Assessment of the Impact of International Interconnection Lines on the Resilience of Argentina and Chile

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Aim of the study

- The activity aims at assessing the impact which an interconnection line can have on the resilience of the power system, i.e. its ability to withstand extreme events and recover as fast as possible

- Probabilistic simulations are carried out evaluating system adequacy when unavailability rate of equipment in a specific area of Chile is highly increased due to adverse external conditions

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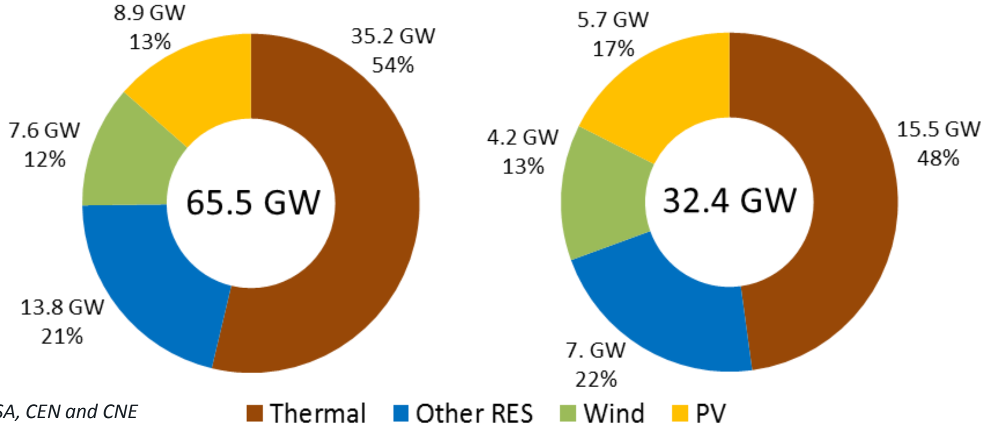
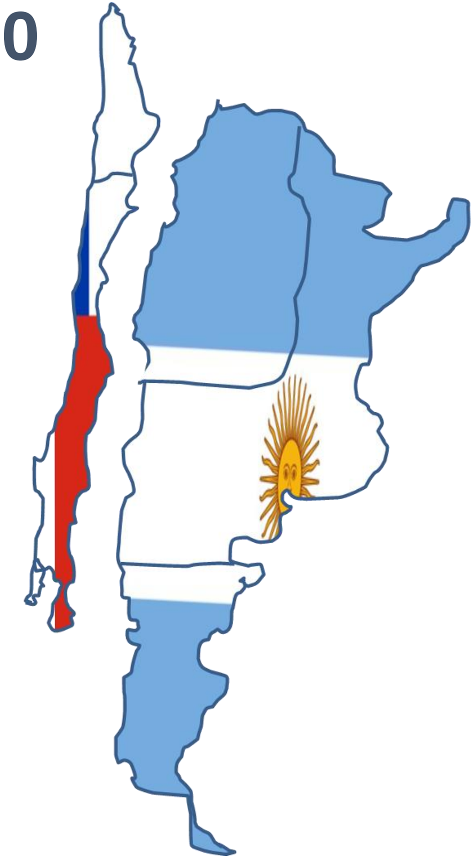
Reference scenario at target year 2030

"**Reference Scenario**" based on publicly available data(*):

- Load: ARG: 230 TWh/year - CHI: 109 TWh/year(**)
- Generation:

Argentina ***Chile***





(*) MINEM, CAMMESA, CEN and CNE

(**) 75% in SIC area and 25% in SING area

Electric power system model

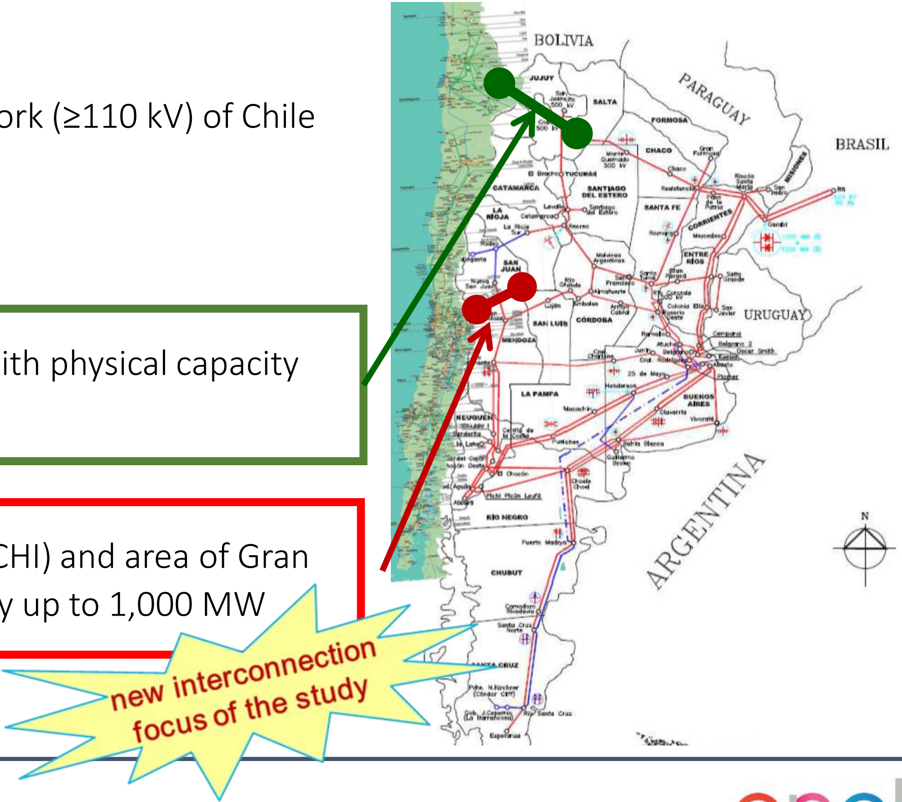
Detailed network model

- Detailed representation of HV transmission network (≥110 kV) of Chile and Argentina

Interconnections Chile and Argentina:

- Existing 220 kV line Andes (CHI) – Cobos (ARG), with physical capacity up to 600 MW

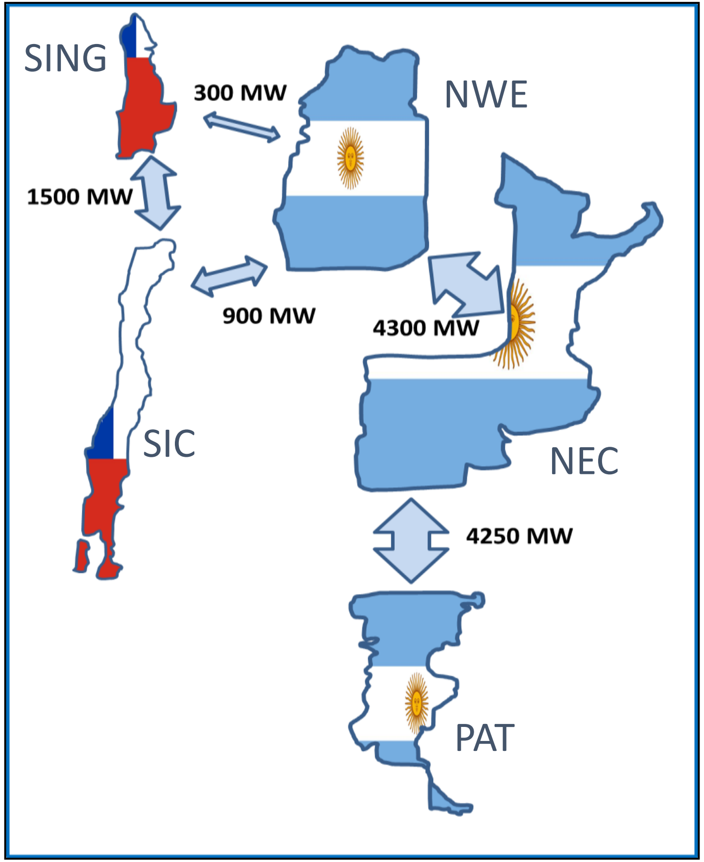
- New interconnection between area of Santiago (CHI) and area of Gran Mendoza (ARG), 500 kV line with physical capacity up to 1,000 MW



Electric power system model

Area model

- Macro areas model applied at each electric power system assuming inter-area limitation in transfer capacity
- Chile:
  - SING: Sistema Interconectado del Norte Grande
  - SIC: Sistema Interconectado Central
- Argentina
  - NWE: North West area
  - NEC: North East and Central area
  - PAT: Patagonia area
- Net Transfer Capacity between the countries: 1,200 MW over a total physical capacity of 1,600 MW



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Main steps of work

1. Selection of the area to be analysed

- Based on historical data from extreme natural events in Chile, one area close to the new interconnection has been identified as the area in which to simulate the impact of extreme natural events

2. Definition of network component unavailability rates to simulate extreme events

- four unavailability levels have been defined for each network component, to simulate different levels of forced downtime caused by extreme events

3. Execution of probabilistic simulations over the Argentina-Chile interconnected systems:

- Simulations have been carried out to obtain expected behaviour of the system in presence of extreme natural events, with and without the new interconnection between countries

Simulation tool GRARE – Grid Reliability and Adequacy Risk Evaluator

State of the art tool to assess system adequacy of large interconnected systems, simulating expected operating conditions (load variation, generation fleet, HV transmission system…) using probabilistic analysis

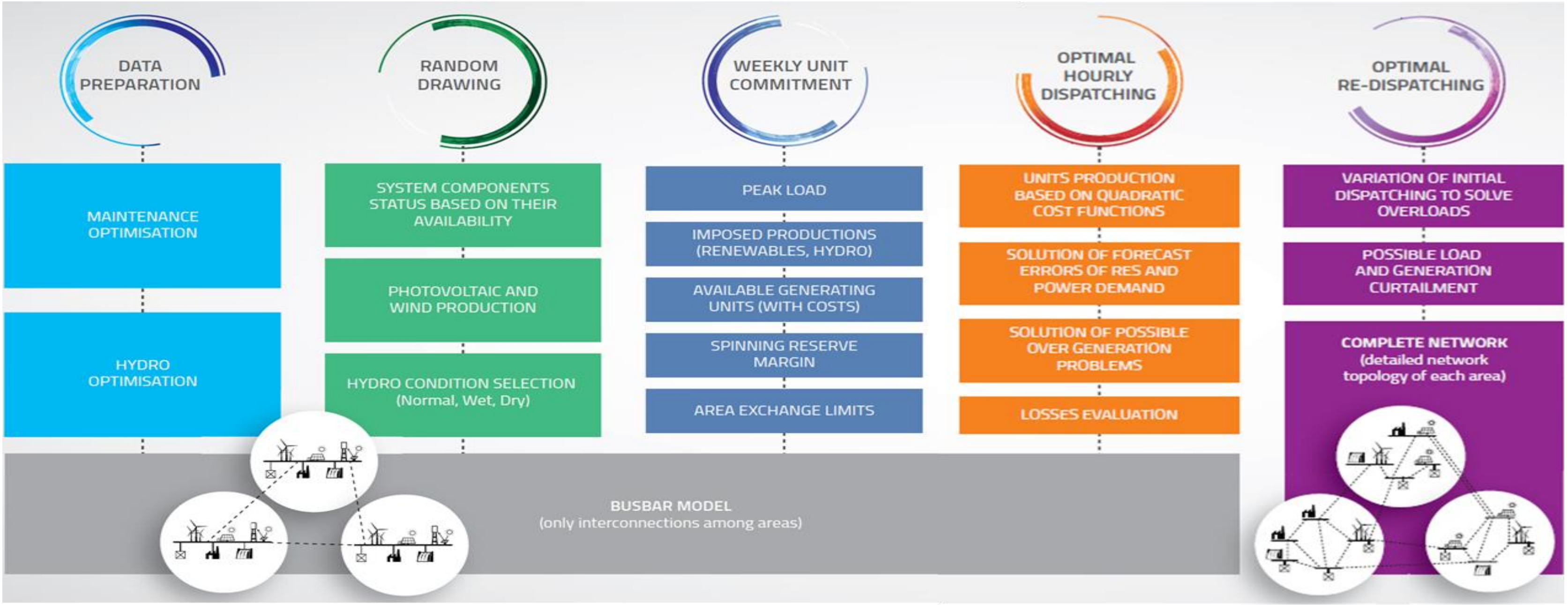
- Probabilistic Monte Carlo method: statistical sampling based on a "hybrid sequential" approach
- Area modelling for the composite transmission-generation system
- Transmission network detail to represent each single area
- Generation fleet dispatched to minimise system cost
- Renewable aleatory production is obtained with a random drawing starting from real producibility figures
- Reserve level evaluation considering: biggest generating unit, uncertainty on load and RES, possible aggregation of Area, fixed % of load

