a critical enabling industry.

Application to the Chilean Economy

The approach is implemented at two levels of aggregation. First, VoLL I and II are estimated for 12 broad economic activities defined in the economic national accounts system by the Central Bank of Chile, covering sectors such as agriculture and fishing, mining, manufacturing, construction, commerce and services. Second, the analysis is refined to 111 detailed activities using the national input–output table, which allows for a more granular view of vulnerabilities across the production structure.

To apply the methodology, electricity consumption by economic activity is estimated using detailed transaction data for 2022 provided by the Chilean National Electricity Coordinator. Monthly electricity withdrawals reported for individual companies and large customers are aggregated to obtain annual consumption levels. Companies are then classified into economic activities defined by the Central Bank of Chile by mapping their registered economic activity codes. For firms with multiple registered activities, all activities are identified, and the main economic activity is determined based on the predominant activity, complemented by artificial intelligence tools and manual validation when required.

Electricity withdrawals associated with distribution companies are adjusted to properly account for regulated customers. Regulated residential and non-residential consumption is identified using billing data from the National Energy Commission. Regulated non-residential consumption is then reallocated proportionally across economic activities based on the consumption patterns of large customers. Although this procedure may introduce some sectoral bias, its impact is considered limited given the relatively small share of regulated non-residential demand in total annual electricity consumption.

Using the resulting electricity consumption estimates together with value-added data for 2022, the methodology is applied to derive VoLL I and VoLL II for the 12 main economic activities. The results, presented in **Table E3**, show significant dispersion across sectors. Activities such as construction, services, business services, and financial intermediation exhibit very high VoLL values, reflecting their high value added per unit of electricity consumed and their central role in supplying services to the rest of the economy. By contrast, energy-intensive sectors such as mining and manufacturing show relatively low VoLL per kWh, as large electricity consumption dilutes the ratio of value added to energy use.

Table E3. VoLL I and VoLL II results for 12 economic activities.

Economic Activity	Energy Consumption 2022 [GWh]	VoLL I Direct Effect [USD/kWh]	VoLL II Systemic Effect [USD/kWh]
1 Agriculture, Forestry and Fishing	2,530.70	10.6	26.03
2 Mining	34,456.36	1.98	02.09
3 Manufacturing Industry	10,689.79	9.94	15.37
4 Electricity, Gas, Water and Waste Management	1,296.40	14.11	66.46
5 Construction	300.91	141.51	148.82
6 Commerce, Hotels and Restaurants	1,945.03	36.23	52.41
7 Transportation, Communications and Information Services	1,986.94	27.21	69.55
8 Financial Intermediation	172.94	144.54	270.79
9 Real Estate and Housing Services	1,131.28	26.01	46.44
10 Business Services	92.55	455.67	2,754.92
11 Personal Services	902.76	58.02	58.8
12 Public Administration	228.47	82.77	84.7
Consumption-Weighted Average		9.95	19.74

When cascade effects are incorporated through the Input–Output inverse matrix, the systemic VoLL, that reflects the impact on national GDP, increases markedly across most economic sectors. Indirect effects capture the propagation of shocks along the production chain: a disruption in one sector not only affects the sector that directly experiences the loss of sales, but also transmits to upstream sectors that supply intermediate inputs and to downstream sectors that rely on those inputs for their own production processes. This chain-reaction mechanism of inter-sectoral linkages amplifies the overall economic impact. Consequently, sectors with strong input–output connectivity, particularly those providing a broad range of intermediate services and inputs, such as business services, transport, and financial intermediation, exhibit especially large increases in total VoLL once these indirect effects are taken into account.

From an aggregate perspective, the consumption-weighted average is about 9.95 USD/kWh because high-consumption sectors (notably mining and industry) have low VoLL per unit. Once systemic effects are included, the consumption-weighted average VoLL II rises to approximately 19.74 USD/kWh.[4]

An important extension is the disaggregation of the electricity, gas, water and waste (EGA) sector into four sub-sectors, including electricity supply and related utilities. This reveals extreme heterogeneity within EGA: the VoLL for electricity supply exceeds 500 USD/kWh for direct effects and 2,000 USD/kWh for systemic effects, far above any other activity, confirming its pivotal role in the economy. At the same time, the average system-wide VoLL remains relatively stable when this disaggregation is introduced, indicating that the aggregate cost of rationing is robust to sectoral detail even though the internal distribution of risk and impact changes sharply.

