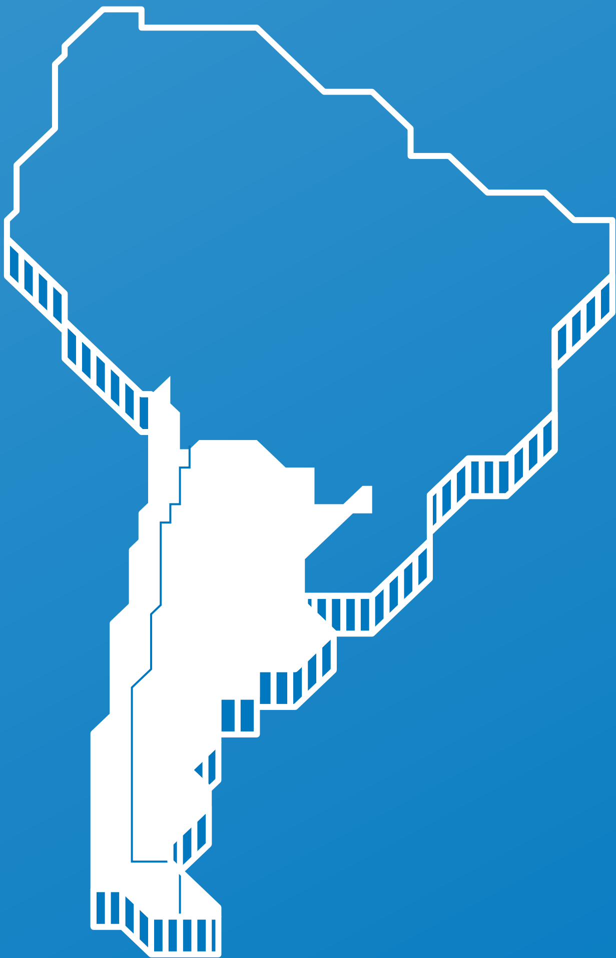
Executive Summary

Foundation

Chile | Argentina



Variable Renewable Energy Sources (VRES) deployment and role of interconnection lines for their optimal exploitation: the **Chile-Argentina** case study

This research series was conducted by Enel Foundation with the technical support of CESI, a world-leading consulting and engineering company in the field of technology and innovation for the electric power sector.

enel Foundation CESI Shaping a Better Energy Future

Concept design and realization
Grafica Internazionale Roma s.r.l.

Number of pages
40 pages

Publication not for sale

Edited By
Fondazione Centro Studi Enel
00198 Rome,
Viale Regina Margherita 137
Tax I.D. 97693340586

Research finalized in January 2018.
Publication issued in May 2019.

Table of contents

List of acronyms

BAT	Best Available Technology
CAMMESA	Compañia Administradora del Mercado Mayorista Eléctrico
CCGT	Combined Cycle Gas Turbine
CEN	Coordinador Eléctrico Nacional
CNE	Comisión Nacional de Energía
COP	Conference of the Parties
GDP	Gross Domestic Product
GHG	Green House Gas
HVDC	High Voltage Direct Current
LCOE	Levelized Cost of Energy
MINEM	Ministerio de Energía y Mineria (Argentina)
NTC	Net Transfer Capacity
PV	PhotoVoltaic
RES	Renewable Energy Sources
SIC	Sistema Interconectado Central
SING	Sistema Interconectado del Norte Grande
VRES	Variable Renewable Energy Sources

1 Introduction

Latin America is endowed with outstanding renewable energy resources, namely wind and solar energy, but some areas offer also a good potential of biomass, hydro and geothermal power production. The current decrease of upfront investment costs in RES power plants makes power production from green resources more and more competitive with conventional generation from fossil fuels, especially considering that the ongoing trend in investment cost reduction is expected to continue in the coming years. In addition, the achievement of the COP21 targets, widely shared by the Latin American countries[1], further enhances the superiority of RES power plants against conventional generation, when accounting the externality costs associated to the power generation (see costs associated to the various GHG emissions and particulate). The two above driving factors (lower investment costs and progressive decarbonisation of the power sector) are prompting an accelerated deployment of RES power plants in Latin America.

Unfortunately, the location of new power plants exploiting RES is strictly constrained to the geographical availability of the resources (wind, sun, geothermal, biomasses, water). Hence, the connection of a large quantity of RES generation shall be carefully examined in advance to avoid operating conditions calling for RES generation curtailment for security reasons (e.g.: overloads due to insufficient power transfer capability; impossibility to balance the system due to the inflexibility of the conventional generation, poor voltage profiles, risk of cascading effects following an outage on a grid component / generating unit, etc.). The limitation in the development of RES generation, particularly the variable generation such as wind and PV, can be overcome exploiting the existing interregional or cross-border interconnections, reinforcing the existing ones and building new cross-border corridors.

Within the context recalled above, this study on "*VRES deployment and role of interconnection lines for their optimal exploitation*" aims namely at examining the optimal technical-economic penetration of Variable Renewable Energy Sources (VRES) generation (wind and solar) in some Latin American (LATAM) countries and clusters of countries accounting for the possible cross border power exchanges.

The study answers the following two questions:
- *What is the optimal penetration of VRES generation within a country considering the technical constraints in system operation while minimising the production costs?*
- *To what extent reinforcing the transmission grid can help enhance the deployment of VRES generation within a country and between interconnected countries?*

1. All Latin American countries signed the Paris Agreement and already ratified the Agreement. See the updated status of Paris Agreement ratification and entry into force on: http://unfccc.int/paris_agreement/items/9444.php

The analysis is performed for the target year 2030 and starts from a given set of thermal/hydro generation that includes the already existing plants, the ones under construction and the planned ones, which will be built before the target year.

This first report is focused on Chile and Argentina (Cluster 1), the second one is focused on Argentina, Brazil and Uruguay (Cluster 2) and the third one is focused on Colombia, Peru and Ecuador (Cluster 3). Finally, there will be a continental report featuring the main findings across the three geographical clusters including all the above-mentioned countries.

Argentina is present in the first two clusters of countries, connected in the first case only to the Chilean system, and in the second one to Uruguay and Brazil. Whereas the first report is based on data and projections collected in 2017, the second one is based on more updated data and projections (collected in 2018).

Furthermore, it should be highlighted that the results of the optimisations carried out during the activities are affected by the characteristics of the interconnected system under examination, notably the load patterns of each country, the conventional generation fleet and the potential of VRES generation deployment in the various regions. These factors have a direct impact on the benefits arising from new VRES plants and the limitations they face. For instance, the presence of big hydropower plants with reduced storage capacity (and for this reason not able to reduce significantly their production without wasting free energy) might represent an operational constraint preventing a higher penetration of VRES technologies, which require high flexibility in the system.

In interconnected systems, the complementarity between the resources and between their availability in different countries is a key driver towards the development of VRES plants, especially when there is enough transmission capacity close to the areas characterised by the higher potential of renewable energy sources. In this context, the interconnection between Chile and Argentina allows a more effective exchange of renewable production surplus whenever necessary with respect to the interconnection on the Eastern border towards Uruguay and Brazil. This is due to the fact that interconnections between Argentina and Chile are located closer to the Argentinean regions with best wind regimes (southern Argentinean region) and also favourable PV regimes (northern Chilean and Argentinean regions).

Therefore, the differences in data used as basis for the optimization (2017 vs 2018) and the overall characteristics of the analysed power systems in the Cluster 1 and 2 cause obviously a slight variation of the optimal amount of wind and PV installable in Argentina: however, as it will be shown, the results remain quite aligned, being the gap between the two final values lower than 10%.

2 The study process

The study was carried out according to the following steps:

- Definition of the **Reference scenario.** The "Reference scenario" is obtained from the information gathered from available studies on the electric power system development for Argentina and Chile at the target year 2030 or for years close to it. This "Reference scenario" represents the starting point to build new scenarios optimising the VRES generation deployment

- **"Best Available Technologies today" scenario ("BAT scenario").** The "BAT scenario" is built starting from the "Reference scenario" by modifying the generation expansion pattern optimising the amount of new VRES generation, particularly PV and wind, taking into account their potential across the territory, and their costs and performances. In the optimisation process, we took into account the system operational constraints in terms of reserve to be warranted in each hour of the year, limits in the power transfer capacity in the transmission grid, requirements on inertia and system stability. In the elaboration we considered the best available technology (BAT) today available for PV and wind power plants.

To better appraise the results of the "BAT scenario" and assess the stability of the results against uncertainties, some variants to this scenario have been investigated:

- *Variant 1*: focused on a scenario of higher demand in the countries due to combination of stronger economic growth, population increase and higher electricity penetration. A significant presence of emobility in the biggest cities is also considered.
- *Variant 2*: focused on a scenario of lower demand, with a higher overgeneration risk. The benefits related to more flexibility of the generation fleet (lower minimum production constraint of existing plants or presence of electrical storage systems) are assessed.

- **"Breakthrough in RES generation technologies scenario" ("Breakthrough scenario").** Finally, a more aggressive scenario has been investigated aiming at an accelerated decarbonisation of the future Chilean and Argentinean power systems. In other words, we have assumed that all new generation assets shall be "carbon free". To do so, we made the hypothesis that the new RES generating units would be based on new technologies that would be able to provide system auxiliary services, like frequency regulation, hence avoiding the need for additional upward and downward reserve, and voltage regulation. Where necessary, to avoid unacceptable overgeneration situations, the VRES power plants are associated to storage devices, the role of which is basically load shifting.

3 Computational tools

The optimisation process is based on a set of deterministic and probabilistic computational tools. In particular, to assess the system adequacy and the risk of over-generation in presence of an increasing share of VRES the GRARE (Grid Reliability and Adequacy Risk Evaluator) software has been adopted. GRARE is developed by CESI and owned by Terna, the Italian TSO. GRARE is a powerful computer-based tool which evaluates the reliability and the economic operation of large electric power systems. GRARE supports medium and long-term planning studies using probabilistic Monte Carlo approach and modelling in detail the transmission networks.

The probabilistic simulation of one operational year considers thousands of different system configurations (different load, availability of generation fleet and transmission networks, VRES power production…), weighted by their probability to happen. With this approach, results depict the expected operation of the whole system, obtained analysing many real operational states, and detailed information about each component of the system can be evaluated.