GRARE
GRID RELIABILITY AND ADEQUACY RISK EVALUATOR

More details available on www.cesi.it/grare

GRARE calculation process

The calculation process is performed as a series of sequential steps starting from a high-level system representation and drilling down to low-level network details



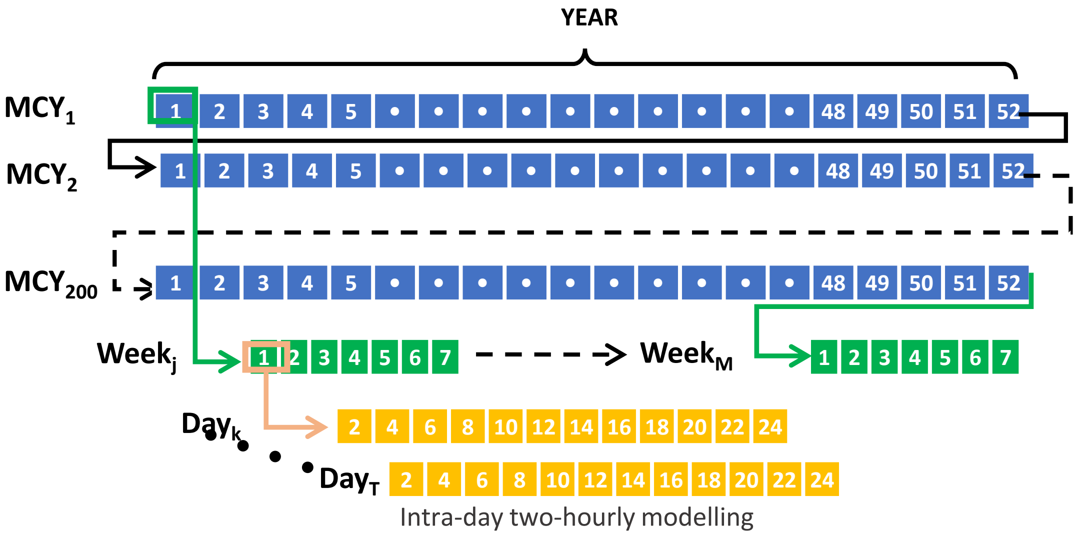
Probabilistic simulations

- Monte Carlo method uses statistical sampling based on “Hybrid Non Sequential” approach
  - Non sequential analyses and optimization of thousands of weeks
  - Sequential analysis and optimization of hydro generation over one year
- Focus on high unavailability levels of system components simulating the impact of extreme natural events on the electric power systems
- Assessment of the impact of the new interconnection on power system resilience in presence of extreme natural events that cause critical network conditions
  - ability of interconnected systems to limit unserved energy

Main features of probabilistic simulations

- 200 Monte Carlo Years (MCY) for the horizon year 2030
  - A Monte Carlo Year (MCY) is a simulation year in which a mix of Monte Carlo variables is applied to take into account the stochastic behaviour of some power system parameters: load forecast error, forced outage rate of generation fleet and network elements, wind and solar generation
- Weekly optimization of power system operation minimizing system costs and unserved energy
- Thousands of grid configurations for each unavailability level under analysis, both with and without the new interconnection line
  - Unavailability of system components is independent from the status of the systems and of the other components
- Focus on the Expected Energy Not Supplied (EENS) and benefits from the new interconnection line
  - Analysis of typical (average) week in Chile and details on SIC area: EENS with weekly and hourly time steps

Probabilistic approach



For each unavailability level under analysis

200 Monte Carlo Years were simulated for the target year

10,400 weeks

72,800 days

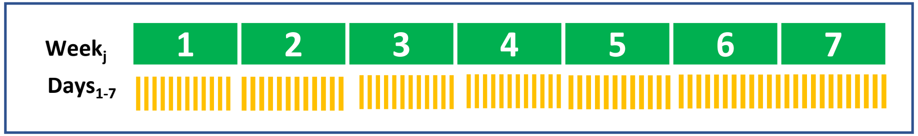
873,600 two-hourly steps (*)

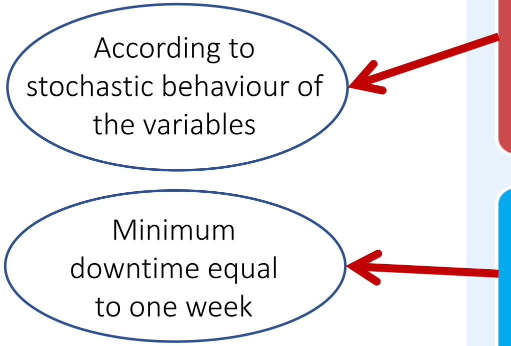
- Optimization of hydropower production over the year
- Optimization of power system operation for every single week
- Outputs processing to provide statistical values on different time frames (hour, week, year)

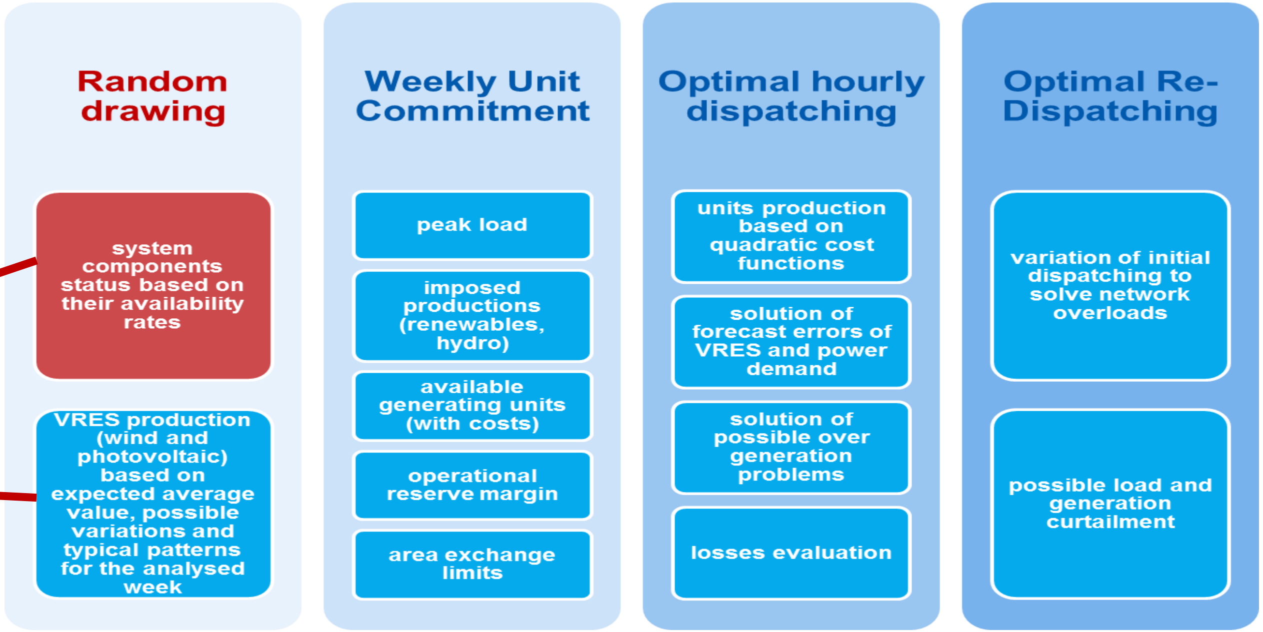
(*) GRARE tool works with a minimum time unit of one hour; however two-hourly steps were used to reduce calculation time

Weekly simulation of system operation

- Independent optimization of each week with intra-day modelling
- For every week the following steps are performed



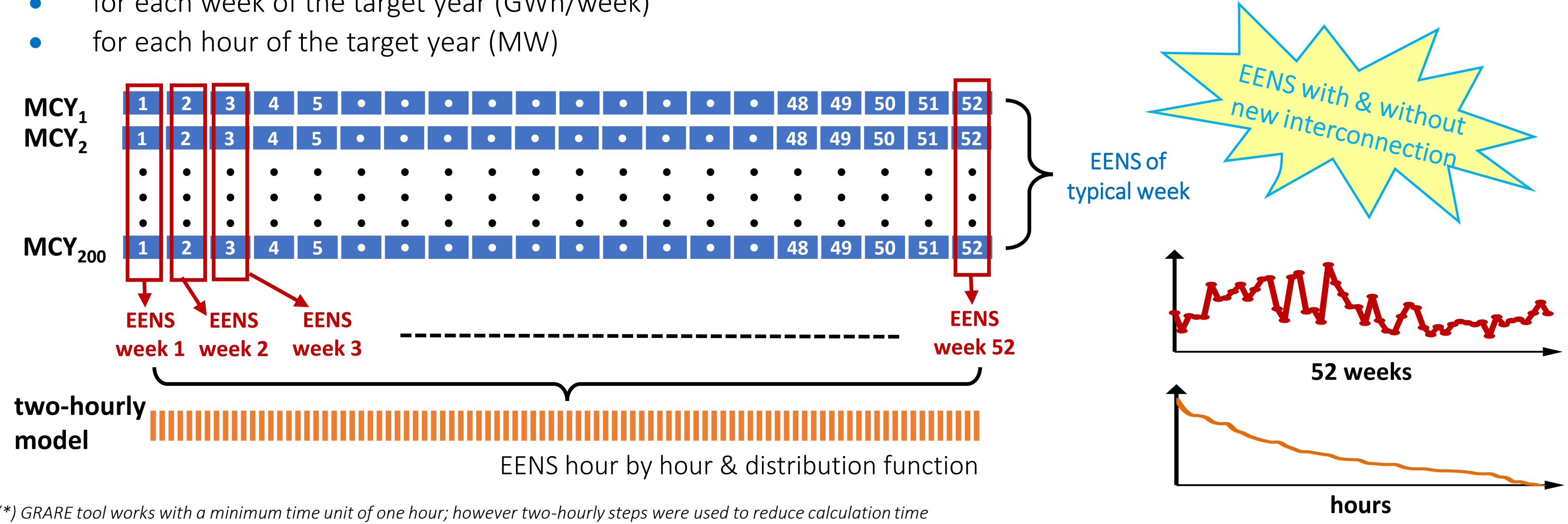




Expected outputs from probabilistic model

Extreme natural events affecting system elements availability could occur at any time of the year. Therefore, they were simulated for each week of the year and a statistical analysis was carried out assessing the Expected Energy Not Supplied