This contrast highlights that macroeconomic impacts of interruptions can substantially exceed those suggested by direct sectoral losses alone, especially when failures originate in the electricity supply or broader EGA complex.

A comparison of VoLL I values for the proposed methodology and the last three studies in Chile is presented in **Table E4.**

Table E4. Comparison of VoLL I results from the proposed methodology and the last three studies in Chile.

<table>
<tr><th>Economic Activity</th><th>Sector</th><th>SYNEX, 2015 [USD/kWh]</th><th>E2BIZ, 2021 [USD/kWh]</th><th>SYNEX+, 2025 [USD/kWh]</th><th>Proposed Methodology [USD/kWh]</th></tr>
<tr><td>Mining</td><td>Mining</td><td>13.20</td><td rowspan="5">3.64</td><td>9.76</td><td>1.98</td></tr>
<tr><td>Agriculture, Forestry and Fishing</td><td rowspan="4">Industry</td><td rowspan="4">8.52</td><td rowspan="4">16.78</td><td>10.6</td></tr>
<tr><td>Manufacturing Industry</td><td>9.94</td></tr>
<tr><td>Electricity, Gas, Water and Waste Management</td><td>14.11</td></tr>
<tr><td>Construction</td><td>141.51</td></tr>
</table>

[4] However, it is important to note that production is assumed to resume only after the disruption event has ended; consequently, the analysis does not account for recovery profiles and overlooks the heterogeneity in intertemporal recovery effects across sectors, as evidenced by recent results.

<table>
<tr><td>Transportation, Communications and Information Services</td><td rowspan="6">Services</td><td rowspan="7">8.52</td><td rowspan="6">9.12</td><td rowspan="7">13.76</td><td>27.21</td></tr>
<tr><td>Financial Intermediation</td><td>144.54</td></tr>
<tr><td>Real Estate and Housing Services</td><td>26.01</td></tr>
<tr><td>Business Services</td><td>455.67</td></tr>
<tr><td>Personal Services</td><td>58.02</td></tr>
<tr><td>Public Administration</td><td>82.77</td></tr>
<tr><td>Commerce, Hotels and Restaurants</td><td>Commerce</td><td>0.65</td><td>36.23</td></tr>
<tr><td>Residential</td><td>Residential</td><td>9.93</td><td>14.31</td><td>14.44</td><td>-</td></tr>
<tr><td>National</td><td>National</td><td>11.03</td><td>5.69</td><td>10.75</td><td>9.95</td></tr>
</table>

The 25 February 2025 Blackout: Estimated Economic Cost

Building on the sectoral VoLL I estimate, the report quantifies the cost of the nationwide blackout of 25 February 2025. The methodology multiplies the VoLL I[5] for each sector by the corresponding unsupplied energy, using detailed outage records from the failure report EAF 089-2025, which provide information on customers (regulated and free), location, timing and duration of interruptions, and total energy not supplied.

The baseline scenario considers the VoLL I value derived from the value-added over electricity consumption ratio for all sectors, and uses the CFCD estimate for regulated residential customers indexed to December 2022. Regulated non-residential customers are assigned the VoLL of the commerce, hotels and restaurants sector. The distribution of regulated residential and non-residential energy among customers follows the 2022 tariff split, with 38% of regulated customers classified as residential and 62% as non-residential. Under these assumptions, the blackout interrupted approximately 81,430 MWh of energy and generated an estimated total economic cost of about 984.2 million USD. The total unserved energy and cost of the blackout per sector is presented in **Table E5.**

Table E5. Cost of the February 25 national blackout, considering 12 economic activities in Chile.

