Final Report

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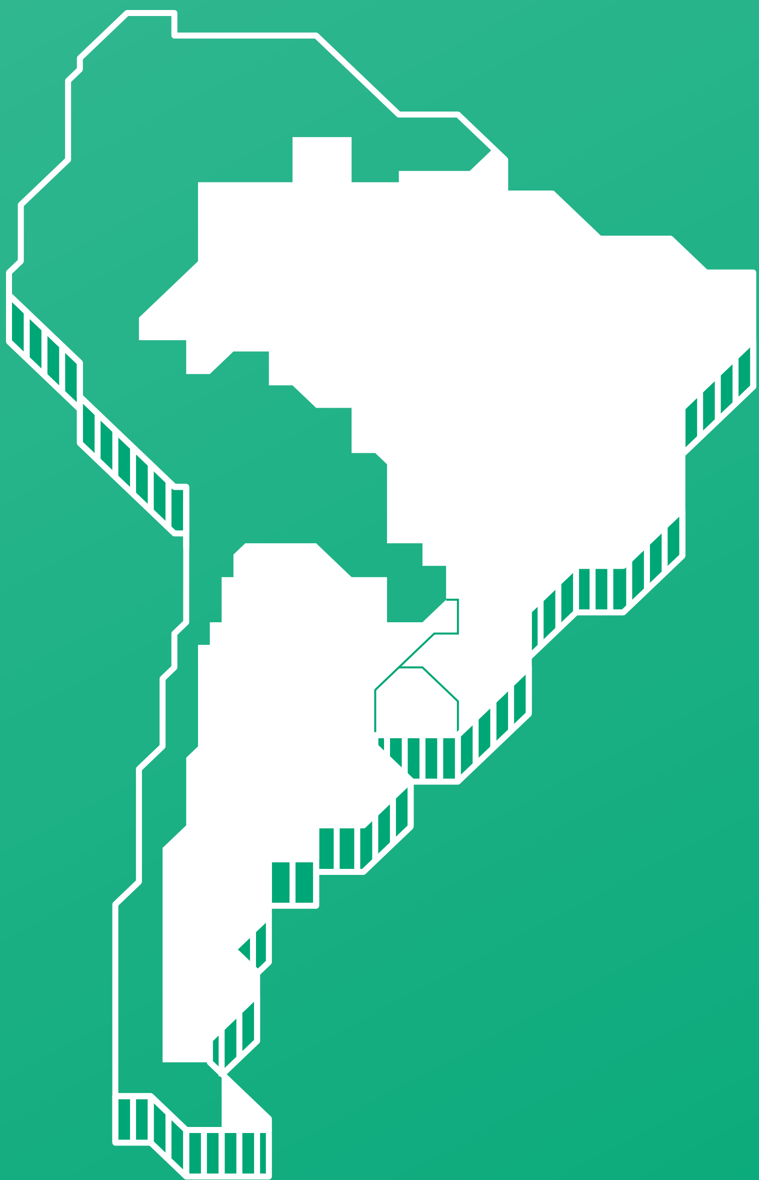

Variable Renewable Energy Sources (VRES) deployment and role of interconnection lines for their optimal exploitation: the **Argentina-Brazil-Uruguay** case study

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LIST OF ACRONYMS

BESS	Battery Energy Storage System
CCGT	Combined Cycle Gas Turbine
CEN	Coordinador Eléctrico Nacional
EENS	Expected Energy Not Supplied
EHV	Extra High Voltage
EOH	Equivalent Operating Hours
GBA	Grand Buenos Aires
GHG	Greenhouse gas
GT	Gas Turbine
HVDC	High Voltage Direct Current
LACE	Levelized Avoided Cost of Energy
LATAM	Latin America
LCOE	Levelized Cost of Energy
LCOT	Levelized Cost of Transmission
MC	Monte Carlo
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PV	PhotoVoltaic
RES	Renewable Energy Sources
RoR	Run-of-River
SEN	Sistema Eléctrico Nacional
ST	Steam Turbine
T&D	Transmission & Distribution
VRES	Variable Renewable Energy Sources

1 FOREWORD

1.1 Introduction

Latin America is endowed with outstanding Renewable Energy Sources (RES), namely wind and solar energy, but some areas offer also a good potential for hydro, biomass and geothermal power production. The current decrease of upfront investment costs in RES power plants make 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, hydro). 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.
As a matter of fact, Latin America is still fragmented in national or regional power pools: SIEPAC (interconnected pool from Guatemala to Panama), the Andean interconnected system (from Colombia to Peru) and the Brazilian system (SIN) interconnected basically with Uruguay and Argentina. Other countries are still fully isolated, like Guyana, Suriname, French Guyana and Bolivia or very weakly interconnected, like Chile where just one cross-border line is in operation between SING (Chile) and SADI (Argentina): the Salta-Andes line with a power transfer capacity of about 200 MW owing to network constraints, despite this line is designed for a capacity of about 600 MW.
Thus, dedicated studies shall be carried out specifically to identify the feasible penetration limits of Variable RES (VRES) generation accounting also for the possible power interchange across interconnection lines so to cope with conditions of power surplus or shortfall. Considering the wide geographical extension of Latin America, the analyses shall be applied at a regional level.