- for the typical week (average of 10,400 analysed weeks)
- for each week of the target year (GWh/week)
- for each hour of the target year (MW)



(*) GRARE tool works with a minimum time unit of one hour; however two-hourly steps were used to reduce calculation time

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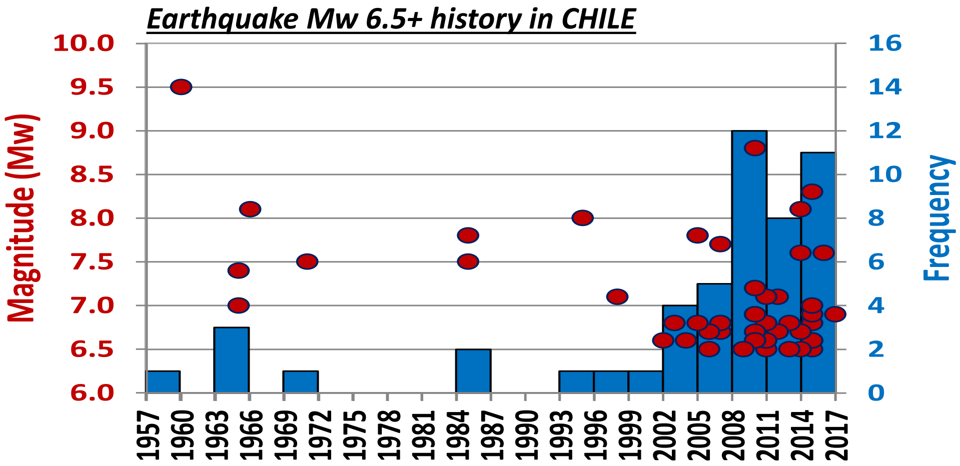
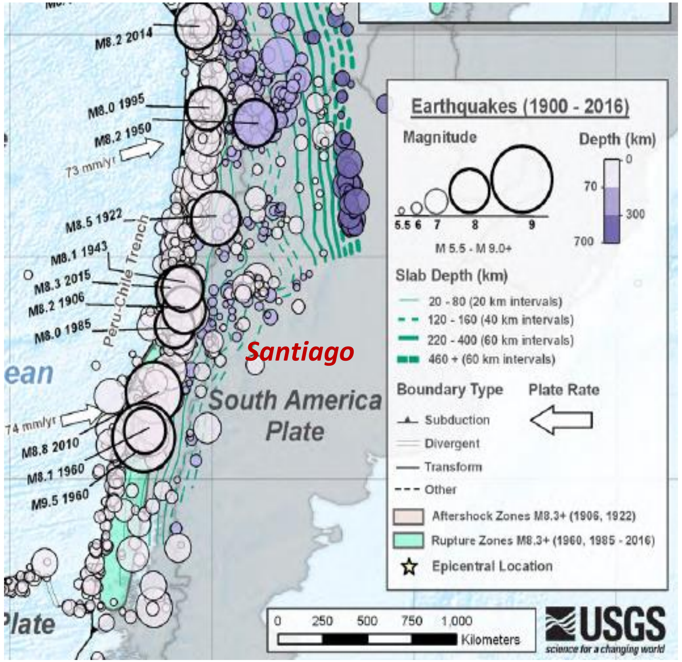
Extreme natural events in Chile

- Historical data registered extreme natural events like heavy storms and earthquakes on the whole territory of Chile also in the area near Santiago
- The frequency of extreme natural events in Chile is growing up in the last decades



Data Source: World Earthquakes™ (www.world-earthquakes.com)



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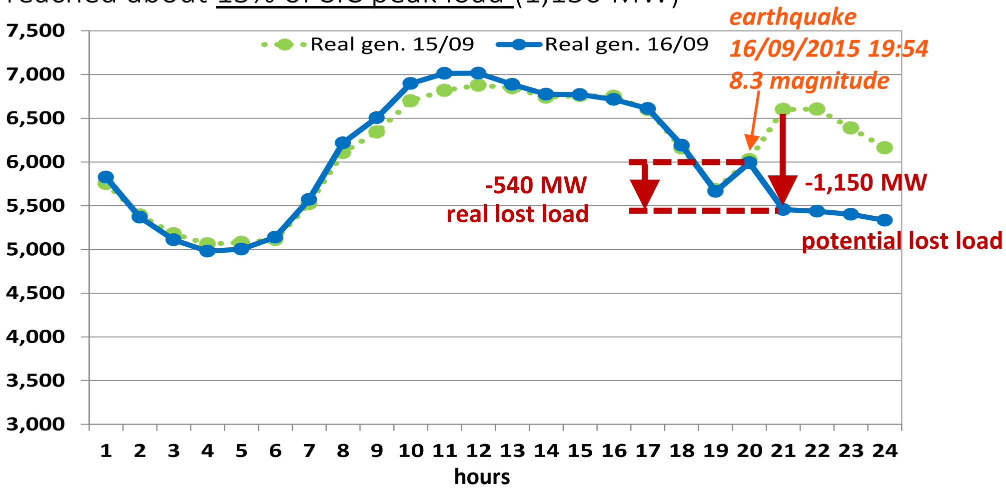
Extreme natural events in Chile-example of real case

Earthquake with magnitude 8.3 in Coquimbo region, 16th September 2015 at 19h54

- About 540 MW generation reduction occurred immediately after the event: real lost load in Coquimbo and Valparaiso regions is equal to 7% of SIC peak load (*)
- The consequences of network damage had also later effects on the availability of system components: considering the demand profile that should have been in the hours after the earthquake took place, the potential unserved load reached about 15% of SIC peak load (1,150 MW)



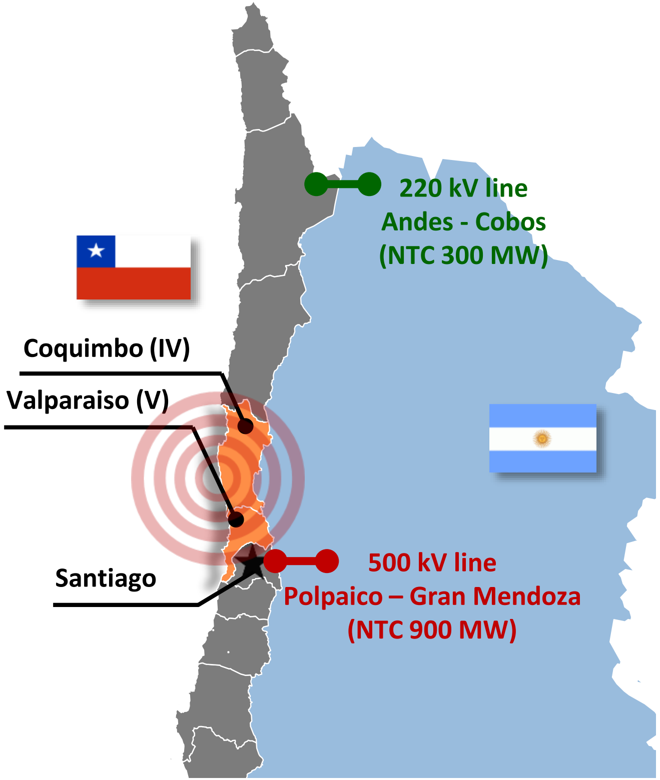
This real case has been used as reference to simulate reasonable extreme events on the electric power system

(*) in 2015, SIC peak load occurred on March 20th and it was equal to 7,577 MW

Source: Coordinador Electrico Nacional (hourly data available on https://sic.coordinador.cl)

Area of interest

- Area with high risk of system components unavailability due to extreme events
- Selected regions: Coquimbo (IV) and Valparaiso (V)
- Extreme events in selected regions could limit power flows from generation centres to load centres affecting the Security of Supply (SoS)
- The new interconnection close to the area of interest could improve the SoS in Chile during critical events



Network in the area of interest

- In the Coquimbo and Valparaiso regions there are very long EHV (Extra High Voltage) corridors (500kV, 220kV, 110kV) from north to south
- Many generators are located in the area. Network availability affects generation exploitation
- Extreme events near the coast could split 500-220kV networks limiting the power flows from north to south Chile
    - ➢ energy not supplied increases
- The new interconnection between Chile and Argentina improves the resilience of the system during critical events increasing the SoS

Unavailability of network components

- Very high levels of network components unavailability have been assumed in Coquimbo and Valparaiso regions to simulate the effect of extreme events in those regions and to assess their impact on the security of the whole Chilean electric power system

- Four scenarios with increased unavailability rates have been compared with baseline scenario not affected by extreme events:
  - Increase in energy not supplied has been highlighted
  - Benefits from increased exchange capacity between Argentina and Chile (+900 MW) during critical events has been assessed analysing scenarios **WITHOUT** and **WITH** the future interconnection line

- Lines, transformers and generation power plants availabilities have been reduced only in the area of interest. Normal availability conditions have been kept in the rest of the system (including the new interconnection line)

- Availability of system components has been simulated with random drawings of outages included in probabilistic Monte Carlo method