	Economic Activity	VoLL I [USD/kWh]	Total Interrupted Energy [MWh]	Total Blackout Cost [USD]
1	Agriculture, Forestry and Fishing	10.6	1,327.87	14,075,422.0
2	Mining	1.98	46,696.68	92,459,426.4
3	Manufacturing Industry	9.94	6,576.56	65,371,006.4
4	Electricity, Gas, Water and Waste Management	14.11	904.03	12,755,863.3
5	Construction	141.51	251.38	35,572,783.8

[5] To estimate the economic cost of the 2025 blackout in Chile, VoLL I is selected over VoLL II. In this type of event, the downstream cost propagation captured by VoLL II is no longer relevant, as all sectors are affected simultaneously and uniformly. Consequently, only VoLL I is considered relevant for this quantification.

6	Commerce, Hotels and Restaurants	36.23	1,279.83	46,368,240.9
7	Transportation, Communications and Information Services	27.21	1,040.60	28,314,726.0
8	Financial Intermediation	144.54	131.39	18,991,110.6
9	Real Estate and Housing Services	26.01	894.75	23,272,447.5
10	Business Services	455.67	36.49	16,627,398.3
11	Personal Services	58.02	578.61	33,570,952.2
12	Public Administration	82.77	176.04	14,570,830.8
13*	Regulated Residential Customer	12.009	8,174.16	98,163,499.5
14*	Regulated Non-Residential Customer	36.23	13,362.09	484,108,484.5
	Total	-	**81,430.48**	**984,222,192.1**

The burden is unevenly distributed across sectors. Mining, manufacturing, commerce, transport, real estate services and regulated customers each represent substantial shares, driven by the combination of their VoLL values and the volume of energy interrupted. Notably, regulated non-residential customers, representing a wide range of commercial and service activities, account for nearly half of the total cost, while regulated residential customers contribute close to 100 million USD.

A sensitivity analysis explores how results change when the VoLL of mining and regulated non-residential customers is replaced by alternative estimates. For mining, survey-based VoLL values are used, reflecting a higher willingness to pay to avoid interruptions; for regulated non-residential customers, the consumer-surplus methodology from recent CFCD studies is applied, which yields lower VoLL figures. In this scenario, the effects of the mining sector and regulated non-residential customers partially offset each other, resulting in a cost reduction of approximately 10%, with the mining sector emerging as the dominant contributor and accounting for more than half of the total economic impact.

This finding underscores two key messages. First, the cost of a given blackout is sensitive to the VoLL methodology adopted for strategic sectors. Second, different VoLL estimation approaches can redistribute the measured burden across sectors, with important equity and policy implications.

Finally, **Table E6** presents the results of an exercise aimed at estimating the economic cost of the national blackout of 25 February by economic activity, applying alternative VoLL values drawn from three failure cost studies adopted by the Chilean regulator, together with the proposed methodology

Table E6. Estimated Economic Cost of the National Blackout of 25 February, by Economic Activity and VoLL Methodology

	Economic Activity	Total Interrupted Energy [GWh]	Blackout Cost [MM USD] SYNEX (2015)	E2BIZ (2021)	SYNEX (2025)	Proposed Methodology
1	Agriculture, Forestry and Fisheries	1.3	11.3	8.8	22.3	14.1
2	Mining	46.7	616.4	310.1	455.8	92.5
3	Manufacturing Industry	6.6	56.0	43.7	110.4	65.4
4	Electricity, Gas, Water and Waste Management	0.9	7.7	6.0	15.2	12.8
5	Construction	0.3	2.1	1.7	4.2	35.6
6	Trade, Hotels and Restaurants	1.3	10.9	0.8	17.6	46.4
7	Transport, Communications and Information Services	1.0	8.9	9.5	14.3	28.3
8	Financial Intermediation	0.1	1.1	1.2	1.8	19.0
9	Real Estate and Housing Services	0.9	7.6	8.2	12.3	23.3
10	Business Services	0.0	0.3	0.3	0.5	16.6
11	Personal Services	0.6	4.9	5.3	8.0	33.6
12	Public Administration	0.2	1.5	1.6	2.4	14.6
13*	Regulated Residential Customers	8.2	81.2	117.0	112.5	98.2
14*	Regulated Non-Residential Customers	13.4	113.8	8.7	8.0	484.1
	Total	**81.43**	**923.9**	**522.8**	**785.2**	**984.2**