The most interesting results are the expected benefits for the system in terms of variation of generation costs, taking into account possible differences in the Expected Energy Not Supplied (EENS[2]). Also the expected production of the VRES plants, considering potential curtailments due to system or transmission constraints, provides important information for the evaluation of their profitability and supports the definition of the optimal amount of power to install.

The definition of the VRES plants producibility based on geographical information combined with the usage of a detailed transmission system model allows to clearly identify the best areas where PV and wind plants should be developed in order to maximize the benefits for the system.

More info on the GRARE tool is available on www.cesi.it/grare.

2 EENS represents the Load that cannot be supplied during the year due to system constraints such as Lack of Power (not enough available generation in the system), Lack of Interconnection (when a higher interconnection with other areas might provide the missing power), Line Overload (when it is necessary to cut some load to resolve line overloads that cannot be resolved only with a different dispatching of generators).

4 Reference Scenario and study assumptions

The "Reference scenario" has been built starting from the available public domain information. The three main building blocks of the "Reference scenario" are: the yearly energy demand, the generation fleet and the structure of the transmission grid. As for Argentina, information on the evolution of the power sector is available until 2025; hence, the perspective scenario until 2030 was completed by applying a load forecast computation, both in energy and peak demand, and a generation expansion plan to ensure the system adequacy. The five-year generation expansion (2026-2030) has been computed assuming a generation expansion based on thermal technologies, namely gas fuelled CCGT, as the most efficient and environmentally friendly among these. The process of optimization of new VRES installations in the "BAT scenario", as well as in the "Breakthrough scenario", is aimed at assessing the technical possibility and the economic convenience to replace part of these new CCGTs required in the "Reference scenario" with PV and wind power plants.
On the contrary, in Chile the demand forecast and generation expansion plan until 2030 are available in the documents published by the Regulatory Authority (CNE) and the Coordinator of Transmission System (CEN). Further, a ten-year transmission expansion plan is worked out by CNE every four years. Though this transmission expansion plan issued by CNE is not binding, it represents a good starting point especially for the assessment of the inter-area transmission capacity at the target year, 2030. All the above inputs were taken into consideration for the "Reference scenario" of the power sector.

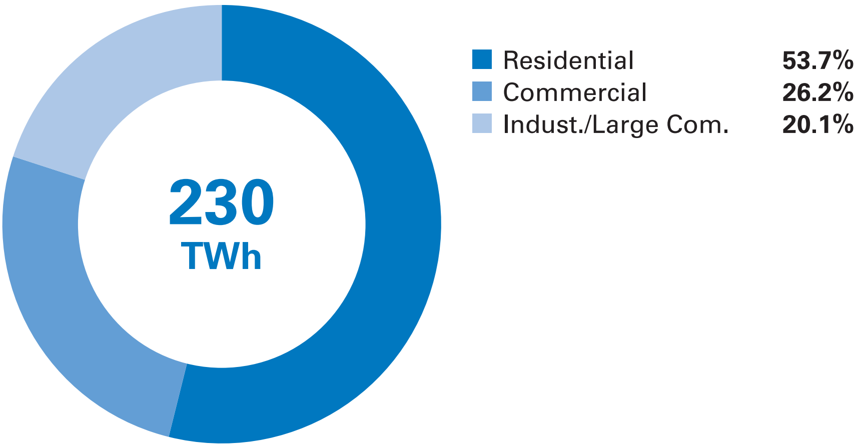
4.1 Reference scenario: Argentina

As mentioned, the *demand* forecast is available only up to 2025 and it is provided by MINEM. An extension up to 2030 has been carried out by CESI taking into account the scenario "*Tendencial*" provided by MINEM for energy demand [1] and the growth of GDP and population expected in the country. At the same time, the peak power demand 2030 was assessed taking into account the information provided by CAMMESA at year 2025. The values obtained for the year 2030 are an electrical energy demand equal to about 230 TWh and a peak power demand of nearly 43 GW.
The most recent load hourly time-series has been rescaled to define the hourly time series able to reach the targets 2030 in term of peak power demand and energy demand during one year. Where information is available, rescaling has also considered how the shares of demand evolve across sectors, e.g. residential vs. industrial.

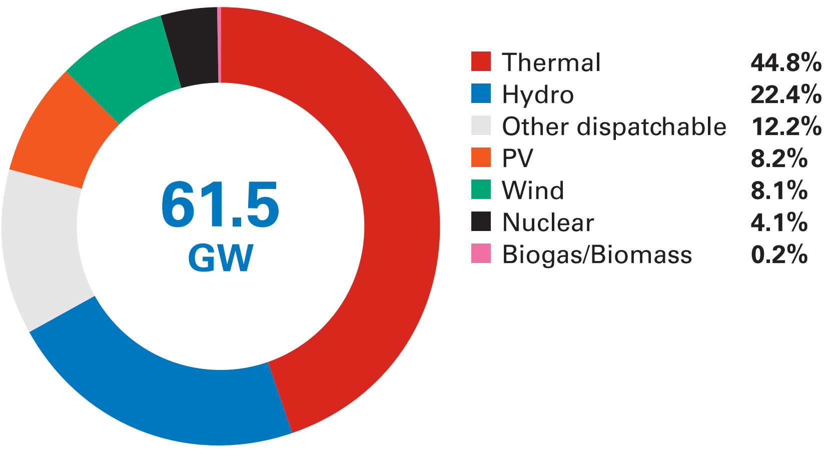
The basis for the definition of the *generation* fleet in the Argentinean system at 2030 is the information provided by CAMMESA and MINEM with the power plants expected at 2025: with respect to the generation fleet available today, an increase of the installed capacity up to 20 GW is expected, out of which nearly 10 GW PV and wind, 2.5 GW hydro, nearly 7 GW thermal and a new nuclear power plant. In addition to that, to cope with the nearly 40 TWh load and more than 7 GW peak demand increase expected from 2025 to 2030, further 7,500 MW of dispatchable power are necessary to keep proper generation adequacy.

Finally, the *transmission* system considered in the "Reference scenario" for Argentina corresponds to the configuration of the network estimated by CAMMESA at 2025. The network reinforcements assumed in this configuration include all the interventions proposed by Transener (the Argentinean company owning and operating the 500 kV transmission network), and in particular a strong improvement of the transmission capacity between Patagonia and Gran Buenos Aires area thanks to a 3,500 MW HVDC link. Some other local and minor network reinforcements were included in the model to remove possible constraints which were caused by the load increase and not by the presence of VRES power plants. In this study the Argentinean system has been considered divided in three macro areas (North West, Centre and Patagonia, respectively called in the document NWE, NEC and PAT), with a Net Transfer Capacity (NTC) between areas defined applying the N-1 criterion to the physical transmission lines belonging to the cut-sets.
The planned developments already represent a challenging target due to the massive investments required, and no further network reinforcements are foreseen from 2025 to 2030. The present study wants to highlight whether some bottlenecks in the transmission capacity can cause a limitation in the VRES exploitation at 2030 and whether other network improvements might be necessary and economically profitable to allow a higher penetration of VRES generation in the Argentinean system.
Figure 1 shows a graphical illustration of the main assumptions considered in the Argentinean "Reference scenario": electrical energy demand, peak power demand and generation fleet, divided among consumer typology, geographical zones and technology respectively, plus a simplified scheme of the geographical division of the Argentinean system, with the values of the NTCs between areas.

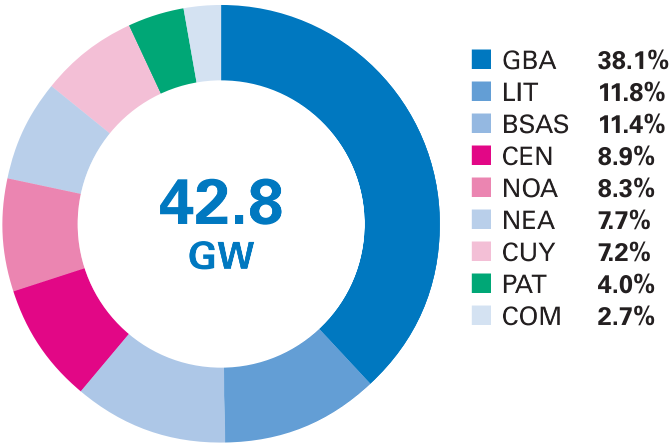
Electrical Energy Demand



Generation fleet



Peak Power Demand



Interconnections between areas

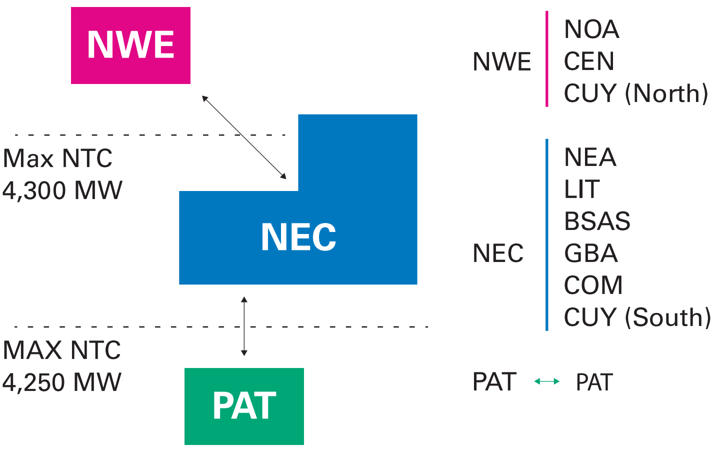


Figure 1 - Reference scenario for Argentina: electrical energy demand, peak power demand, generation fleet and NTCs
Note: GBA: Gran Buenos Aires; BSAS: Buenos Aires; COM: Comahue; LIT: Litoral; NEA: Noreste Area; CEN: Centro; CUY: Cuyo; NOA: Noroeste Area; PAT: Patagonia. [Source: MINEM and CAMMESA, data elaborated by CESI]

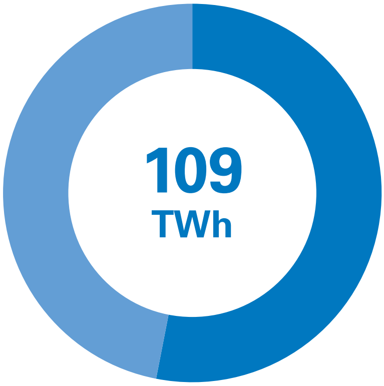
4.2 Reference scenario: Chile

The long term *demand* forecast for Chile is available up to 2036. The demand forecast in the time period 2016-2036 for the two Chilean systems SIC-SING published by CNE [2] has been used to define the energy demand for "Reference Scenario" 2030 (109 TWh), while the most recent transmission development plan published by the Coordinador Eléctrico Nacional [3] was the reference for the peak power demand definition (15,745 MW).
The historical hourly time-series available have been rescaled to calculate the hourly time series of demand expected in 2030, considering the expected peak power demand and forecasted energy demand in 2030. Also for Chile, where information is available, rescaling has also taken into account how the shares of demand evolve across sectors.
The basis for the definition of the *generation* fleet to be adopted in the "Reference scenario" for Chile is the development plan published by the Coordinador Eléctrico National in January 2017 [3]. An increase of 6.9 GW of installed capacity, of which 3.1 GW PV and 2.9 GW wind, has been considered with respect to the situation at 2016. With this set of generators, preliminary simulations showed a high value of expected energy not supplied (EENS), mainly concentrated in the evening hours, due in particular to the unpredictability of the PV and wind generation which are introduced to great extent, but are not able to ensure the coverage of the increased electrical energy and power peak demand (+42 TWh and +6 GW respectively). To reduce this value and ensure an acceptable level of generation adequacy, 2,800 MW of new dispatchable generation are needed, able also to limit the amount of the energy generated by the existing expensive oil power plants. With these additional plants, in fact, the EENS remains limited to less than 10^{-6} of the total Chilean electricity demand, and the use of expensive oil plants is limited only to the critical conditions in which cheaper generators are not available.