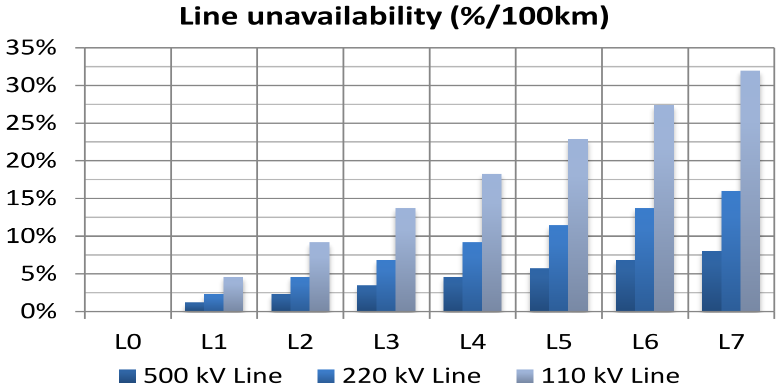
Unavailability of network components

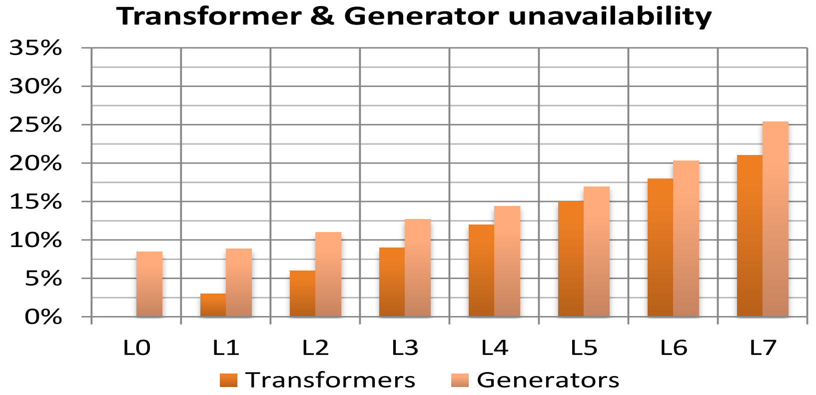
Type	Unit	Unavailability Level							
		L0	L1	L2	L3	L4	L5	L6	L7
Line 500 kV	%/100km	0.0114	1.14	2.28	3.42	4.56	5.70	6.84	7.98
Line 220 kV	%/100km	0.0228	2.28	4.56	6.84	9.12	11.40	13.68	15.96
Line 110 kV	%/100km	0.0456	4.56	9.12	13.68	18.24	22.80	27.36	31.92
Transformer 500/220 kV	%	0.03	3.00	6.00	9.00	12.00	15.00	18.00	21.00
Transformer 220/110 kV	%	0.03	3.00	6.00	9.00	12.00	15.00	18.00	21.00
Generators (*)	%	8.50	8.90	11.00	12.70	14.40	16.90	20.30	25.40

(*) average unavailability of generators in the area of interest

normal unavailability (no extreme events)

high unavailability levels simulated





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Results

Results are shown according to the following three indicators that measure the **Expected Energy Not Supplied (EENS)**. EENS can be defined as the energy not served to the load due to unavailability in generation and/or transmission system components, taking into account also restrictions made up by the transfer capacity of network components

1) **EENS in Chile**: EENS of the average week in Chile

2) **Weekly EENS in SIC**: EENS over the year with focus on SIC area

3) **Hourly EENS in SIC**: energy not supplied expected in a single hour in SIC area

Expected energy not supplied (EENS)

The following causes of energy not supplied have been considered in GRARE model

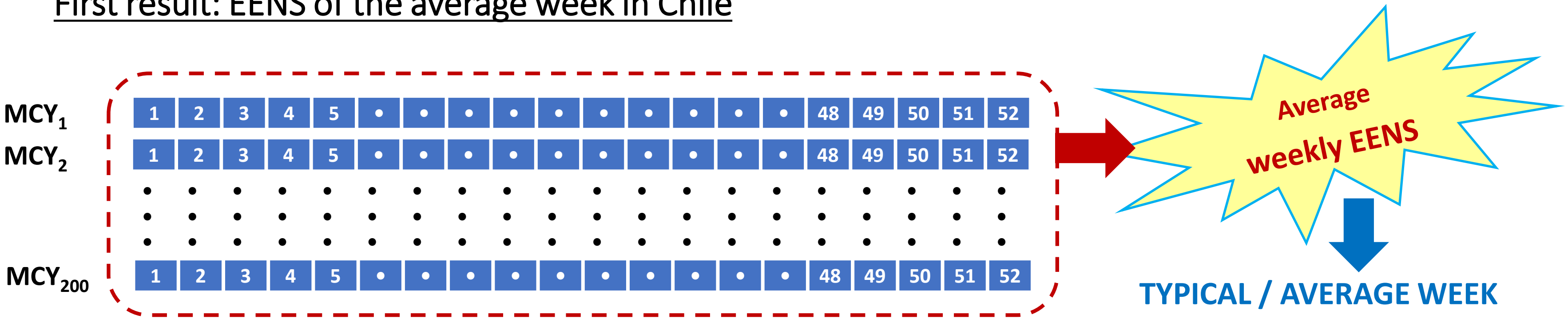
- **Lack of Power (LOP)**: the dispatched power plants of the whole system are not be able to fulfil the demand. The dispatched units may be not enough to meet the demand due to forced outages of power plants or intermittency of VRES
- **Lack of Interconnection (LOI)**: the exchange capacity with neighbouring areas is not always enough to cover the import need
- **Line/Transformer Overload (LTO)**: overload of network elements, like lines and transformers, that cannot be solved
- **Network Splitting (NSP)**: formation of network islands, due to the unavailability of one or more links in the network, with demand greater than generation
- **Isolated Node (ISN)**: out of service of lines or transformers which causes isolated loads

Key risks of extreme events

- Extreme events like heavy storms and earthquakes could be very damaging to network components forcing them unavailable also for long periods
- These events produce the unavailability of many system components at the same time, causing possible lack of power in the system, lack of interconnection, line and transformer overloads but also increasingly critical network splitting situations affecting the possibility to supply the load
  - Under normal conditions, network splitting situations are limited; first of all because normal conditions are considered during planning phase and second because, in general, the system operator is able to limit these situations working promptly on the rest of the network
  - On the contrary, the extreme conditions simulated in this activity increase a lot network splitting situations due to multi-outages in the system. Therefore network splitting and isolated node situations play an important role in EENS assessment
- An in-depth monitoring of network components has been applied in the area of interest to analyse not only system problems but also local critical situations (500-220-110 kV lines, 500/220 kV transformer)

EENS in Chile – Average week

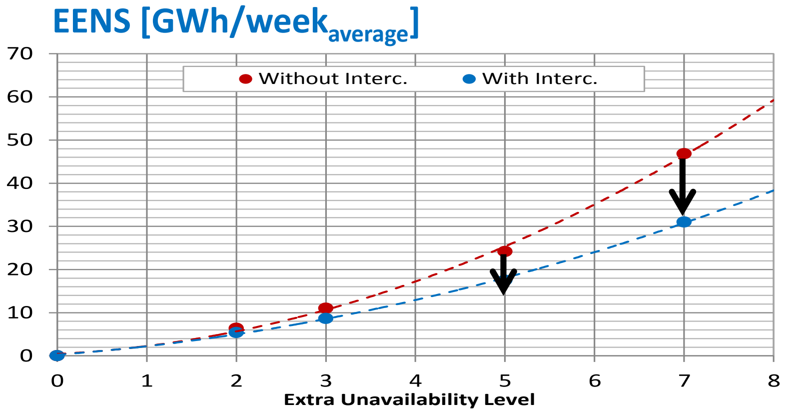
First result: EENS of the average week in Chile

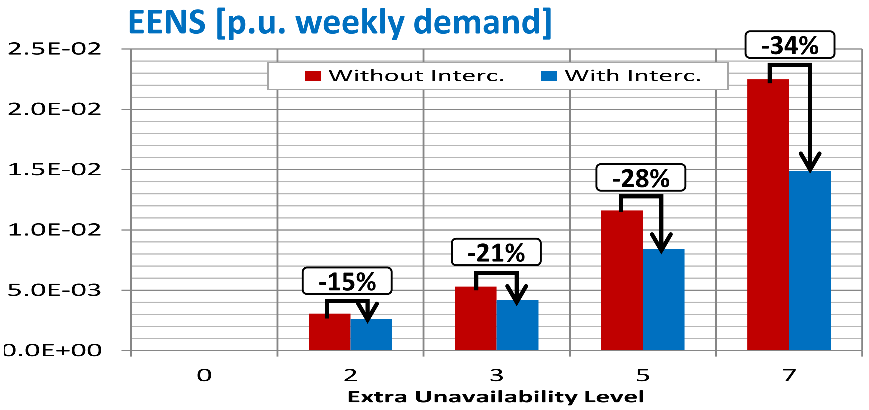


For each simulated unavailability level (L0, L2, L3, L5, L7), both with and without the new interconnection line

- 10,400 weeks (200 Monte Carlo) Years with thousands of grid configurations were simulated
- 10,400 values of EENS (GWh/week) in Chile were recorded and the average value of weekly EENS was calculated to highlight, in a first step, the global increase of unserved energy with growing unavailability of network components

EENS in Chile – Average week





- Nearly parabolic growth of EENS has been highlighted from simulation results when extreme events increase their impact on the system components
- The new interconnection allows to reduce the unserved load increasing the security of supply during extreme events
- Benefits from the new interconnection grow with increasing unavailability level: up to 34% of load saved at the highest level

EENS in Chile – Average week

- Average weekly EENS across unserved load reasons

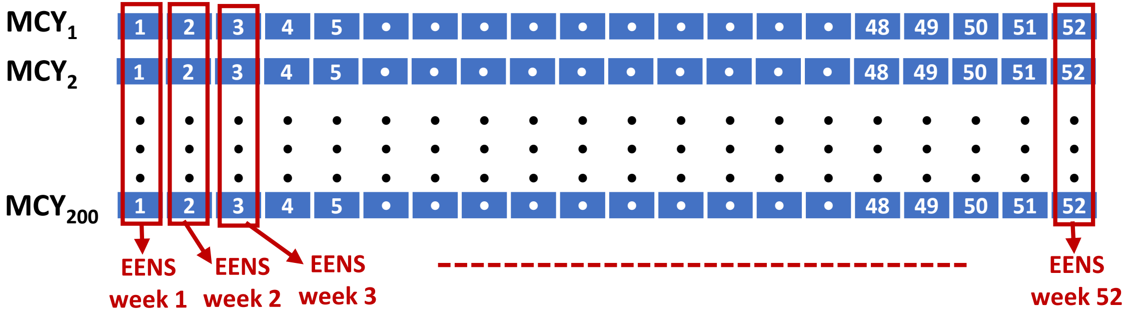
Scenarios	Unavailability Level	New Interconnection	LOP [GWh/wk]	LOI [GWh/wk]	LTO [GWh/wk]	ISN [GWh/wk]	NSP [GWh/wk]	TOTAL [GWh/wk]	EENS Reduction	EENS [p.u. demand]
SCENARIOS	L0	Without	0.0	0.0	0.01	0.01	0.04	0.06	*-6.3%*	2.7E-05
		With	0.0	0.0	0.01	0.01	0.04	0.05		2.6E-05
	L2	Without	0.0	0.4	2.0	0.7	3.3	6.4	*-14.9%*	3.1E-03
		With	0.0	0.0	1.4	0.7	3.3	5.4		2.6E-03
	L3	Without	0.0	1.0	4.1	1.1	4.9	11.0	*-21.4%*	5.3E-03
		With	0.0	0.1	2.7	1.1	4.9	8.7		4.2E-03
	L5	Without	0.0	3.5	10.7	1.7	8.2	24.2	*-28.0%*	1.2E-02
		With	0.0	0.3	7.2	1.7	8.2	17.4		8.5E-03
	L7	Without	0.0	9.6	23.5	2.4	11.4	46.8	*-33.9%*	2.2E-02
		With	0.0	1.1	16.0	2.4	11.4	30.9		1.5E-02