The results show that, although the total interrupted energy is fixed, the estimated cost of the event varies widely across methodologies, ranging from approximately USD 523 million to USD 984 million. This variation is driven mainly by differences in the valuation of sectors with either high electricity consumption or high economic losses per unit of unserved energy, particularly mining and regulated non-residential customers. Overall, the results illustrate that methodological choices strongly influence both the aggregate magnitude and the sectoral allocation of blackout costs, highlighting the need for transparent and consistent VoLL assumptions in the economic assessment of large-scale supply interruptions.

Indirect and Long-Term Impacts of Blackouts

The report emphasises that frequent outages and low levels of reliability generate impacts that extend well beyond immediate production losses. Recurrent blackouts can induce persistent changes in consumer behaviour, business strategies and public policy responses, shaping long-term investment decisions and altering the trajectory of the energy transition. Households and firms may invest in backup diesel generators, distributed solar generation, storage and other resilience measures that would be largely unnecessary in a highly reliable system. These responses, while rational at the individual level, modify long-term demand for grid electricity, affect the pace and pattern of electrification, and redistribute costs and benefits across society.

One critical dimension of these indirect impacts relates to the electrification of end uses, particularly transport and heating. The adoption of electric vehicles depends fundamentally on stable access to charging infrastructure. Empirical evidence from China shows that an increase of one average monthly outage is associated with an approximately 1% reduction in electric vehicle sales, with effects that persist for several years. In electricity systems subject to frequent interruptions, consumers may therefore delay or avoid the transition to electric mobility, or incur additional costs to secure backup supply, slowing decarbonization and exacerbating inequality between those who can and cannot afford resilience solutions.

Similar dynamics arise in the electrification of heating. In regions with high reliance on electric heating, supply interruptions can have immediate and severe welfare impacts. For example, in Texas, where more than 60% of households depend on electric heating, the winter blackouts of 2021 left millions of users without adequate heating, reinforcing perceptions of vulnerability associated with electric heat in the absence of reliable supply or backup options. Such experiences can undermine confidence in electrification strategies and encourage continued reliance on fossil-based or hybrid alternatives.

Persistent reliability problems also tend to accelerate the deployment of autonomous and hybrid energy solutions. In Puerto Rico, following the collapse of the grid after Hurricane Maria in 2017, more than 40,000 households installed solar photovoltaic systems with battery storage, effectively becoming domestic “micro power plants”. This process has contributed to the development of one of the world’s largest virtual power plants, illustrating a structural shift away from exclusive dependence on the centralized grid, driven directly by repeated failures of the traditional system.

In other contexts, unreliable supply has fostered widespread reliance on backup generation. In Nigeria, a well-documented “generator economy” has emerged, with more than 22 million diesel and gasoline generators supplying electricity to approximately 30% of households and small businesses. While these solutions provide short-term reliability, they entail high economic, environmental and social costs, and further weaken the financial sustainability of the central grid. Governments have responded to these dynamics through regulatory, fiscal and planning interventions. In South Africa, for instance, building regulations require that more than 50% of domestic hot water demand in new buildings be met through non-grid-dependent technologies, such as solar thermal systems, heat pumps or hybrid configurations, reflecting a policy-driven adaptation to chronic grid instability. More recently, in Spain, following the April 2025 blackout, a royal decree was enacted to strengthen network resilience by enhancing monitoring and control systems and accelerating permitting processes for hybrid generation plants with storage.

These indirect and long-term impacts are not fully captured by conventional VoLL measures, which focus primarily on immediate production losses. Nevertheless, they are central to understanding the full social cost of repeated outages and highlight the importance of designing policies that strengthen system reliability and resilience, while avoiding uncoordinated shifts away from the grid that may undermine the long-term sustainability of the electricity system.