Definition of Chilean *transmission* system has been based on the updated version of the transmission development plan ("Propuesta De Expansión De Transmisión Del Sistema Eléctrico Nacional 2017") [3] published by the Coordinador Electrico Nacional in January 2017. The analysis is focused on the SING and SIC systems which constitute the main areas of the Chilean system. The network reinforcements planned up to 2030 have been considered and some other minor and local improvements have been introduced in areas where the network constraints were caused by load increase and not by the presence of VRES power plants.
The system is considered divided in two macro areas (SING and SIC), because this section will remain the most critical one in future scenarios with increasing level of VRES generation, as highlighted also in the analysis of the impact of VRES on the future energy mix of Chile published by the Ministry of Energy of Chile at the end of 2015 [4].

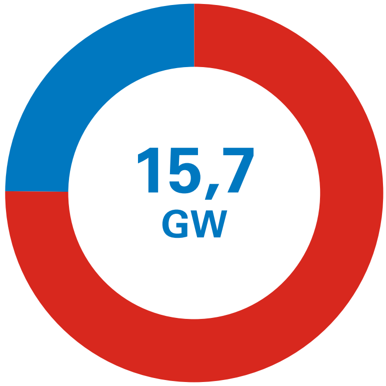
Figure 2 depicts the distribution of electrical energy and power peak demand among the different classes of consumers and areas considered in the "Reference scenario" for Chile at 2030. Furthermore, the composition of the generation fleet and the value of the NTC assumed between SING and SIC systems are illustrated.

Electrical Energy Demand



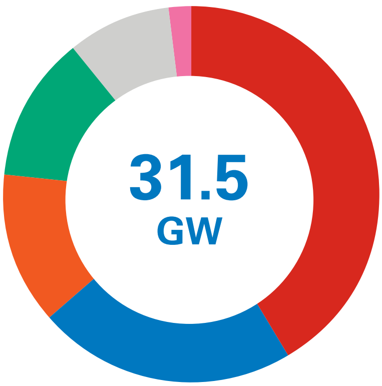
Regulated	**53.1%**
Free	**46.9%**

Peak Power Demand



SING	**75.2%**
SIC	**24.8%**

Generation fleet



Thermal	**41.6%**
Hydro	**22.1%**
PV	**13.2%**
Wind	**12.5%**
Other dispatchable	**8.9%**
Biomass	**1.7%**

Interconnections between areas

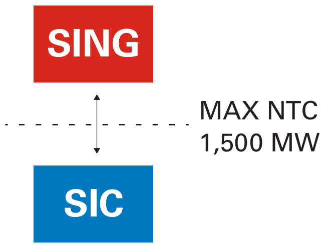


Figure 2 - Reference scenario for Chile: electrical energy demand, peak power demand, generation fleet and NTC. [Source: CEN and CNE, data elaborated by CESI]

4.3 International interconnections

In a first step, the assessment of the optimal technical and economic penetration of VRES power plants in the Argentinean and Chilean systems is performed on each single country, considered as isolated. The assessment takes into account possible transmission network reinforcements aimed at allowing a better exploitation of PV and wind resources. No energy exchanges with neighbouring countries are taken into account, looking for the best development of the VRES penetration to meet energy and peak power demand internally to each country.

Once the solution for each isolated country is found, the operation of the two interconnected systems is simulated, to evaluate whether the possibility to exchange power across the border can increase the optimal amount of installable VRES capacity. Also in this case, no energy exchange with other countries is simulated.

The following two interconnections are modelled between Chile and Argentina:

- the existing line Salta-Andes, with the power exchange increased to 600 MW[3];
- another future line in the area of Gran Mendoza-Santiago, with the possibility to exchange up to 1,000 MW.

The NTC between the two countries is assumed equal to 1,200 MW, accepting a transient overload in case of tripping the interconnection line having the highest power transfer capacity.

3 Currently the limit is set around 200-250 MW due to problems in the SING area, which cannot export more to Argentina without causing overloads and dynamic instability. It is assumed that at 2030 these issues will be definitively solved, also thanks to the SIC-SING interconnection, and that the power exchange limit will be determined by the capacity of the line.

5 Best Available Technology today scenario

The "Best Available Technologies today" scenario ("BAT scenario") represents the result of the optimization process which defines the optimal technical and economic penetration of VRES power plants that can be introduced in the "Reference scenario", replacing the more expensive thermal generation. Thanks to probabilistic simulations performed with GRARE software, the expected yearly operation of the systems is evaluated considering operational constraints (system reserve, power transfer capacity of the transmission network, uncertainty in the PV and wind production) and production costs, thus enabling the calculation of possible benefits for the systems compared to the "Reference scenario".
In the elaboration, we considered the best available technology (BAT) available today for PV and wind power plants, with their possible limits and constraints introduced in the power system. In particular, the variability of the production requires that the system has enough upward and downward reserve of generation to cope both with sudden variations of generation and also with unexpected significant differences between the forecasted generation and the real one over longer periods.
Given the pattern of the production profile, PV generation is more predictable, and requires in general lower reserve than an equivalent wind generation.

5.1 Argentina – isolated system

At the end of the computational process, the optimal amount of VRES by the year 2030 is 8,000 MW PV and 7,000 MW wind for a total VRES installed power of 15,000 MW. This means an additional amount of 5,000 MW with respect to the "Reference scenario". This additional VRES makes it possible to reduce 2,000 MW of dispatchable generation that was introduced in the "Reference scenario" (par. 4.1) to ensure the system adequacy.
The investment in VRES technologies provides benefits for the system of about $ 150 million/year, thanks to the savings in the generation costs and avoided investments in new dispatchable plants, which are higher than investment costs for new VRES and costs due to a small increase of EENS.
The expected LCOE for PV is 44.3 $/MWh, and for wind is 41.7 $/MWh.
In general wind power plants have a lower LCOE and a higher production, but PV is cheaper in terms of annuity per installed MW, so more PV power plants can be installed with a lower amount of money.
Table 1 shows the resulting installed capacity per technology in each area of the Argentinean system.

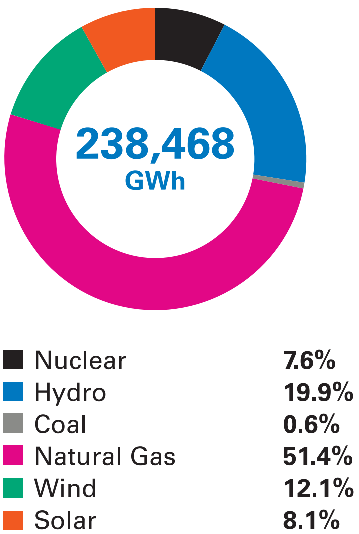
Table 1 - Argentina: total VRES installed capacity in the BAT scenario [MW]

AREA	PV installed capacity	Wind installed capacity
NEC	18	3,500
NWE	8,000	300
PAT	0	3,200

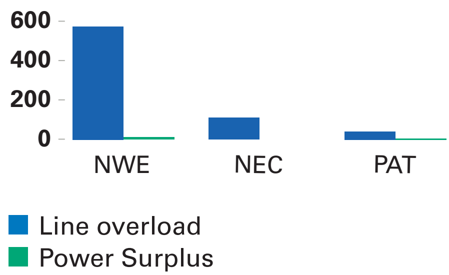
In this scenario, PV plants produce more than 19.3 TWh per year and wind plants more than 29 TWh per year. There is a risk of PV production curtailment, evaluated in 440 GWh, due to the network constraints close to the interconnection between NWE and NEC, while wind production is affected only by a limited curtailment risk. The NTC limit of the cut-set NWE - NEC is reached in some operating conditions with the power flowing from NWE to NEC, for a duration equal to about 120 hours, while the interconnection PAT – NEC is not saturated during the year. NWE is a net importing area from NEC. The net import is equal to 7.5 TWh, resulting from 12.5 TWh import and 5 TWh export.
Two transmission lines (the Recreo – Malvinas in NWE one and East-West corridor Rio Diamante – Charlone – Junin close to the NWE-NEC cut-set) are expected to limit for more than 1,500 hours/year the possibility to exploit the most economic generation and in particular the PV production, requiring its curtailment in some cases. The evaluation of the possible benefits for the system deriving from the improvement of the transmission capacity of these lines has been performed and is reported below.

Figure 3 shows the mix of energy sources used in each area to supply the load, the energy exchanges between areas and the risk of RES curtailments with the amount of energy required to be redispatched due to network constraints.