[1] Almost all Latin American countries signed the Paris Agreement and a large majority of them 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

Within the context recalled above, this study aims at examining the optimal economic penetration of VRES generation (namely wind and solar) in some Latin American (LATAM) countries and regions within the countries accounting for the possible cross border power exchanges.

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.

The first report of this study was completed in January 2018 and was focused on Chile and Argentina (Cluster 1). This second report is focused on Argentina, Brazil and Uruguay (Cluster 2) and will be followed by a third one 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 was based on data and projections collected in 2017, this second report 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%.

1.2 Contents of the report

This report describes the activities performed and the results of the analysis on the Argentinean, Brazilian and Uruguayan systems aimed at assessing the optimal economic penetration of VRES generation (wind and PV) taking into account the operational constraints, and evaluating the impact of such VRES generation on the operational costs and the power flows in the power systems.
The information collected and the Reference Scenario described in the Inception Report [1], which represents in the best way the basic situation expected at the target year in terms of demand, generation and transmission lines, are the basis for the performed assessments.

The evaluation of the optimal penetration of VRES generation is carried out assessing and comparing the economic benefits which might result for the system from the investment in new technologies (traditional dispatchable or PV and wind) when existing or planned generation fleet is not adequate to cover the power peak and load demand.

Chapter 2 illustrates the activities aimed at defining an upper bound limit of VRES installed capacity in the power system under investigation, considering system operational constraints and assuming that the new PV and wind plants are operated in the system according to today criteria. In particular, the highest amount of VRES (wind farms, PV solar) that can operate in the system without jeopardizing the security of the grid considering the system reserve needs and avoiding high shares of VRES production curtailments is defined. In fact, the new VRES plants typically replace production provided by the thermal generating units which, according the most common current practice, are responsible to ensure, thanks to their dispatchability, the balance between load and generation in every moment.

This first analysis takes into account the system wide operating constraints such as the needs for upward and downwards secondary and tertiary reserves and the “must run” units, hence ensuring among others a suitable capability for ramp up/ramp down to face the load pattern and the variability of wind and PV. Most critical conditions will be analysed with a deterministic approach.
At the end of this task, an upper bound of the feasible VRES penetration in a whole country or in the various regions of a country is defined, assuming that the VRES power plants do not support the operation of the system for instance providing downward reserve and that the VRES production curtailments must be limited.

Chapter 3 presents a detailed investigation performed on the power systems taking into account, on one hand, the additional constraints which might be introduced by the limits of the transmission network capacity, and, on the other hand, a greater flexibility in the operation of the VRES power plants, which in a future perspective will be able to actively support the system operation with services that currently are not possible due to technological limitations or to regulatory restrictions. New features and technological developments, including a wider diffusion of energy storage systems, will allow the PV and wind plants to increase their penetration without jeopardizing the security of supply. In this view, system operational constraints are loosened, considering a reduced reserve need and without taking into account restrictions concerning the inertia in the system, which will be overcome by the presence of advanced VRES technologies and flexible storage systems.

One year of operation at the target year is simulated with a probabilistic approach based on Monte Carlo method for increasing levels of VRES until maximum economic convenience is reached with adequate generation fleet.
For every simulation, which summarizes the results of thousands of different system configuration weighted by their likelihood to happen, main outcomes are provided, such as:

- solar and wind production and curtailments due to overgeneration and line overloads;
- overall generation costs for each area;
- average annual value of Expected Energy Not Supplied (EENS);
- a summary of NTC, energy exchanges and saturation hours for each interconnection.

Benefits for the system are evaluated in terms of generation costs, considering where necessary also investment costs, and adequacy of the generation (measured through the possible variation of the Expected Energy Not Supplied index). The comparison of these benefits calculated with different amount of VRES production provides the information necessary to define the optimal configuration.
A similar approach allows to assess also investments in Transmission system, which bring benefits to the system which have to be compared with the costs of the improvement of the network.
At the end of Chapter 3, the optimal amount of VRES power plants is estimated for the Argentinean, Brazilian and Uruguayan power system considering the countries as isolated systems and then considering them as interconnected.
Evaluations of possible benefits for the systems coming from the improvement of the network are presented in case there are significant congestions which limit the VRES generation and increase the overall production costs.
Moreover, the expected operation of the systems with the resulting generation fleet is also evaluated for different hydrological conditions, in order to verify that security of supply does not become critical during adverse years.

Chapter 4 introduces two Variants, aimed at evaluating the behaviour of the system in case of some major changes, such as different demand and generation fleet. In these conditions, new optimal VRES penetration is estimated, in order to investigate how the results are affected by the variation of main assumptions.

Chapter 5 reports the outcomes of some Load Flow calculations performed on deterministic snapshots representative of particular situations, such has high or low load and different levels of renewable generation (PV, wind and hydro). This allows to highlight how the power flows between the areas selecting some specific cases among the thousands analysed with the probabilistic approach.