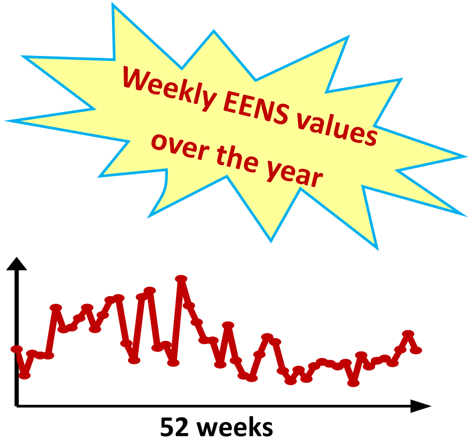
(LOP: Lack Of Power; LOI: Lack Of Interconnection; LTO: Line and Transformer Overload; ISN: Isolated node; NSP: Network Splitting)

- Network splitting situations become more and more frequent during critical events due to multiple outages of network components
- The highest unavailability levels (L5, L7) produce EENS three orders of magnitude higher than the normal condition (L0)
- The new interconnection improves power flows management reducing network overloads and increasing security of supply

Weekly EENS in SIC

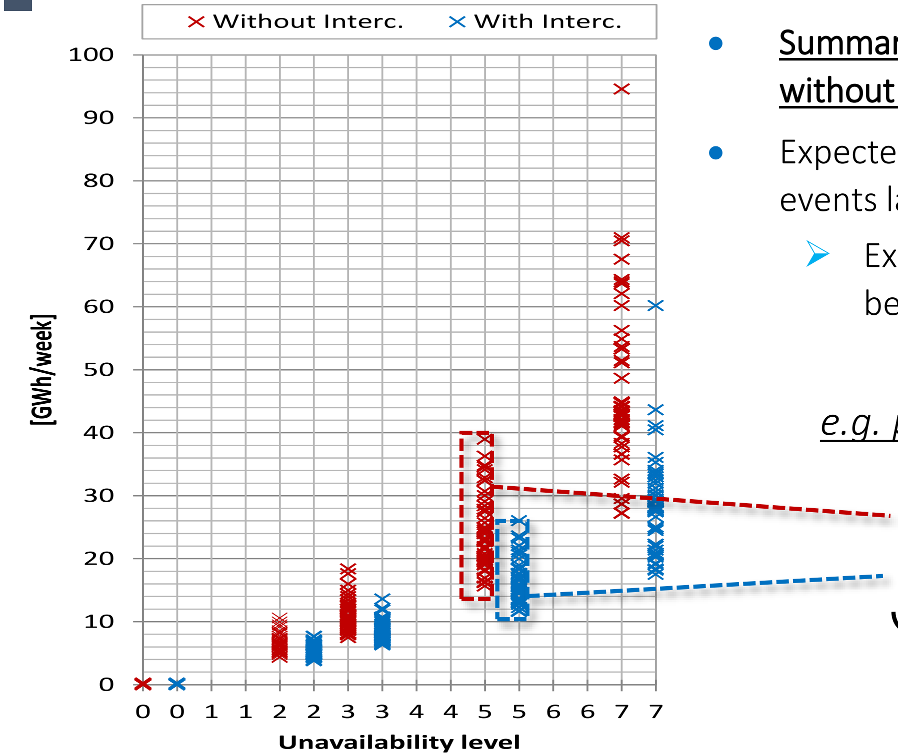
Second result: EENS over the year with focus on SIC area





- EENS of SIC was calculated for each week of the year (52 values)
- The value of every single week is the average of a 200-week sample with different conditions of system components availability, VRES production and day-ahead load forecast applied at the same week of the target year
- Comparison of results with and without the new interconnection allows to assess the saved demand (i.e. the avoided EENS) thanks to the interconnection

Weekly EENS in SIC



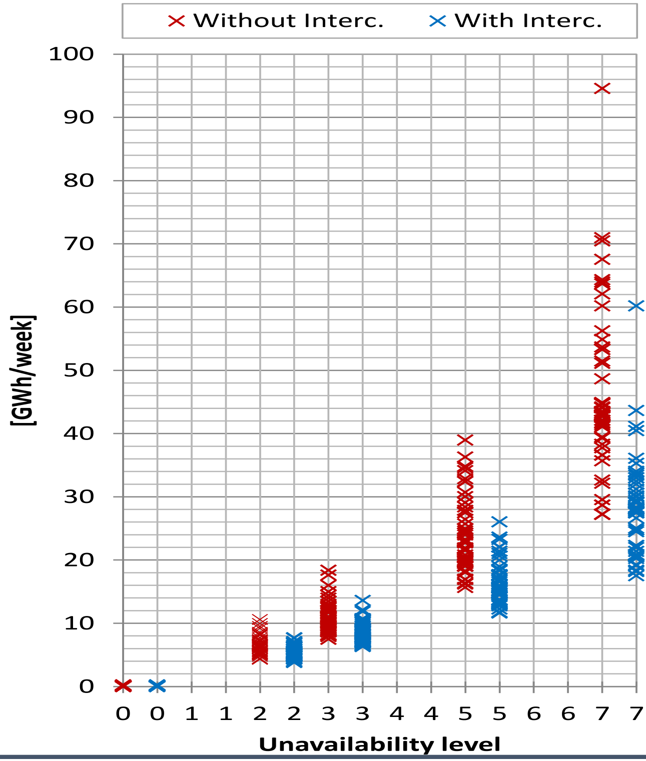
- <u>Summary of weekly EENS for all analysed scenarios, with and without the new interconnection</u>
- Expected energy not supplied if network outages due to extreme events last one week
  - Extreme events simulated for each week of the target year because their occurrence is unpredictable

<u>e.g. potential weekly EENS with Level 5</u>

- *range 15 ÷39 GWh/week without intercon.*
- *range 12 ÷26 GWh/week with intercon.*

avoided EENS 3 ÷13 GWh/week

Weekly EENS in SIC



Summary of the main statistical parameters

- Without new interconnection

GWh/wk	L0	L2	L3	L5	L7
Max	0.3	10.6	18.4	39.0	94.6
Min	0.0	3.6	7.4	15.2	23.2
Avg	0.1	6.3	11.0	23.9	46.1
94%ile	0.2	9.2	15.0	34.6	67.6
6%ile	0.0	4.4	8.1	16.4	28.6

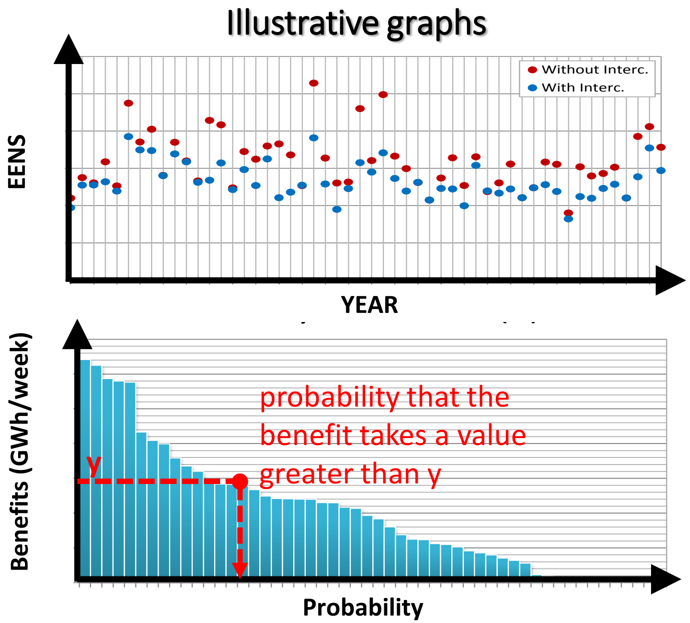
- With new interconnection

GWh/wk	L0	L2	L3	L5	L7
Max	0.3	7.7	13.6	26.0	60.2
Min	0.0	3.3	6.0	11.6	17.0
Avg	0.0	5.3	8.4	16.4	28.1
94%ile	0.2	7.0	10.7	22.1	40.5
6%ile	0.0	4.0	6.5	12.2	18.4

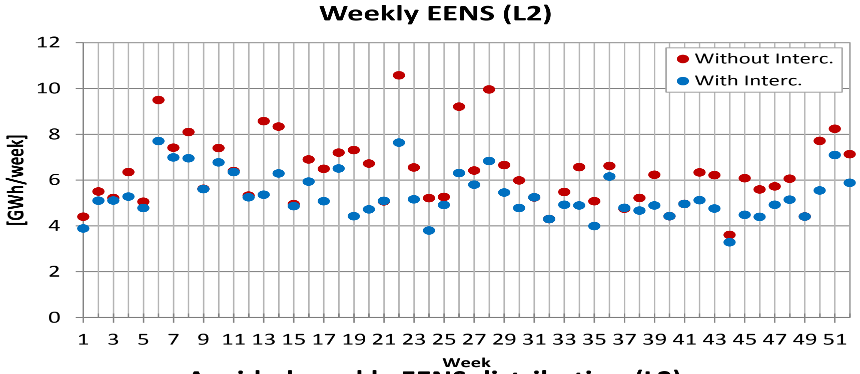
Weekly EENS in SIC

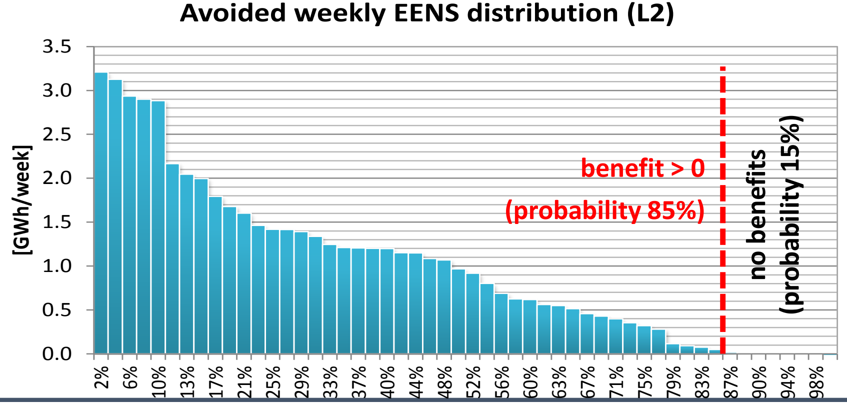
Quantitative results and more details about the effect of the new interconnection on the security of supply are shown in the following slides, for each selected level of system components unavailability

- Weekly values of EENS (GWh/week) over the year
  - Without interconnection: red points
  - With interconnection: blue points
- The difference between red and blue points represents the avoided EENS, therefore the benefit from the interconnection (GWh/week)
- Benefit (or avoided EENS) distribution functions are highlighted