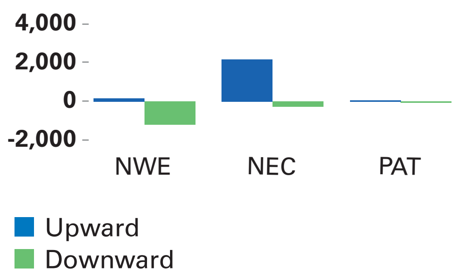
ARG - TOTAL



Curtailed Energy [GWh]



Redispatching for line overload [GWh]



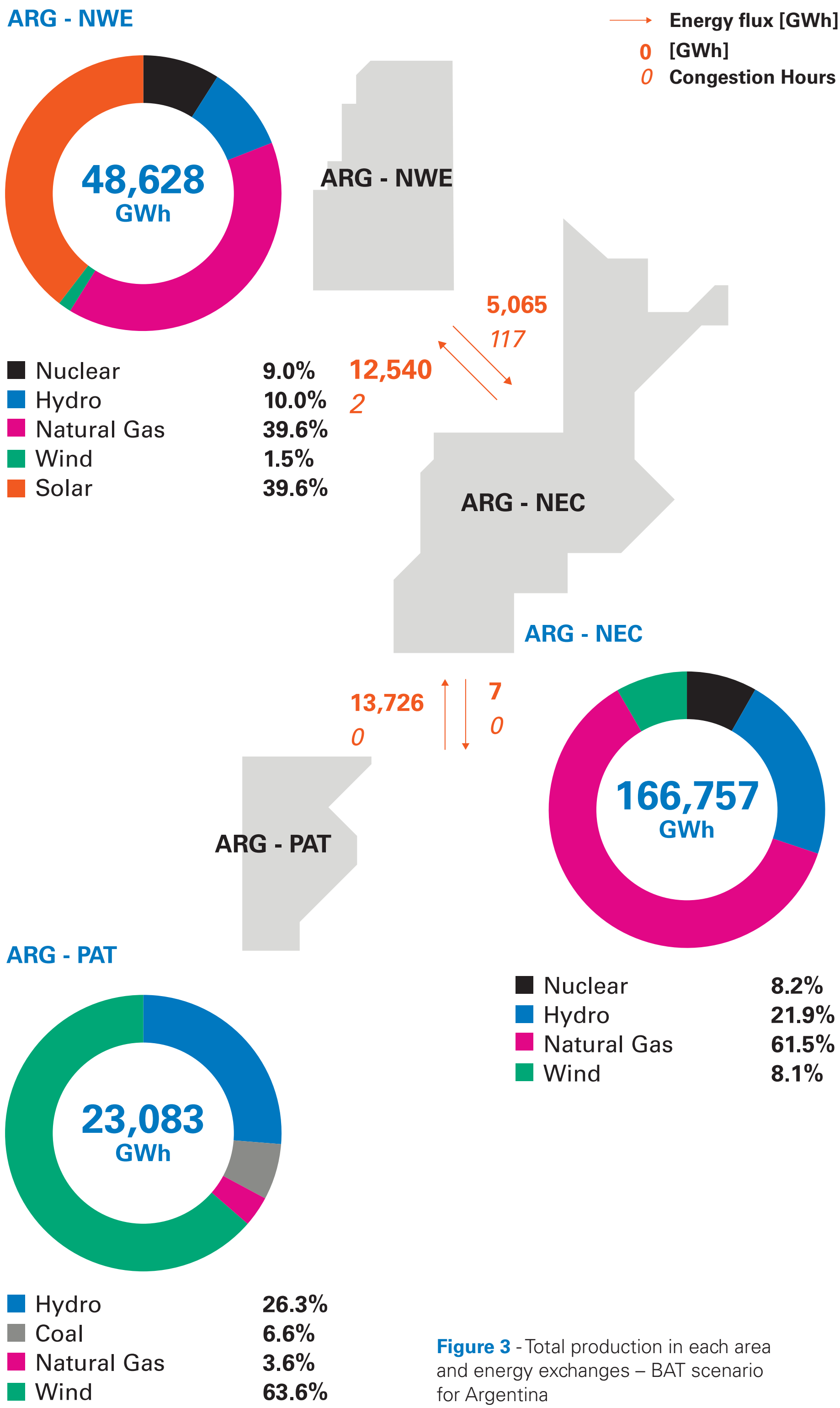


Figure 3 - Total production in each area and energy exchanges – BAT scenario for Argentina

5.1.1 Assessment of possible benefits arising from network reinforcements

Reinforcement of the transmission grid to reduce the risk of VRES curtailment

The transmission capacity improvement of the lines which represent a bottleneck for the optimal exploitation of cheap generation can constitute an investment which brings benefits to the system higher than the relevant costs.

Simulations show that the removal of the constraints on both the lines brings the risk of curtailments of PV down to negligible values, while if only the constraint on one line is removed, the risk of curtailment is reduced by 230 GWh or 360 GWh, depending on which line is considered.

The possibility to use cheap generation instead of a more expensive one constitutes a benefit for the system that can be assessed in $ 70 million/year, in case both the lines are improved or $ 2245 million/year in case of the upgrade of only one line.

The costs of such transmission capacity upgrades is not available in detail but, based on the available information, it is anyway possible to estimate different cases and calculate relevant annuities to be compared with the benefits. For instance, the limiting factor for one line is not the conductor ampacity but some other local constraints (for instance, measuring equipment in the substations): the investment required to improve its transmission capacity is then very low, because is limited to the replacement of these components, and can be evaluated much lower than a half million dollars. The comparison between the corresponding annuity, which is smaller than a tenth of the investment, and the generated benefit shows that the investment is strongly convenient, to exploit at the best the conductors. In the other case, the line is still in the design phase, and the increase of its transmission capacity would require a different type of conductor, increasing its realization cost. With an estimation of the impact of the different conductor on the overall line costs and considering the length of the line, it is possible to appraise that an investment around $ 110 million might be required. The annuity is then close to $ 10 million/year, showing that also in this case the investment would be beneficial.

No network reinforcements, but different distribution of VRES to avoid risk of curtailment

Other possible ways to avoid curtailments of PV generation in NWE have been investigated, examining the operation of the Argentinean system with a different mix of PV-wind installed capacity or a different distribution of PV generation over the territory. Aim of the evaluations was the assessment of the possible benefits for the system in case less PV power plants are present in the area which is constrained by the limited transmission capacity of the lines, and replaced by wind generation in the south or PV in NEC, where the solar irradiation is lower.

In both cases, the risk of PV production curtailment is significantly reduced, and the system has positive benefits thanks to the fact that, when some PV plants are installed in different areas than NWE, the limited transmission capacity of the two lines does not represent a strong constraint to the exploitation of cheap energy. Even in situations where PV power plans are installed in locations with lower potential, and the overall PV production in the system gets reduced, there might be positive benefits for the system.

Table 2 - Argentina: total VRES installed power in the BAT scenario modified to avoid network congestion [MW]

AREA	different mix PV-wind		different distribution of PV plants	
	PV installed capacity	Wind installed capacity	PV installed capacity	Wind installed capacity
NEC	18	3,700	850	3,700
NWE	7,200	300	6,370	300
PAT	-	3,400	-	3,400

5.2 Chile – isolated system

The research of the optimal amount of additional VRES generation, based on the "Best Available Technology today", with respect to the installed power already considered in the "Reference scenario", confirmed a very good alignment of the total VRES installed capacity acceptable by the Chilean system with the amount already planned by CNE and CEN. As explained in paragraph 4.2, at 2030 in Chile are foreseen about 4,200 MW of PV power plants and 4,000 MW of wind power plants, and the results of our evaluations provided a higher total amount (of 200 MW). It is worth noting that, on the contrary, there is a significant difference in the distribution of the overall VRES installed capacity between the PV and wind technologies. Despite a quite balanced situation considered in the "Reference scenario", the results in the "BAT scenario" showed that PV generation is much more convenient than wind, thanks to the very favourable environmental conditions, which include wide areas with one of the highest potential in the world, and very low expected price for the installation of PV power plants in Chile.
From the simulations performed with GRARE tool, the LCOE of the PV generation is expected to be as low as 27.3 $/MWh against 68.4 $/MWh for the wind production. This difference, combined with the fact that the installation of a PV plant is cheaper than a wind one with an equivalent power, leads to the fact that the optimum mix of PV-wind generation in addition to the "Reference scenario" is strongly biased towards PV, in a ratio nearly to 6:1.
Table 3 provides the total VRES installed capacity resulting from the optimization process in the BAT scenario, divided between the technologies and the SIC and SING zones.

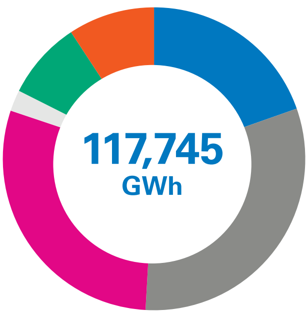
Table 3 - Chile: total VRES installed power in the BAT scenario [MW]

AREA	PV installed capacity	Wind installed capacity
SIC	3,900	3,500
SING	475	535

No VRES curtailments are expected due to network constraints.
SING and SIC exchange energy through the interconnection, with a net export from SING to SIC equal to 4.5 TWh resulting from an export from SING to SIC of 5.1 TWh and an import of 0.6 TWh.
The power flowing between the interconnection reaches its NTC for about 300 hours during the year, mainly in the direction from SING to SIC. This congestion level is absolutely acceptable.
The amount of added VRES power plants is not enough to reduce the need for 2,800 MW dispatchable generation inserted in the "Reference scenario" to ensure an acceptable level of EENS. However, the system can get the benefit arising from the substitution of expensive energy produced by thermal generators with cheaper energy produced by VRES. The benefit can be estimated in about $ 8 million/year.

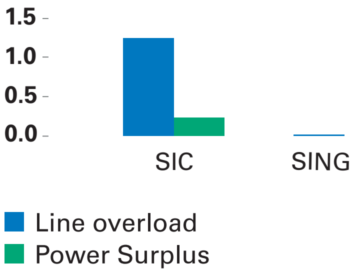
Figure 4 shows the main results which summarize the expected yearly operation of the Chilean system (production by energy sources, interarea energy exchanges, risk of RES curtailments and redispatching due to network constraints).