Policy Recommendations

The analysis of the Chilean VoLL framework, its application to the 2025 blackout and the international comparison yield several implications for policy and regulation. While the report presents these in detail, they can be synthesized around four overarching directions:

1. **Explicitly integrate systemic resilience into electricity system planning and regulation**
   The economic cost of the Chilean National Electric System blackout of 25 February 2025, estimated at over USD 900 million, is comparable in magnitude to annual capacity payments in Chile, which are close to USD 1 billion. This comparison demonstrates that low-probability, high-impact events features, within a few hours, an economic value equivalent to a full year of structural instruments designed to ensure system adequacy and reliability.

   However, while regulation explicitly internalizes the cost of generation capacity adequacy, systemic risks associated with network resilience are treated implicitly, in a fragmented manner, and ex post. This regulatory asymmetry (between generation and networks, and reliability and resilience[6]) results in insufficient incentives for resilience investment, particularly in distribution networks, where improvements translate directly into higher tariffs, while their benefits materialize over the long term.

   Advancing towards a coherent framework requires the explicit incorporation of resilience criteria into planning, and therefore, policy and regulation, treating blackouts as high-impact, low-probability risks with non-negligible expected economic losses. This entails developing resilience standards justified through cost–benefit analysis, adapting technical regulations and remuneration mechanisms, and creating instruments that allow system resilience benefits to be internalized.

   Importantly, integrating resilience should not be understood as an additional cost, but rather as an insurance mechanism designed to mitigate losses associated with high-impact, low-probability catastrophic events. Moreover, the explicit incorporation of mechanisms to ensure adequate levels of resilience constitutes a correction to restore economic coherence between the system's actual risks and the mechanisms governing the electricity market.

[6] It is important to emphasize that electricity networks account for approximately 95% of supply discontinuities, yet reliability mechanisms continue to focus predominantly on generation capacity.

Transmission planning: from permissive recognition to operational implementation

With respect to transmission investment, the current regulatory framework, particularly the *Reglamento de los Sistemas de Transmisión y de la Planificación de la Transmisión*, contained in *Decreto Supremo* N°37 del *Ministerio de Energía*, issued under the *Ley General de Servicios Eléctricos* and administered by the CNE, establishes the institutional and methodological basis for the expansion of the national transmission system.

Under this framework, Article 92 of *Decreto Supremo* N°37 explicitly provides that transmission expansion studies must consider resilience as an expansion criterion, and that projects may be justified not only on economic efficiency grounds but also to mitigate high-impact low -probability (HILP) risks. This article establishes the legal basis for incorporating risk considerations into planning decisions, including situations where reinforcement is required to mitigate extreme events.

This is, in principle, a positive development. The framework does not restrict planning exclusively to N–1 reliability or congestion cost minimization, and it enables projects to be proposed where justified by risk considerations. However, despite this formal openness, the regulation does not currently specify detailed methodologies for the quantitative assessment of HILP risks. In practice, the absence of explicit probabilistic criteria, resilience metrics, or standardized cost–benefit methodologies for tail-risk mitigation creates an implicit barrier to implementation. Projects justified primarily on resilience grounds face greater scrutiny, particularly when their short-term tariff impact is visible and immediate.

Over the last few years, a substantial body of technical work has been developed in Chile and worldwide proposing structured methodologies for probabilistic risk assessment and for valuing resilient transmission enhancements, including the mitigation of tail risks associated with multiple contingencies, common-mode failures, and extreme events[7]. Notably, the Coordinador Eléctrico Nacional has, in previous planning cycles, adopted sound methodological approaches to identify and propose network reinforcements explicitly aimed at enhancing system resilience. However, some of these proposals were not ultimately incorporated into the official expansion plan elaborated and approved by the CNE.

This experience suggests that the remaining constraint is not primarily technical. The analytical tools exist; the system operator has demonstrated the capacity to apply them. Rather, the core dilemma appears to lie in the political economy of short-term tariff effects. Resilience investments often increase the regulated transmission revenue requirement in the near term, while their benefits, the avoidance of catastrophic losses, are realized probabilistically and are therefore less visible in conventional regulatory assessments.