Weekly EENS in SIC

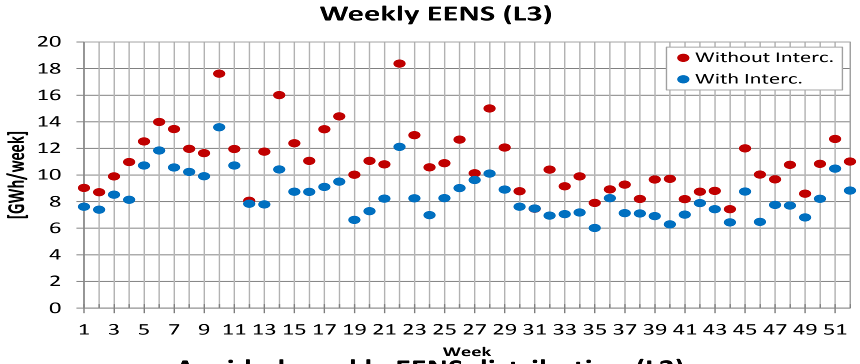


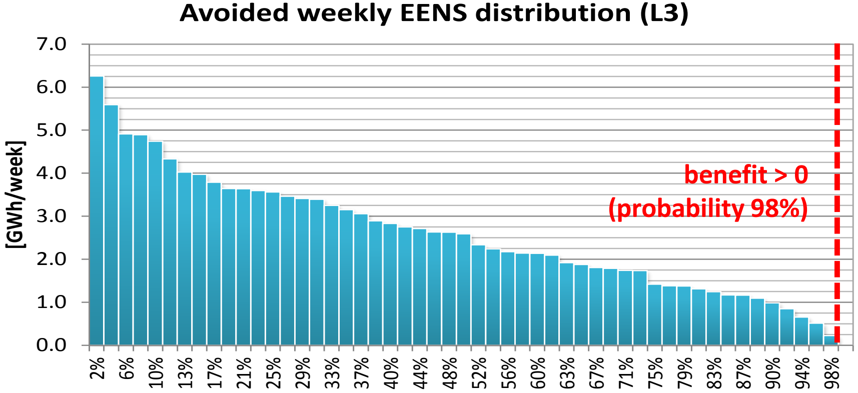


Unavailability level: L2

- Maximum weekly EENS
  - Without: 10.6 GWh/week
  - With: 7.7 GWh/week
- Minimum weekly EENS
  - Without : 3.6 GWh/week
  - With: 3.3 GWh/week
- Avoided EENS with new interconnection line
  - Max: 3.2 GWh/week
  - Min: 0.0 GWh/week
  - Avg: 1.0 GWh/week

Weekly EENS in SIC

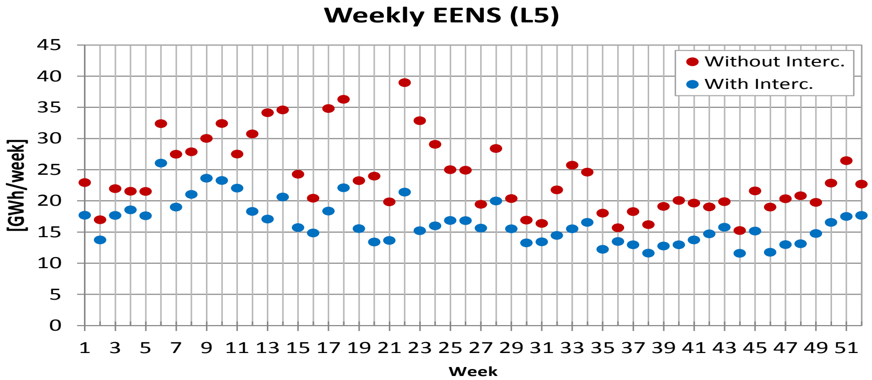


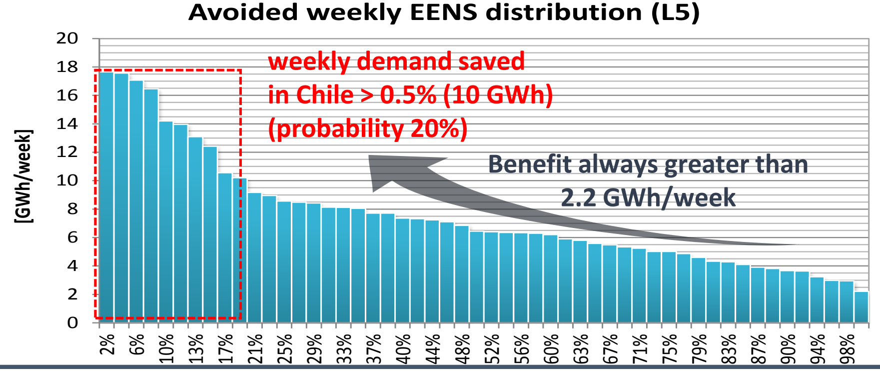


Unavailability level: L3

- Maximum weekly EENS
  - Without: 18.4 GWh/week
  - With: 13.6 GWh/week
- Minimum weekly EENS
  - Without: 7.4 GWh/week
  - With: 6.0 GWh/week
- Avoided EENS with new interconnection line
  - Max: 6.3 GWh/week
  - Min: 0.0 GWh/week
  - Avg: 2.6 GWh/week

Weekly EENS in SIC

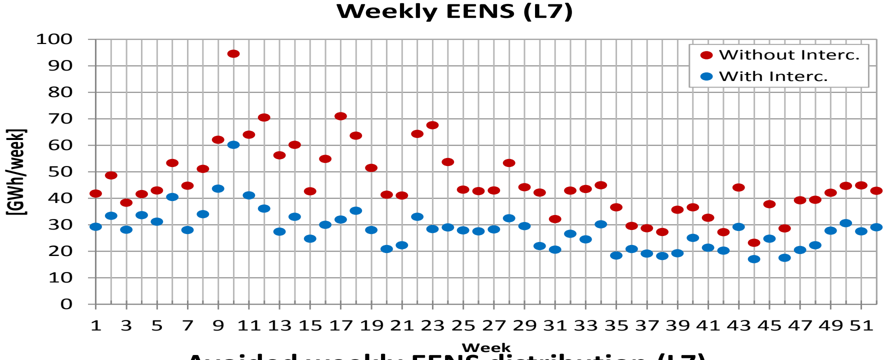


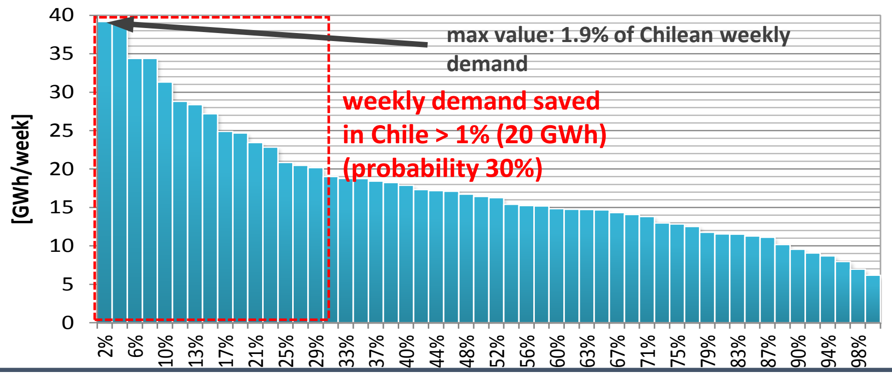


Unavailability level: L5

- Maximum weekly EENS
  - Without: 39.0 GWh/week
  - With: 26.0 GWh/week
- Minimum weekly EENS
  - Without: 15.2 GWh/week
  - With: 11.6 GWh/week
- Avoided EENS with new interconnection line
  - Max: 17.6 GWh/week
  - Min: 2.2 GWh/week
  - Avg: 7.5 GWh/week

Weekly EENS in SIC



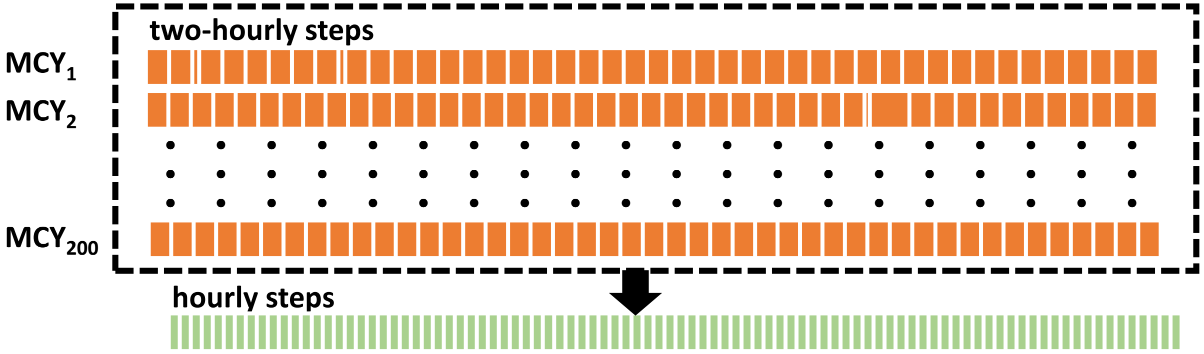


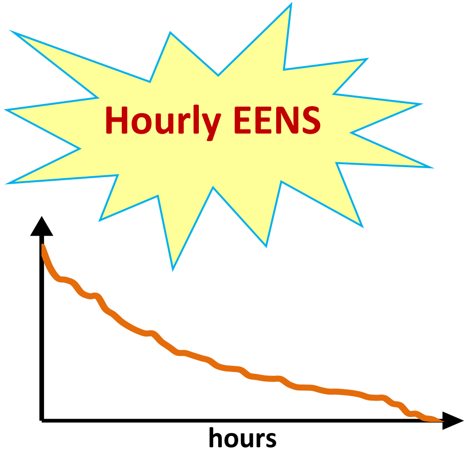
Unavailability level: L7

- Maximum weekly EENS
  - Without: 94.6 GWh/week
  - With: 60.2 GWh/week
- Minimum weekly EENS
  - Without: 23.2 GWh/week
  - With: 17.0 GWh/week
- Avoided EENS with new interconnection line
  - Max: 39.2 GWh/week
  - Min: 6.2 GWh/week
  - Avg: 18.0 GWh/week

Hourly EENS in SIC

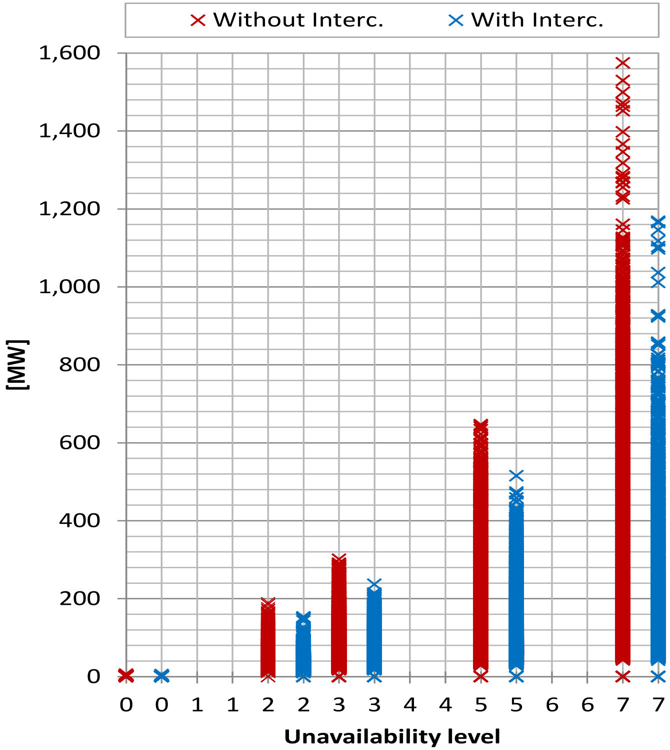
Third result: energy not supplied expected in a single hour