CHILE - TOTAL

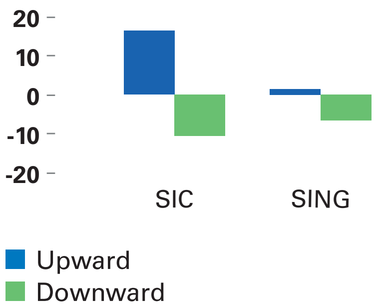


Hydro	**19.6%**
Coal	**31.3%**
Natural Gas	**29.2%**
Other Res	**2.2%**
Wind	**8.3%**
Solar	**9.2%**

Curtailed Energy [GWh]



Redispatching for line overload [GWh]



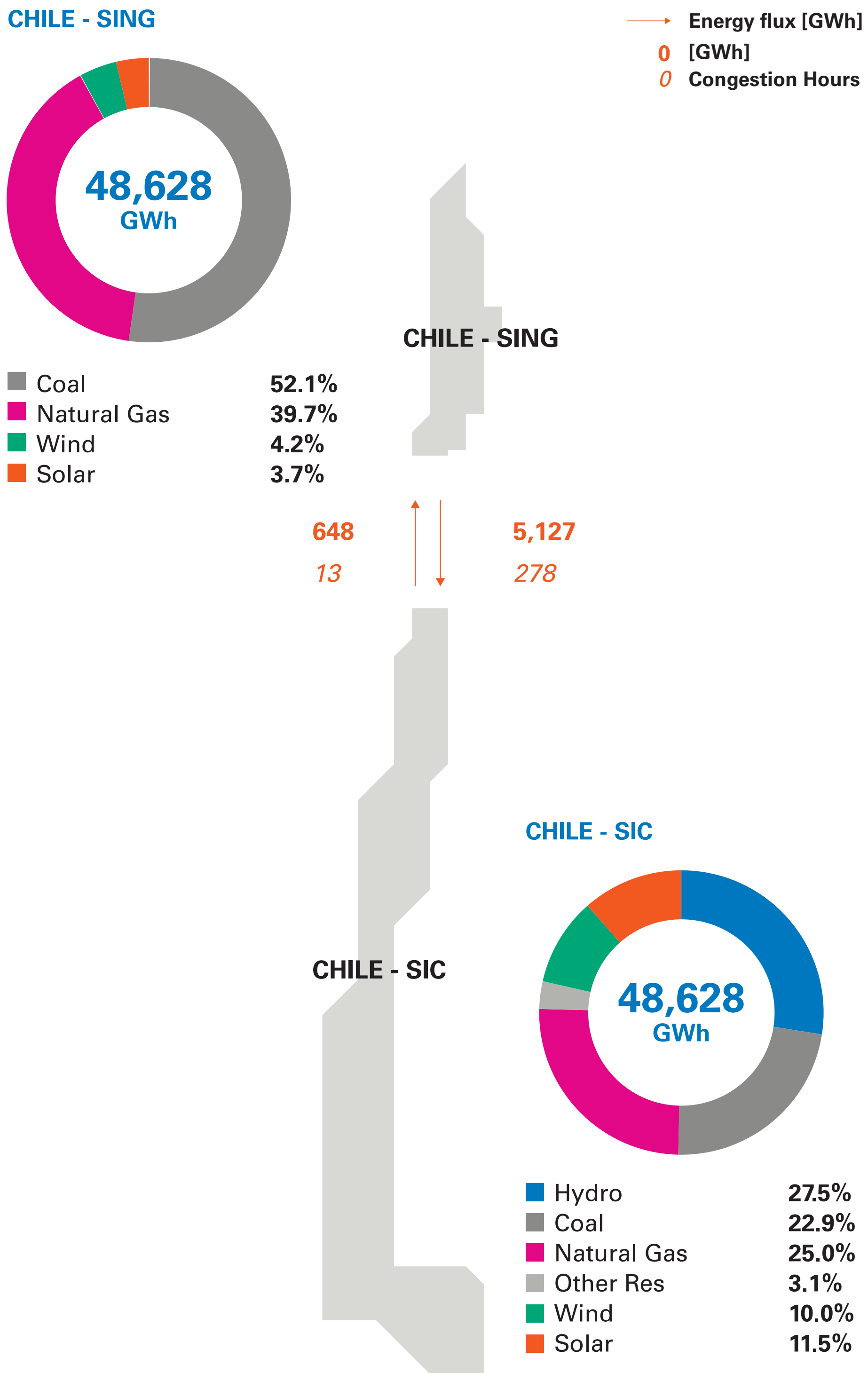


Figure 4 - Total production in each area and energy exchanges – BAT scenario for Argentina

5.3 Argentina and Chile interconnected systems

Following the analysis of the Argentinean and Chilean systems considered as isolated, a further computational process has been carried out focusing on the two systems interconnected through the lines described in paragraph 4.3. The possibility to exchange up to 1,200 MW brings the following positive effects with respect to the sum of the results obtained for the isolated countries:

- Higher Security of Supply: EENS reduced by -70%, reaching a value equal to about 3.5×10^{-6} of the total load;
- Lower risk of VRES curtailments: the PV power plants can inject in the grid nearly 350 GWh more with respect to the "Reference scenario" (risk of curtailment is reduced by -80%). The expected wind generation does not change and its curtailment remains negligible.
- Power market coupling provides a reduction of the overall generation costs by more than $ 35 million (-0.3%).

Energy exchanges between the countries are equal to 3.6 TWh from Chile to Argentina and 2.6 TWh from Argentina to Chile, with Chile turning out to be a net exporter of about 1 TWh.

These energy exchanges, which show a very high utilization of the interconnections, higher than 5,000 equivalent hours at full power, are mainly caused by the possibility to levelise the power generation costs between the two countries leading to bidirectional power exchanges over the year. It is worth underlining that such a high utilisation factor of the interconnection lines is due not only to the presence of VRES, but to a different conventional generation mix.

Considering the reduction of the energy costs made available by the possibility to have access to more economic generation, the presence of the interconnection provides benefits to the whole system evaluated equal to $ 43 million/year, shared in a quite balanced way between the countries. According to the assumptions described in [5], this annuity corresponds to a NPV around $ 550 million: the investment in the new interconnection would bring positive benefits to the system if its cost is lower than this value.

5.3.1 Additional VRES installed capacity in the BAT interconnected scenario

When the two systems are interconnected, also the technical constraints vary with respect to the ones applicable in the isolated case. For instance, the reserve need for the interconnected system is lower than the sum of the reserves needed by the two isolated countries, thanks to the possibility of better compensating the variability of VRES generation. This creates favourable conditions to allow a further increase of PV and wind installed capacity, which is also supported by the fact that the risk of PV production curtailments is lower, reducing the impact that the limitation of the generation can have on the cost of energy.

Considering the positive effects of the interconnection on the technical constraints of the whole system, it has been computed that it is possible to have 1,500 MW of VRES power plants in each country in addition to the amount defined in the "BAT scenario" for the isolated cases.

Simulations of the operation of the interconnected system in presence of these additional 3,000 MW of PV and wind installed power have been carried out. The distribution of the new plants between the technologies and over the territory within each country has been kept in the same proportion as defined for each isolated countries. In fact, the balance between PV and wind and the geographi-

cal distribution correspond to the optimization of the investment in VRES power plants, and this remains valid to a large extent also when the systems are interconnected.
The final total amount of installed capacity divided by area is reported in the following Table 4.

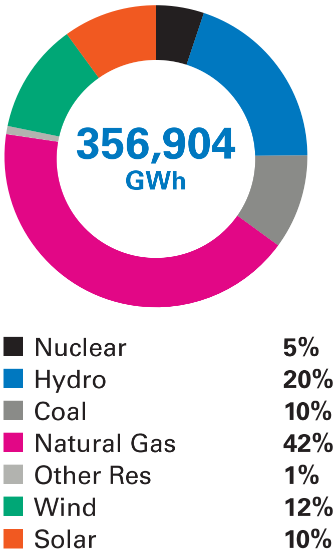
Table 4 - Total VRES installed power in BAT interconnected scenario [MW]

AREA	PV installed capacity	Wind installed capacity
NEC	18	3,770
NWE	8,940	300
PAT	0	3,490
SIC	4,930	3,720
SING	730	535

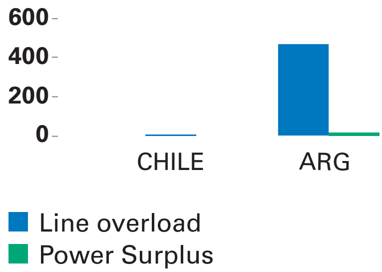
The introduction of additional 1,500 MW VRES power plants in each country further reduces the need of dispatchable generators described in the "Reference scenario" for the isolated countries, avoiding the investment in one 500 MW plant in Argentina and one 350 MW plant in Chile.
In addition to that, the energy produced by PV and wind plants replaces thermal generation, with a fuel saving higher than $ 350 million/year.
The risk of curtailment of the generation by new added PV plants increases, with an effect on their expected LCOE in Argentina which slightly increases up to 45.9 $/MWh, while in Chile remains around 27.3 $/MWh. Expected LCOE for wind plants remains in line with previous values, around 42.1 $/MWh in Argentina and 68.3 $/MWh in Chile.
Concerning the interconnections between Argentina and Chile, the high production of the wind power plants in Argentina reduces the need for import, and the net exchange becomes a bit more than 0.5 TWh: the energy exchanges on the SIC-NWE section are balanced while on the SING-NWE section the energy is transferred mainly from SING to NWE.
Total benefits for the whole system are calculated considering the savings and the costs for the new VRES plants: with respect to the situation with only the interconnection between the countries analysed in paragraph 5.3, the introduction of new PV and wind power plants generates benefits for about $ 100 million/year, thanks to the reduction of fuel costs but mostly to the possibility to avoid the construction of two dispatchable generators (850 MW in total) not required anymore. These possible benefits would be lost in case the execution of VRES projects and their connection to the grid would be delayed for any reasons.

Figure 5 shows the results of the expected operation of the two interconnected systems in presence of the additional 3,000 MW VRES plants. With this configuration, Argentina supplies about 23% of the net load with PV and wind production, and Chile about 22%. If losses are also considered, these percentage are reduced by 1%, reaching respectively 22% of the gross demand for Argentina and 21% for Chile, as reported in Figure 5.