However, the economic losses estimated in this report for the 25F blackout (among other events) provide concrete and quantifiable evidence of the magnitude of the costs associated with insufficient resilience. In this sense, the 25F event transforms what might otherwise be

[7] Panteli, M., Moreno, R., Trakas, D., Jamieson, M., Mancarella, P., Strbac, G., & Hatziargyriou, N. (2026). Fundamentals of Power System Resilience: Disruptions by Natural Causes. John Wiley & Sons.

perceived as abstract or speculative benefits into a tangible benchmark for policy evaluation, reinforcing the case for integrating resilience considerations explicitly into transmission planning and regulatory decision-making.

If resilience-enhancing projects are adopted within the formal transmission planning process, Chilean regulation already provides the appropriate implementation channel: once included in the transmission expansion plan, such projects are mandated, tendered, and remunerated under the regulated transmission framework. Therefore, the institutional architecture required to implement resilience upgrades is already in place. What is needed is the explicit integration of resilience valuation into the planning methodology, supported by transparent cost–benefit-risk analysis that incorporates expected avoided losses derived from VoLL-based assessments.

Distribution regulation: correcting incentive distortions

In distribution networks, the challenge is more structural. The current remuneration model is based on the “model firm” approach, whereby tariffs are calculated using a benchmark efficient company and forward-looking (greenfield-type) cost assumptions. Investment decisions are largely decentralized, and companies retain strong incentives to minimize capital expenditures in order to reduce costs relative to the benchmark.

While this approach promotes static efficiency, it creates a structural bias against resilience investment. Enhancements in network robustness, undergrounding, redundancy, sectionalization, automation, or improved fault management, increase capital costs immediately, while their benefits materialize in the form of reduced frequency and duration of interruptions over time. Under the current scheme, there is limited regulatory recognition of these long-term systemic benefits, and companies may rationally prioritize cost containment even if this results in lower reliability levels.

There is increasing consensus that resilience-oriented investments in distribution require additional regulatory support mechanisms. Several alternatives are available.

One option is a more centralized approach, whereby the regulator mandates specific resilience investments deemed socially efficient and incorporates them explicitly into the tariff base. This may require evolving from purely greenfield benchmarking toward hybrid or brownfield benchmarks that better recognize legacy assets and the actual topology and constraints of existing networks.

Alternatively, within a more decentralized framework, reliability and resilience enhancements could be incentivized through performance-based regulation. For example, explicit premiums or strengthened output-based incentives linked to service quality indicators could reinforce reliability as a valued output of distribution services, rather than treating it merely as a constraint. In such a framework, resilience would be remunerated not simply as cost recovery, but as performance delivery.

2. **Interpret VoLL with caution in sectoral comparisons and investment prioritization**
   VoLL does not linearly reflect the economic relevance of different sectors. Activities with low electricity consumption may exhibit high VoLL values, while electricity-intensive sectors such as mining may present more moderate values per unit of unserved energy. This characteristic can distort sectoral comparisons and investment prioritization if the productive structure and energy intensity of each sector are not explicitly considered. Consequently, VoLL should be used as a complementary economic signal rather than as a sole indicator of sectoral importance or systemic criticality.

3. **Explicitly acknowledge that there is no single "correct" VoLL**
   VoLL estimation methodologies capture different dimensions of the cost of unserved energy. In particular, value-added–based approaches estimate direct productive economic losses, while survey-based methods reflect users' stated valuations of electricity supply interruptions. As these approaches respond to different analytical and regulatory objectives, their results are not directly comparable. Accordingly, the application of VoLL should be explicitly conditioned on its intended purpose, whether for system planning, compensation mechanisms, assessment of extreme events, or resilience analysis.

4. **Ensure methodological and sectoral consistency in VoLL estimation**
   The interpretation and regulatory use of VoLL require coherence in the selected methodology, the definition and disaggregation of economic sectors, and the treatment of regulated and unregulated customers, regardless of the period in which the calculation is performed. Uncoordinated methodological changes generate results that are difficult to compare over time and introduce scope for arbitrariness in regulatory studies. Given the role of VoLL in planning, operational, and economic evaluation decisions, its estimation should be based on explicit, transparent, and stable criteria.