- EENS of SIC was calculated for each hour of the year (8,760 values) to analyse the possible impact of extreme natural events on a single hour
- The value of every single step (two-hourly) is the average of a 200-step sample with different conditions of system components availability, VRES production and day-ahead load forecast applied at the same week of the target year
- Hourly results (8,760 hours) were extracted by two-hourly steps (4,380)

Hourly EENS in SIC



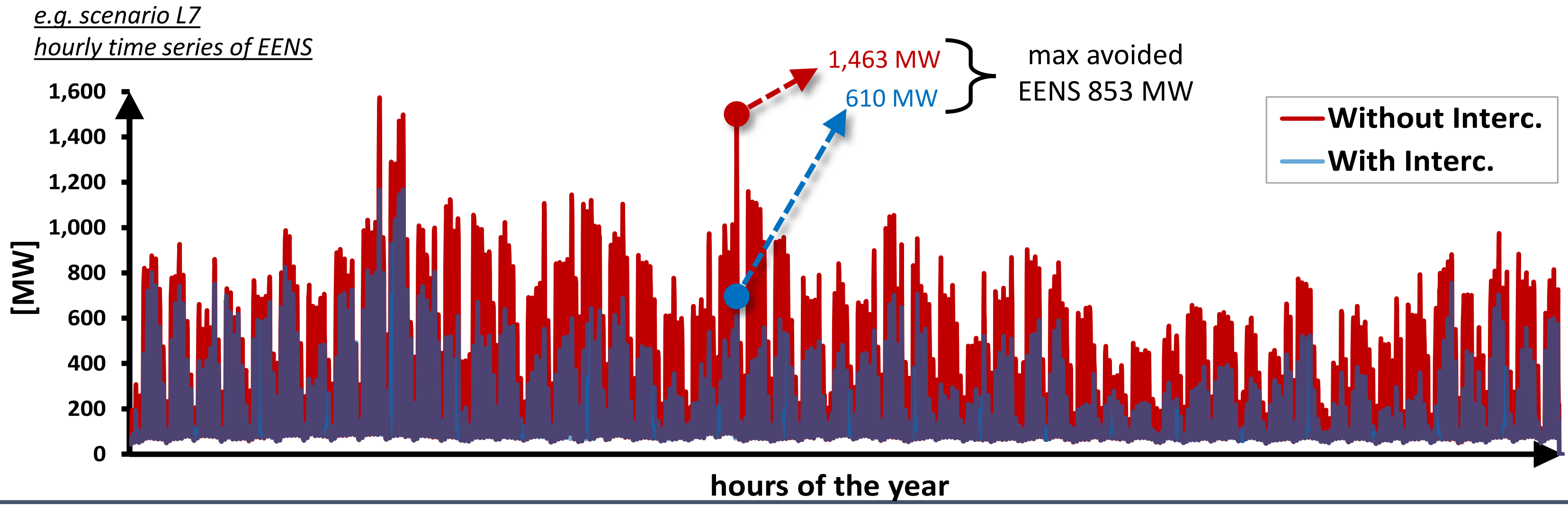
- Maximum EENS expected in one hour

[MW]	Without Intercon.	With Intercon	Difference
L0	6	5	-1
L2	190	153	-37
L3	301	237	-64
L5	646	515	-131
L7	1,575	1,168	-407

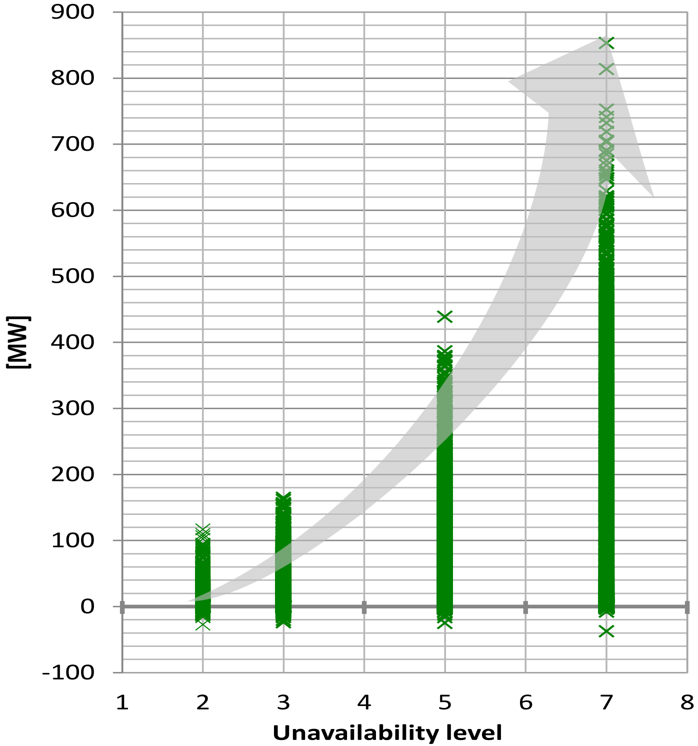
- Without the new interconnection the maximum hourly unserved load in SIC could reach **13% of peak power demand with the highest unavailability level (L7)** simulated with GRARE
- The new interconnection is able to reduce unserved load during extreme events by up to more than 25%

Avoided hourly EENS in SIC

- The difference between the hourly time series of EENS resulting from scenarios without the new interconnection (red line) and scenarios with the new interconnection (blue line) allows to <u>assess the EENS avoided in SIC thanks to the new interconnection, hour by hour</u>



Avoided hourly EENS in SIC



- Benefits from the new interconnection on security of supply increase with growing system components unavailability
- <u>Maximum avoided energy not supplied in SIC in a single hour</u>:
  - L2: 1.0% peak load (117 MW)
  - L3: 1.4% peak load (164 MW)
  - L5: 3.7% peak load (439 MW)
  - L7: 7.2% peak load (853 MW)
- The maximum benefit from the new interconnection is close to its NTC with the highest simulated unavailability (L7): NTC 900 MW = 7.6% of SIC peak load
- Benefits in a single hour are in a wide range (negative values could occur in a very limited set of hours)

Hourly EENS in SIC

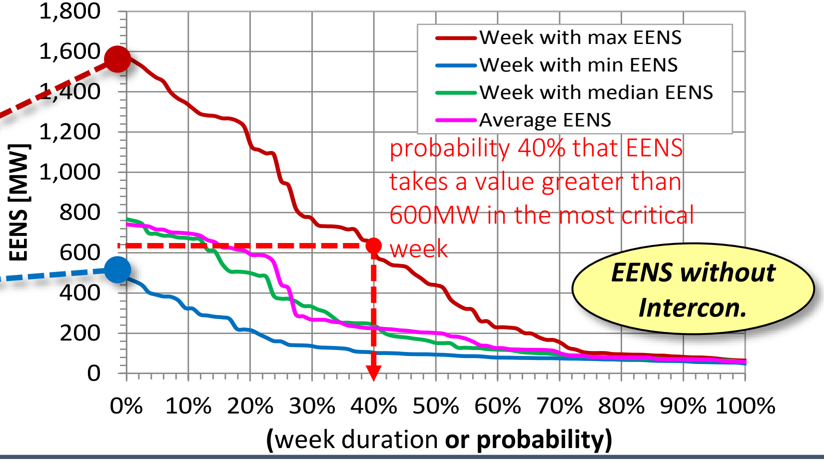
More details about the impact of extreme events on a single hour are highlighted in the following slides. The following results are shown for each unavailability level

- Hourly EENS distribution functions over a week for different weeks of the year
  - Weeks with minimum and maximum weekly EENS providing the range of possible results depending on when the extreme event could occur
  - Week with median EENS
  - Average week (typical week)

Maximum lost load in the most critical week for security of supply (e.g. 1,575 MW)

Maximum lost load in the least critical week for security of supply (e.g. 475 MW)

e.g. scenario L7



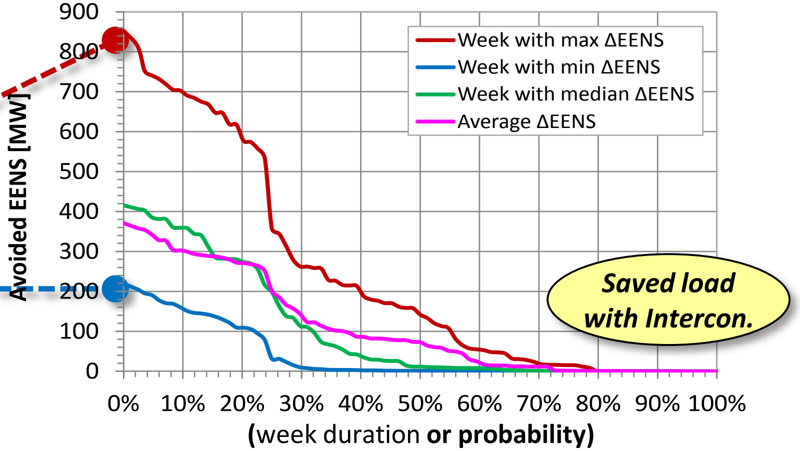
Hourly EENS in SIC

- Hourly saved load distribution functions over a week are highlighted. Saved load is the avoided EENS due to the new interconnection as difference between EENS without or with the interconnection in the same hour of the year. Different weeks are shown
  - Week with maximum benefit (the greatest reduction of weekly EENS)
  - Week with minimum benefit (the smallest reduction of weekly EENS)
  - Week with the median value of weekly EENS reduction
  - Average week (typical week)

Maximum saved load in the most critical week for security of supply (e.g. 850 MW)

Maximum saved load in the least critical week for security of supply (e.g. 220MW)

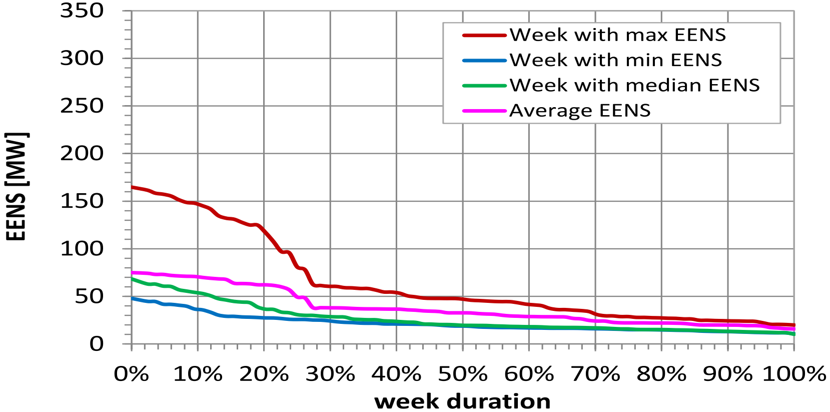
e.g. scenario L7



Hourly EENS in SIC without the new interconnection

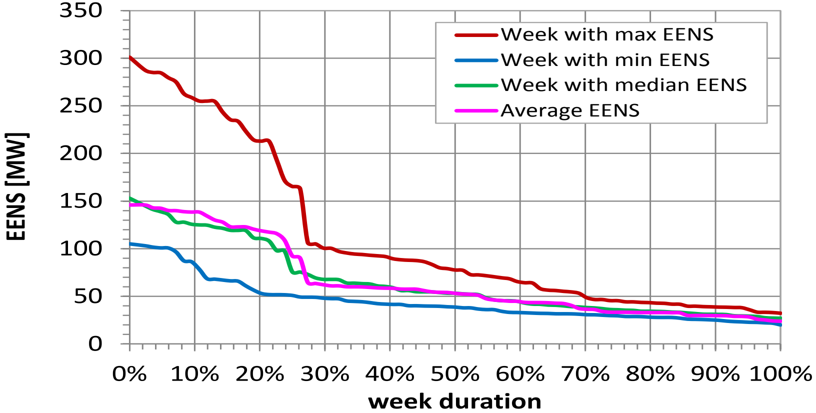
Unavailability level L2

- Simulated extreme events cause EENS in every hour of the week
- Without interconnection, the maximum hourly lost load in a week is in the range 48÷165 MW (0.4÷1.4% SIC peak load)