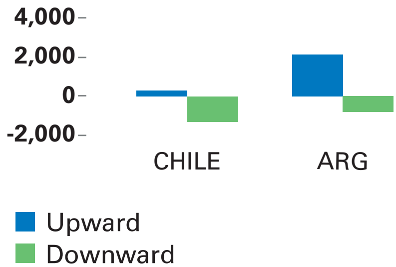
TOTAL SYSTEM (CHI+ARG)

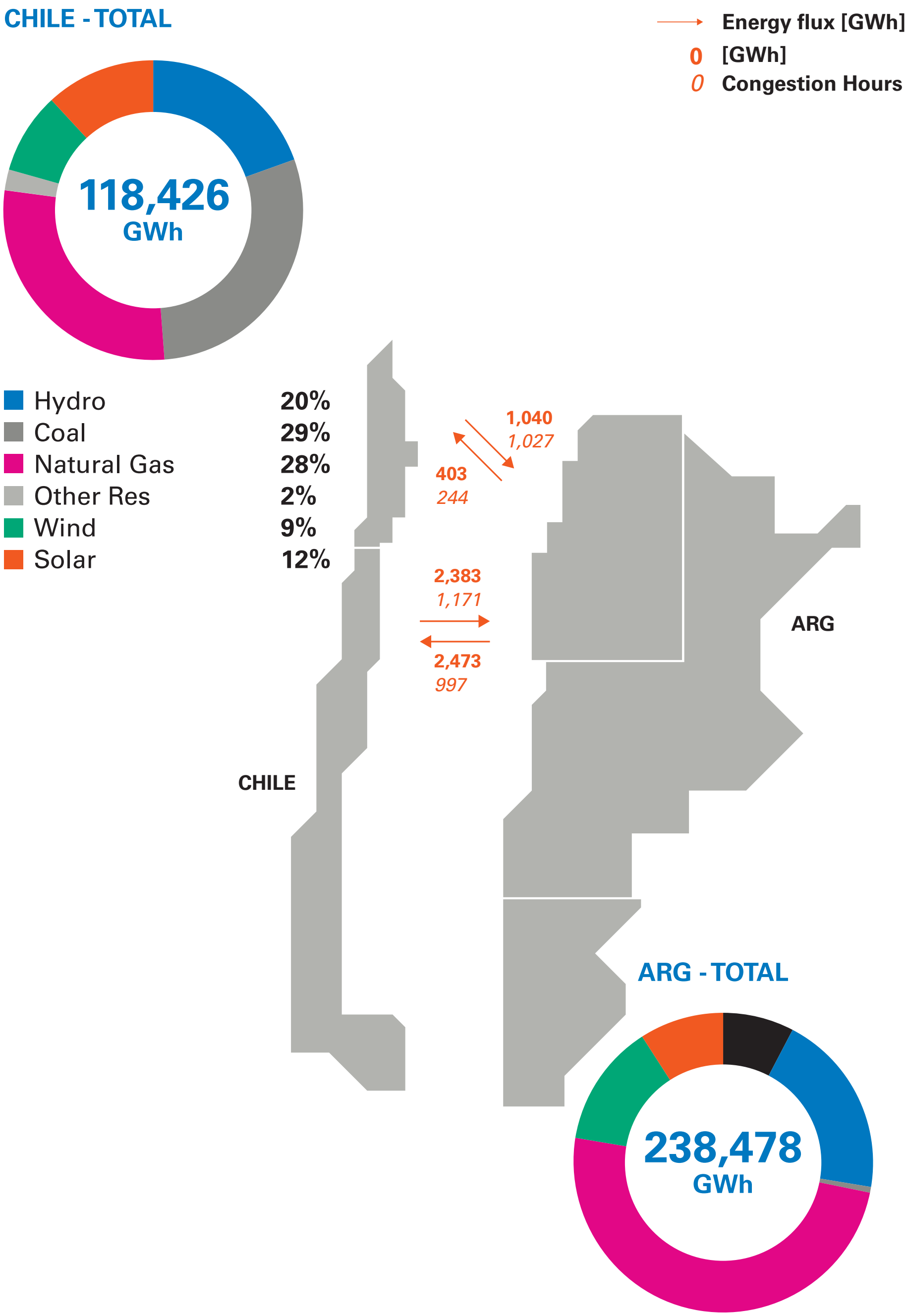


Curtailed Energy [GWh]



Redispatching for line overload [GWh]





Nuclear	8%
Hydro	20%
Coal	1%
Natural Gas	49%
Wind	13%
Solar	9%

Figure 5 - Total production and energy exchanges – BAT interconnected scenario with additional VRES

5.4 Sensitivity analyses

Three further simulations have been carried out on the configuration of the Argentinean and Chilean power systems resulting from the last analysis of the interconnected countries with additional VRES generation. These three sensitivities want to provide information about the operation of the system in the following conditions:

- possible delays in the development of dispatchable generation in Argentina, which has been modelled with a reduced installed capacity of future dispatchable plants;
- dry year, with a lower generation by hydro power plants;
- wet year, with a higher generation of hydro power plants.

5.4.1 Possible delays in the development of dispatchable generation in Argentina

The analysis presented so far showed that in the next years a massive development of the generation fleet, both in terms of VRES and dispatchable power plants, will be required especially in Argentina, to fulfil the expected demand increase in the countries.

To highlight how a possible slower development of the generation fleet in Argentina can impact the operation of the power system, its costs and the security of supply, a simulation removing 2,000 MW of dispatchable power (CCGTs) has been carried out.

The main results are the following:

- As expected, the Argentinean system shows a reduced level of generation adequacy, as the EENS increases nearly ten times, reaching almost 20 GWh (close to $1x10^{-4}$ of the total load). All the main causes (lack of available power in the system, lack of interconnections between areas, network constraints) increase considerably with respect to the original case. In Chile also a slight increase of EENS is present, which is caused by a general lack of power in the overall system due to missing production capacity and by line overloads not resolvable with the available generation resources.
- In absence of 2,000 MW of economic dispatchable generation in Argentina, the energy exchanges from Chile to Argentina increases considerably, reaching nearly 1.9 TWh.
- The fuel costs increase by $ 82 million for the whole system, as more expensive generation must be used. At country level, in Argentina the costs remain comparable to the "BAT Scenario" because the usage of a more expensive generation is compensated by an overall lower production, while almost all the additional costs are located in Chile due to the higher export. It is worth underlining here that the increase of the energy exchanged from Chile to Argentina (+1.5 TWh) means that the latter has to spend more money and the Chilean production companies totalize higher revenues selling more energy. These effects must be added to the pure fuel cost variation in each country.
- The risk of PV generation curtailments in NWE area is reduced by 20%, corresponding to 50 GWh of higher production absorbed by the grid.

From these results it is possible to notice the necessity of a strong focus on the long term planning of the power system in Argentina, to ensure that the generation development is well aligned with the growth of the power peak and load

demand and that the load can be supplied in a reliable and economic way.
A stronger growth of VRES power plants would not be able to completely solve the problems related to a Lack of Power, which are mainly concentrated in evening hours when PV is not available. Very high amount of additional plants would be required to improve the generation adequacy to more acceptable values, but they are not compatible with the system operational constraints.

5.4.2 Dry and wet hydrological years

The optimal amount of PV and wind power plants defined in the "BAT Scenario" considered average hydrological conditions. Further simulations have been carried out to verify how much the system operation is modified in case of dry or wet conditions. In fact, it is strongly affected by high variations of the hydro resource availability, given the high percentage of electricity produced with hydropower plants. In particular, dry conditions can jeopardize the security of supply because of the increasing risk of lack of power in case other resources are not available to compensate the reduction of hydro power, and because of the lower amount of redispatchable resources to fulfil the operational constraints.

Dry year

The simulation of the operation of the system in dry conditions has been performed assuming that in Chile the energy which can be produced from hydro resource is reduced by 30% with respect to the "BAT Scenario", while in Argentina the reduction is assumed equal to 10% based on the available historical data series.
The main results are summarized below:

- EENS increases by 65% (3.7 GWh against 2.2 GWh) but remains still in acceptable ranges. In Chile the value becomes nearly three times than before (attaining 0.5 GWh) while in Argentina the variation is about +50% (reaching 3.2 GWh).
- Dispatchable thermal generators have to produce 11.5 TWh more (+5.6%), and the corresponding cost increase is $ 636 million.
- Energy exchanges between the countries are affected, and Argentina becomes a net exporter towards Chile for an amount around 0.7 TWh, highlighting the important role of the interconnections in terms of mutual support.
- Lower risk of PV curtailments in NWE area (80 GWh, equal to a reduction of 30% of the expected energy cut).

These results show that the amount of VRES and dispatchable generation identified at the end of the analysis of the "BAT Scenario" (paragraph 5.3.1) allows a proper operation of the system also in dry conditions though with non-negligible additional dispatching costs. In fact inevitably, higher fuel costs are required in case lower hydro production is available, and a small growth of the EENS is expected, but there is no risk of an unacceptable decrease of system adequacy.

Wet year

The simulation of the system behaviour in a wet hydrological year has been carried out assuming that 10% more energy is available from hydropower plants in both countries. In this case, no critical impact on the security of the systems is expected, because more resources are available in the system.

The main results are listed below:

- EENS reduces by 30% (1.5 GWh against 2.2 GWh), with the highest effect visible in NWE with a reduction of 35%.
- Dispatchable thermal generators have to produce 6.6 TWh less (-3%), and the corresponding cost saving is $ 360 million.
- Energy exchanges between the countries are aligned with "BAT scenario", and Argentina remains a net importer for an amount around 0.5 TWh.
- Higher risk of VRES curtailments due to both overgeneration and transmission network constraints. Most visible effects in NWE (+60 GWh possible cuts of PV production).

As expected, in a wet year the system can operate with lower fuel costs and lower EENS. The only slightly negative effect is the increase of OG risk.

5.5 Geographical location of VRES plants and connection process

The analysis of the different solutions aimed at limiting the risk of PV generation curtailment present in the "BAT scenario", especially in the Argentinean case, showed that many different possible approaches can be adopted, which provide similar overall benefits for the system. The best mix of PV and wind installed power determined in the "BAT scenario" represents the optimal solution in a long term planning. In case of network constraints, the optimal solution can be slightly adjusted to ensure that constraints are not violated.

However, the detailed optimal roadmap for deploying such a massive VRES installed capacity depends on specific constraints such as the availability of terrains (and not only of the best primary energy potential) and the authorisation time needed for the project development and the connection of the VRES power plants to the transmission grids. This latter issue is of utmost importance. In fact, the actual development of VRES plants will have to deal with the need to effectively connect them to the transmission network since the difficulty to get an access point to the grid where to inject the power might increase the cost of the projects. Many local network improvements also at lower voltage levels will be probably needed to enable the new power plants to reach the transmission system, and this detailed evaluation is part of the activities that need to be performed during the short-mid term planning of the system.