Unavailability level L3

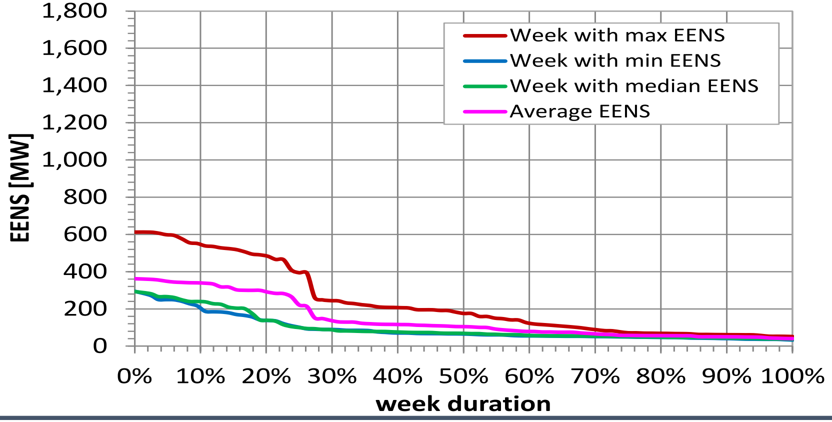
- Simulated extreme events cause EENS in every hour of the week
- Without interconnection, the maximum hourly lost load in a week is in the range 105÷300 MW (0.9÷2.5% SIC peak load)



Hourly EENS in SIC without the new interconnection

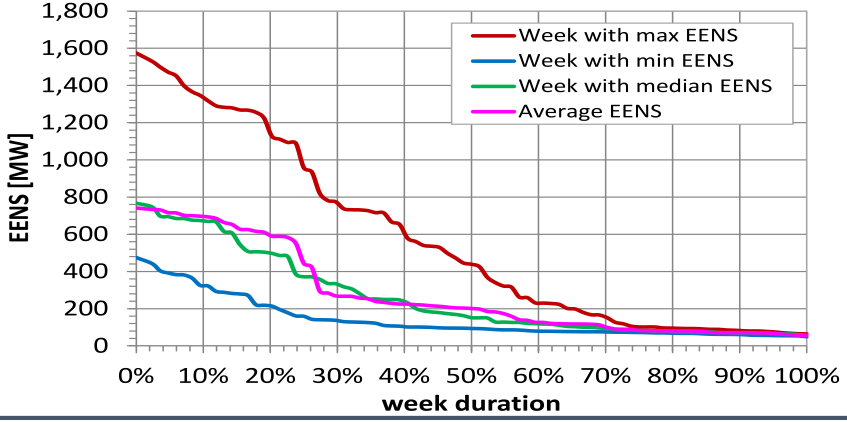
Unavailability level L5

- Simulated extreme events cause EENS in every hour of the week
- Without interconnection, the maximum hourly lost load in a week is in the range 295÷612 MW (2.5÷5.2% SIC peak load)



Unavailability level L7

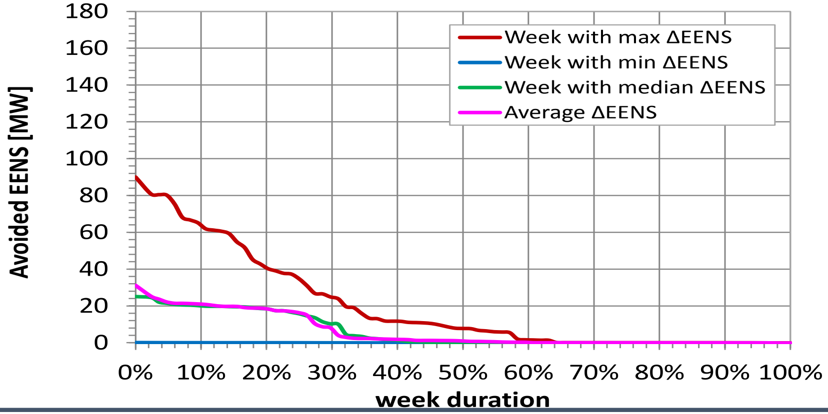
- Simulated extreme events cause EENS in every hour of the week
- Without interconnection, the maximum hourly lost load in a week is in the range 475÷1,575 MW (4.0÷13.3% SIC peak load)



Hourly EENS in SIC - Saved load with interconnection

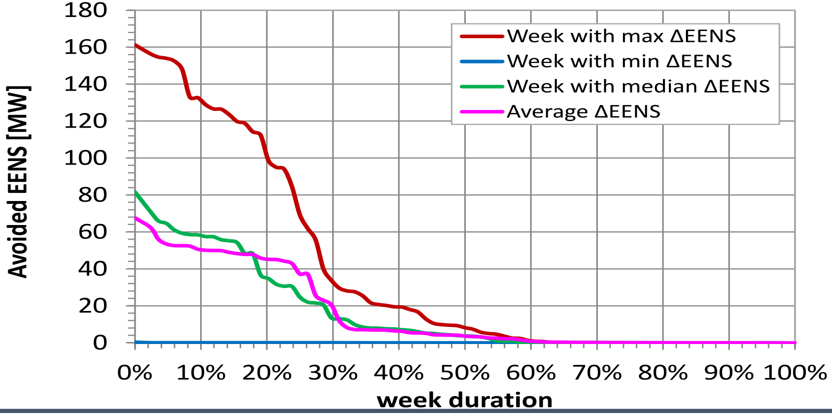
Unavailability level L2

- With the new interconnection the maximum avoided EENS in a week reaches 90 MW (0.8% SIC peak load)
- The new interconnection allows EENS reduction in 60% of the hours of the week



Unavailability level L3

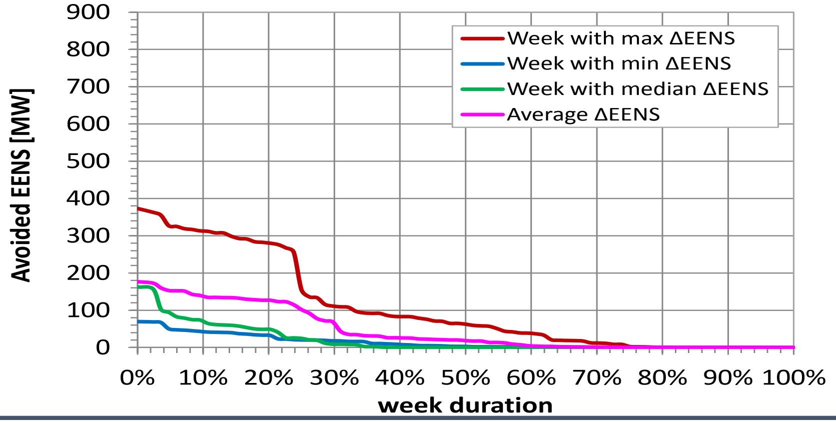
- With the new interconnection the maximum avoided EENS in a week reaches 164 MW (1.4% SIC peak load)
- The new interconnection allows EENS reduction in 60% of the hours of the week



Hourly EENS in SIC - Saved load with interconnection

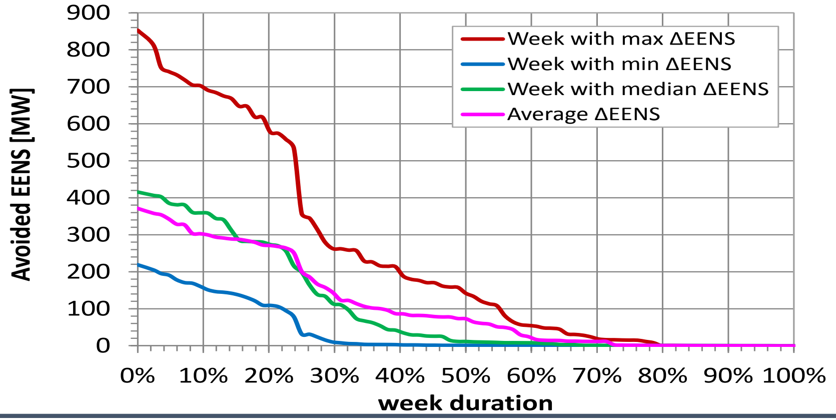
Unavailability level L5

- With the new interconnection the maximum avoided EENS in a week is between 70 MW and 373 MW (0.6÷3.1% SIC peak load)
- The new interconnection allows EENS reduction in 75% of the hours of the week



Unavailability level L7

- With the new interconnection the maximum avoided EENS in a week is between 219 MW and 853 MW (1.9÷7.2% SIC peak load)
- The new interconnection allows EENS reduction in 80% of the hours of the week



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Conclusions

- Extreme events with impact on the electric power system over a week cause a large range of weekly lost demand depending on the system components availability and the period of year events can occur
- Extreme natural events affecting electric power system cause a worsening on the security of supply, which quickly decreases with increasing intensity of the critical event (parabolic trend)
- In SIC area, the weekly energy not supplied due to the most critical event analysed (*) could reach the following values
  - 1.1÷4.5% average weekly demand of Chile, without new interconnection
  - 0.8÷2.9% average weekly demand of Chile, with new interconnection

  Benefits from saved load during one week in the range 12÷69 MUSD (**)
- Security of supply benefits from the new interconnection assuring growing benefits with increasing system components unavailability (assuming that the interconnection remains available)

(*) the highest unavailability level considered causes an impact on the system similar to the one occurred with the earthquake in 2015
(**) Value Of Lost Load (VOLL) assumed equal to 2 MUSD/GWh

Conclusions

- The new interconnection between Chile and Argentina would allow a more flexible operation of both electric power systems
  - During normal conditions it allows a better exploitation of sources
  - During contingency conditions it is able to increase the resilience, reliability and efficiency of both electric power systems
- The new interconnection is able to reduce unserved load during extreme natural events (up to -41% of EENS in the most critical week)
- Among the analysed cases, maximum unserved load in one hour reaches 13% of SIC peak load (1,575 MW) without the new interconnection
  - the new interconnection allows the reduction of EENS saving up to 7.2% of SIC peak load (850 MW)
- The new interconnection has limited influence on EENS due to damages on distribution network. Mitigation of this part of EENS might be provided by distributed generation or storage connected to the areas affected by the curtailments

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