Looking also at examples from other countries where the VRES penetration have been already increasing for the last years, it is reasonable to foresee that new substations on the 500 kV lines will be required to make available more frequent points of possible access to the transmission system. This is valid in particular in the areas with high solar irradiation or wind availability where the lines are long and the amount of power that should be transferred is high.

6 Breakthrough in VRES technologies scenario

Starting from the results of the BAT scenario, which showed in some cases a very competitive LCOE from PV and wind power plants also thanks to the favourable environmental conditions present in Argentina and Chile, a more aggressive scenario has been investigated aiming at an accelerated decarbonisation of power systems in the two countries.

It has been assumed that system technical constraints which were limiting the installation of additional PV and wind in the systems are removed, and therefore VRES power plants can be introduced even further than in the BAT scenario. New hypotheses were made on the new VRES units assuming they would be based on innovative technologies able to provide system auxiliary services, like frequency regulation, hence limiting the need for additional upward and downward reserve, and voltage regulation. Reduction of reserve need can be also obtained thanks to future more effective methods for weather and production forecasts or an improved regulatory framework which allows grouping the production offer and the regulation capability of different power plants: these actions will allow to define expected production profiles with higher accuracy, thus limiting the required support of dispatchable units.

It is assumed also that a share of VRES power plants is associated to storage devices, the role of which is basically load shifting which also constitutes a support for a better "dispatchability" of PV and wind production within a limited time frame and power. In order to ensure that a proper amount of energy is available to be shifted from periods with high VRES production to periods with risk of EENS, a maximum storage capacity equal to 5 hours is supposed in the definition of the optimal solution.

Based on the information available in [6] and [7], in the economic evaluations it has been considered a cost equal to $ 0.5 million for a 1 MW turnkey system FOB[4] with a storage capacity of 5 MWh, plus 10% of costs for transport, and a 10years lifetime. An efficiency of 0.9 has been included as a ratio of the energy that the storage systems are able to inject in the system and the energy that they have stored, taken from the system.

In this scenario, the energy produced by VRES power plants replaces a more expensive generation fulfilling the technical constraints of the system. In particular, the maximum power transfer between areas is taken into account. The optimal VRES installation capacity is obtained when their LCOE remains below the cost of the thermal generators that are substituted. The LCOE of renewable plants is calculated considering the investment costs and the expected production which is also affected by the risk of curtailments.

No externalities, such as reduction of GHG, have been taken into account, which would represent additional benefits brought about by the introduction of VRES plants. Then, considering externalities the convenience to install PV and wind plants would further increase.

4 Free On Board, according definition of Incoterms 2010.

It is important to underline how storage systems can represent a good solution to reduce curtailments of PV production, shifting some energy from peak production hours to the period with decreasing production or even to evening and night hours. Thanks to the repetitive pattern of PV production profile, storage systems can be effectively used daily to store energy during daylight hours and release energy at evening. This makes storage systems perfectly fit when combined with PV plants. On the contrary, when there are good wind conditions, overgeneration caused by wind power plants can last for long periods, also many days, and storage systems would not be able to fully recover the curtailed production, due to the limited storage capacity and impossibility to get discharged regularly. Thus, in order to limit possible curtailments of wind power plants, it is more important to ensure a proper transmission capacity able to evacuate the generated power.

6.1 Argentina – isolated system

Argentina isolated system has been investigated starting from the results obtained in the "BAT scenario"; in the isolated case (paragraph 5.1), the optimal technical and economic amount of PV and wind plants was equal to 15 GW. Since in the "Breakthrough scenario" the system technical constraints such as inertia and reserve need are not binding, the possibility to include additional 11 GW of VRES plants turns out to be economically viable. It is also necessary to install 3,000 MW of storage capacity suitably distributed in the system and preferably close to the new plants. This allows to recover part of the energy that otherwise would be curtailed to avoid overgeneration in the system.
Additional PV plants are distributed in NWE and in NEC area, because, as already seen in "BAT scenario", the interconnections between NWE and NEC are not strong enough to evacuate the power when full PV production is concentrated in the first area.
Wind production is also spread in PAT and NEC, because the transmission capacity from PAT to NEC can become a bottleneck during periods with high wind regimes.
To limit the risk of wind generation curtailments in PAT and ensure the optimal exploitation of the very good potential in that area, it is necessary to further increase the NTC between PAT and NEC. To this aim, it is assumed that, thanks to the presence of high amount of storage systems in NEC and NWE, it is possible to loosen the strict N1 criterion and increase the NTC from 4,250 MW to 5,400 MW. In fact, in this operating conditions, even if a line of the PAT-NEC cut-set trips causing the need to suddenly reduce the export from PAT to NEC by about 1 GW, the missing import can be compensated with the usage of storage, and the stability of the overall electrical system can be maintained.
Table 5 shows the amount of PV, wind and storage installed power added to the Argentinean system in the "Breakthrough scenario" with respect to the "BAT scenario", under the assumption of the increased NTC between PAT and NEC.

Table 5 - Argentina: added VRES and storage installed power [MW] in the Breakthrough scenario with respect to BAT

AREA	PV installed capacity	Wind installed capacity	Storage
NEC	1,100	4,950	1,500
NWE	1,650	-	1,000
PAT	-	3,300	500

The added plants can inject more than 40 TWh directly into the grid, while the risk of curtailments attains 600 GWh. Thanks to the storage system, 450 GWh can be recovered. Hence, the total energy which the system can absorb is equal to 40.5 TWh. Thanks to this contribution, overall PV and wind plants are able to supply more than 38% of the net load.
With the same configuration of the new plants, if the NTC between PAT and NEC is kept at 4,250 MW, the curtailments in PAT would attain 1,350 GWh.
The LCOE of the new PV and wind generation when the increased NTC is considered remains in the range 44.546 $/MWh. Considering also the cost for the storage, the overall LCOE of PV, wind and storage together reaches nearly 52 $/MWh.
The high amount of energy produced by VRES which can be also partially dispatched thanks to the storage systems, makes not necessary anymore the fossil fuelled dispatchable generation introduced in the "Reference scenario" (and still present in the "BAT scenario" for an amount equal to 5,500 MW). For the sake of completeness, the comparison between the costs needed to produce 40 TWh with traditional dispatchable generation and with the proposed combination of PV, wind and storage, shows a saving for the system around $ 575 million/year (about 7% of the thermal generation costs in the "BAT scenario").

6.2 Chile – isolated system

Also for the Chilean system, the starting configuration for the "Breakthrough scenario" is the result of the "BAT" one, reported in paragraph 5.2, i.e. 8,400 MW of PV and wind power plants.
The possibility to include storage systems for load shifting and the reduced need of reserve for the system create the conditions to allow the installation of additional 7,000 MW of PV and wind plants, which must be supported by 2,000 MW storage systems, with a storage capacity of 5 hours. The amount of new VRES plants and their geographical localization is shown in Table 6, which reflects the PV/wind ratios found also in the "BAT scenario". Storage is mainly concentrated in SIC area as it represents the one with the largest share of demand and generation.

Table 6 - Chile: added VRES and storage installed capacity [MW] in the "Breakthrough scenario" with respect to "BAT"

AREA	PV installed capacity	Wind installed capacity	Storage
SIC	4,750	1,070	1,970
SING	1,190	-	30

These new added plants are able to inject 15.5 TWh directly into the grid, while there is the risk to cut more than 1.8 TWh due to overgeneration. Thanks to the storage system, more than two thirds of this curtailed energy can be saved, and, taking into account the overall efficiency, the net energy recovered and injected back to the grid is more than 1.1 TWh. Hence, in total the systems absorbs 16.6 TWh of energy produced by the new VRES plants. Considering the energy produced by PV and wind plants identified in the "BAT scenario", the net load is covered for more than 34% by these renewable resources.
The amount of energy recovered by the storage systems is enough to avoid most of the EENS present in the "Reference scenario" if 2,800 MW dispatchable generation were not included in the generation fleet. As a consequence, the new 7,000 MW VRES plants can be deemed able to substitute the additional fossil fuelled dispatchable generators required in the "Reference scenario", keeping a suitable level of generation adequacy thanks to the storage systems.
The interconnection between SING and SIC does not represent a strong constraint and doesn't limit the exploitation of the additional VRES plants.
The cost of the storage systems is high, and even if it is often used to save PV production which otherwise would get curtailed, the resulting cost of the recovered energy remains above 140 $/MWh, calculated as cost of storage systems divided by the amount of energy injected back into the grid.
Considering the whole PV-wind-storage system, the resulting LCOE is about 44.4 $/MWh, still competitive with respect to many traditional thermal plants.
It is possible also to conclude that the investment in 7,000 MW PV and wind plants and 2,000 MW storage systems would remain more profitable than the investment in 2,800 MW dispatchable generators (CCGTs) to produce 16.6 TWh, giving to the system a benefit of about $ 350 million/year.

6.3 Argentina and Chile interconnected systems

Finally, the case with the Argentinean and Chilean systems interconnected has been evaluated. The presence of the interconnections allows to reduce the risk of PV production curtailments, especially in NWE.
It is worth underlining that both the presence of the storage system and the interconnections support a better exploitation of the VRES plants. When storage systems are already available in a country, the benefits obtained thanks to the interconnections are partially offset, since part of the curtailed energy is already recovered by the storage.
Referring to the amount of PV, wind and storage installed power defined in Table 5 and Table 6, when Argentina and Chile are connected, the risk of PV production curtailments is reduced by about 180 GWh.

Thanks to the better exploitation of the PV and wind resource with lower risk of curtailment and to the favourable conditions of the interconnected system, it is confirmed that 3,000 MW new VRES plants can be further added in the system as happened also in the "BAT scenario". These additional PV and wind power plants have 8.7 TWh net production (considering a curtailment of 1.9 TWh of which 0.9 TWh are recovered thanks to storage system, both values referred only to the production of the added plants). In this final configuration, PV and wind generation covers 41% of the net load in Argentina and 37% in Chile.

7 Variants

Two Variants have been examined with respect to the "Reference scenario", aimed at appraising to what extent the optimal solution identified during the performed analysis fits against possible different evolutions of the power systems.
The main key parameters that are modified with respect to the "Reference scenario" are:

- electric demand;
- generation evolution;
- possibility to have big electrical storage systems.

Both the variants have been investigated on the system with interconnected countries taking into account the system constraints which are considered in the "BAT scenario", starting from the amount of PV and wind plants defined there.

7.1 First Variant

In the first Variant a higher demand scenario has been evaluated, under the hypothesis of a stronger economic growth of the two countries and a high penetration of the emobility in the biggest cities. The overall demand is increased by 8% with respect to the "Reference scenario", and the load pattern modified especially during the night as a consequence of the presence of electrical vehicles. Also an important change in the generation fleet has been taken into account, with a significant step to support the transition to a carbonfree condition of the system: coal plants (except one) have been replaced with CCGT technology, with higher efficiency and lower specific CO_2 emissions. Moreover, the possibility to include in the system three hydro pumped storage plants, for an overall installed power equal to 1,600 MW has been investigated, to reduce the situations with overgeneration and lack of power. In a scenario with higher load, the transmission system is in general more stressed, showing more bottlenecks and risk of curtailments due to overloads. Reinforcements of the critical transmission lines in Argentina analyzed in paragraph 5.1.1 are necessary and included in the simulations. Thanks to the load increase, there is the possibility to include in the whole interconnected system 2,900 MW of additional PV and wind plants divided between countries and technologies according to the ratios already identified for the "BAT scenario". Furthermore, other 2,000 MW can be installed when hydro pumped storage plants are introduced.
In fact, the load increase reduces the risk of VRES curtailments due to overgeneration, and creates the conditions for the introduction of additional PV and power plants. Due to the high construction costs, the introduction of hydro pumped storage plans is not convenient from an economic point of view, even if they allow a higher VRES penetration. Evaluation of such kind of plants should be done considering other advantages they can offer to the system in the short term and real time operation, for instance for fast frequency regulation, and not only for the load shifting and the reduction of the risk of curtailments.
The presence of additional 2,900 MW of PV and wind power plants reduces the need for dispatchable generation, providing savings related to less fuel consumption and avoided investments in thermal plants. The expected overall benefit arising from these additional 2,900 MW of VRES power plants can be estimated in about $ 110 million/year. These benefits are to be considered as additional with respect to the "BAT scenario".

7.2 Second Variant

In the second Variant a lower demand scenario has been considered, under the assumption of a generally reduced economic growth and an increase of the energy efficiency.
According to the load reduction also the generation fleet has been modified compared to the "Reference scenario", in particular no new dispatchable generation has been added because the generation considered in the targets of each country was enough to guarantee the system adequacy. Furthermore, 1,600 MW of pumped storage has been included in the Variant 2 in order to reduce the risk of curtailments of the energy produced by the new VRES plants due to overgeneration conditions, which become more frequent with the reduced demand.
Simulations have been carried out considering a PV and wind installed power equal to the amount defined for the "BAT scenario" for the interconnected countries. Even with the support of the hydro pumped storage, the production of this high amount of PV and wind power plants is often limited in this low load condition. The risk of energy curtailments increases above 1 TWh, about three times more than in the "BAT scenario".
A scenario with 3,000 MW lower VRES installed capacity has been simulated, and it turns out that avoided investment costs and increased fuel costs for the thermal dispatchable generation are very similar. It means that the two solutions with different level of VRES installed capacity would bring to the system similar benefit. This result highlights a good stability of the identified solutions, which remains close to the optimum also when big changes in the demand happen.

In this second Variant, the effect of a reduction of the technical minimum for the generators has also been analysed. Solutions able to increase the flexibility of the generation fleet, and in particular aimed at decreasing the value of the minimum generated power that must be operating in the system, in general allow a higher penetration of VRES plants because reduce the constraints which can limit their production. When simulating a reduced minimum power limit of the thermal generators, the curtailments of PV and wind production due to overgeneration are about 300 GWh that is the half of what was calculated when adopting the standard technical minimums for thermal plants.
The combined effect of a different dispatching and reduced overgeneration provides benefits around $ 100 million/year. This benefit should be compared with the costs of the improvement in the conventional generation fleet flexibility. These costs are difficult to be estimated and can vary in a wide range depending on generation technology and commissioning year (for existing generation). The definition of the actual costs for such upgrade and the assessment of the benefits actually provided to the system should be done according to the project.

8 Conclusions

The analysis aimed at assessing the optimal economic and technical amount of PV and wind power in the Argentinean and Chilean systems at 2030 taking into account the transmission system, showed that in these two countries there is the opportunity for a massive deployment of VRES generation.
The best mix of new generation varies in the two countries, depending on the availability of natural resource and on the expected installation costs.
In the "Best Available Technology scenario", it turns out that in Argentina the optimal amount of VRES power plants at the target year can attain 15 GW, whereas in Chile 8.4 GW, in line with the existing plans by CNE and CEN. In Argentina the expected LCOE of the two technologies is similar in the range 41.7-44.3 $/MWh, while in Chile LCOE for PV is much lower than for wind (27.3 $/MWh vs 68.4 $/MWh), which indicates a strong convenience to install more PV than wind power plants. The produced renewable energy is equal to 48.7 TWh in Argentina (more than 21% of the demand) and 20.7 TWh in Chile (about 19% of the demand).
Some network reinforcements not included in the Argentinean transmission development plan are suggested to support the exploitation of PV power plants limiting the risk of curtailments.
When the electrical systems of the two countries are interconnected, there is convenience to install additional 1,500 MW VRES plants in each country, thanks to the reduced risk of curtailment and a more levelised load profile that can be supplied by the plants. In this scenario, the overall PV and wind production would reach 78 TWh, equal to nearly 23% of the total demand.
In the "Breakthrough scenario" some system technical constraints are relaxed, under the hypothesis that VRES power plants will be able to provide required ancillary services and would not increase the upward and downward reserve need. Storage systems are also distributed in the areas to support flexibility of VRES production and recover part of the energy that would be lost in case of overgeneration or transmission system congestions.
Under these assumptions, the optimal installable VRES capacity increases, with additional 11 GW in Argentina (plus 3 GW of storage) and 7 GW (plus 2 GW storage) in Chile. These new added plants would produce 40.5 TWh in Argentina and 16.6 TWh in Chile. Thanks to this contribution, the coverage of the net load in the two countries increases up to more than 38% in Argentina and 34% in Chile.
Again, when the two countries are interconnected, further 3 GW of PV and wind plants can be introduced, reaching overall total production by these technologies equal to more than 135 TWh, which corresponds to nearly 40% of the overall demand.
Two Variants have been investigated to evaluate the behaviour of the system in case some major changes (such as higher or lower demand, different generation fleet, presence of hydro pumped storage plants) take place with respect to the assumptions at the basis of the "Reference Scenario".
The results showed that in case of higher load, it is advantageous to add further VRES generation, whilst in case of lower demand, the benefits remain flat also when reducing PV and wind power plants with respect to the "BAT scenario".
Figure 6 shows the net load coverage by PV and wind plants in the different analysed scenarios. To assess the overall RES contribution to the electricity supply, it is necessary to add the energy produced by hydro plants, which in both countries turns out to be about 21% of the net load.

Electrical Energy Demand

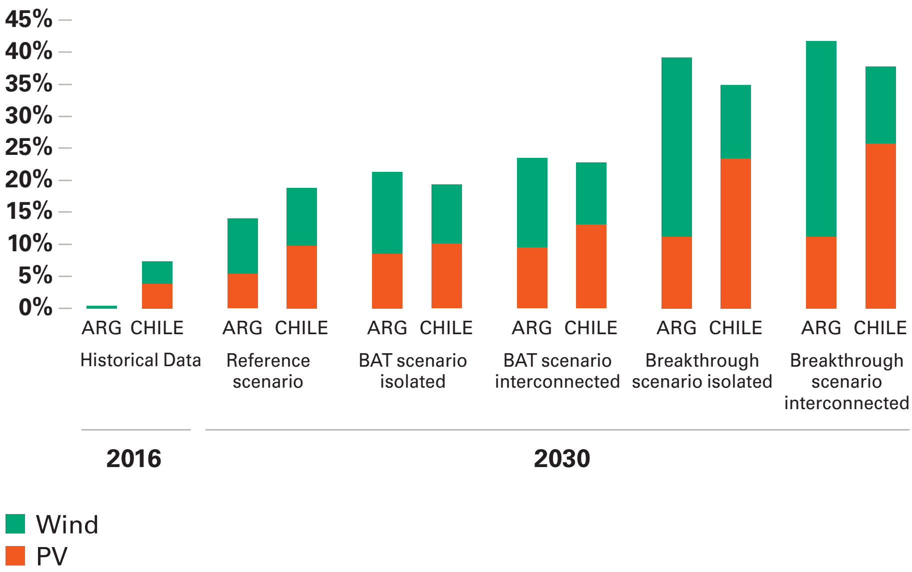


Figure 6 - Net load coverage by PV and wind plants in different scenarios

The analysis highlighted how the investments in transmission system and in storage systems can support the exploitation of VRES plants, allowing a higher penetration. Storage systems with a storage capacity of some hours perfectly fit with the high penetration of PV plants, as they can modify their production pattern, shifting energy to the evening, when typically there is a higher risk of EENS.
On the contrary, high transmission capacity is necessary to avoid congestions in areas where high amount of wind plants are installed. In fact, with good wind regimes high production can last for long periods, which cannot be managed with standard storage systems. In order to ensure a good exploitation of wind potential it is then necessary that enough transmission capacity is available, to evacuate the produced power. The presence of high amount of storage devices in the network can also enable the possibility to increase the NTC between areas without affecting the security of the system, thus allowing a higher transmission capacity without building new lines.Then, the evaluation of the benefits due to investments in storage or new lines must be carried out with a coordinated approach to proper represent their interaction.

9 References

[1] Ministerio de Energía y Mineria, "Escenarios Energéticos 2025", December 2016

[2] Comisión Nacional de Energía, "Informe Definitivo De Previsión De Demanda 2016-2036 SIC–SING", January 2017

[3] Coordinador Eléctrico Nacional – Dirección De Planificación Y Desarrollo, "Propuesta De Expansión De Transmisión Del Sistema Eléctrico Nacional 2017", January 2017

[4] Ministerio de Energía, Gobierno de Chile – Energía 2050, "Mesa ERNC – Una mirada participativa del rol y los impactos de las energías renovables en la matriz eléctrica futura", December 2015

[5] CESI Report B7012438, "Inception Report – Data Collection and Scenario for Chile-Argentina case study"

[6] World Energy Resources, "E-storage: Shifting from cost to value. Wind and solar applications", 2016

[7] Lazard, "Lazard's levelized cost of storage analysis – version 3.0", November 2017

Foundation

Research Series
supported by

Shaping a Better Energy Future