2 ASSESSMENT OF THE TECHNICAL LIMITS OF VARIABLE RENEWABLE GENERATION PENETRATION WITHIN A COUNTRY DUE TO SYSTEM OPERATION CONSTRAINTS

2.1 Introduction

The purpose of this task is to assess a preliminary limit of VRES installed capacity in isolated Argentinean, Brazilian and Uruguayan power systems in 2030 scenario, focusing on the frequency control requirements (secondary and tertiary regulations), under the assumption that i) VRES plants do not support the system operation with proper functionalities (such as frequency regulation, inertia or at least reduction of system unbalances) and ii) a limited risk of production curtailment is accepted.

The analysis takes into account the characteristics of the existing and future generation fleet together with the most restrictive load conditions for RES operation, coherently with the data collected in the Inception Report [1]. The ability of conventional generation to provide the upward and downward reserve needed to face the increasing penetration of VRES production is checked, and it is estimated the maximum VRES installable capacity ensuring that the reserve requirement is fulfilled by the conventional plants in service (in Brazil it is assumed that reserve is also provided by hydropower plants, due to their high presence in the system). According to the said assumptions, PV and wind power plants do not support actively the system operation providing regulation capacity, reserve or other ancillary services.
The VRES taken into account are wind farms and solar PV. There are several combinations of installed power of these sources that can be integrated in the power system still ensuring that the conventional power plants are able to provide the needed reserve. One of the main outcomes of the analysis is then a description of the allowable combinations of wind and PV installed power.

At this stage, network constraints are not considered, but a system wide analysis is carried out considering the demand and generation mix. This means that a single bus-bar model is used to model the whole power system of each nation (Argentina, Brazil and Uruguay).
A more detailed model with a single bus-bar for each system area is then used to provide some further considerations about how the VRES geographical distribution could be limited due to cross-area interconnection limits internal to each power system.

2.2 Methodology

This chapter reports details about methodology and analysis process for a preliminary evaluation of the admissible VRES penetration in each country for the 2030 scenario. The analysis is carried out assuming the condition of isolated system, i.e. without power exchanges with the neighboring countries.

The analysis is performed for every Country by means of a simplified model where they are represented as a single bus-bar system, where load and generation are connected and must be balanced. For Argentina, a second step is carried out considering the division in smaller areas. These areas are modelled as bus-bar systems and connected through lines which allow the power to flow from one area to another up to defined limits, calculated as net transfer capacities. In this case, the balance in every area must take into account also the net value of import-export through the interconnection lines. This second step has not been performed for Brazil because, even when the areas are represented by equivalent bus-bars, the system remains a meshed network if the complexity of the transmission network is properly consider. In this case the estimation of the limits loses its value because the power exchanges between areas cannot be determined in a realistic way between bus-bars systems connected by fictitious links. The correct power flows can be calculated only using the detailed network model which is considered in the simulations performed during the following Task, and this allows the assessment of the realistic limits of VRES penetration in the different areas.

Load level and constraints on generation are defined according to the assumptions described in the following paragraphs. The balance in each area must be ensured considering also the secondary and tertiary reserves requirements which are necessary to allow the electric system to manage both the uncertainty of the load and the variability of RES generation, without jeopardizing the security of the system.
The limited net transfer capacity between the different areas inside each country has been investigated in order to evaluate how it can influence the maximum amount of VRES that can be installed in each area.

This procedure is based on a deterministic approach taking into account the critical operating conditions for the power system in presence of VRES generation, generally represented by off-peak load and peak solar radiation conditions. In particular, in off-peak operating hours, a high value of wind generation forces the conventional power plants to generate energy at a very low level. Even in this condition it should be guaranteed a proper amount of reserve in order to cope with the normal fluctuations of load and VRES.
The same problem could occur during the hours with high level of solar radiation and low load.

2.2.1 Description of the computational approach

In this activity only two variable energy sources are taken into account: wind farms and solar PV.
These sources typically have different hourly patterns of production and their forecasts are uncertain. The PV solar has a more predictable hourly pattern of production – since it depends on the solar radiation – and peaks during the central hours of the day. The wind farms production in general is more variable due to the strongly non-linear correlation between the wind intensity and the produced power and to the usual changes of wind conditions in the areas where the plants are located. The uncertainty of the wind production forecasts is for this reason typically greater than the uncertainty of solar PV.

Because of the differences in the uncertainty of the productions by PV or wind, different shares of PV/wind installed capacity cause different effects on the reserve management of the system. It is then not possible to calculate the maximum acceptable amount of generic VRES, but it is necessary to define pairs of admissible values: the more PV plants are installed, the less wind farms are suitable to be installed and vice versa.

Due to these reasons, the study calculates some admissible pairs of values which belong to the border of the allowable area on the Wind / PV plane. At each amount of installed PV corresponds a maximum amount of installed wind farms and vice versa. A theoretical example of the resulting pairs of PV-wind admissible capacity is provided in Figure 1, to show how the results will be presented in the following chapters.

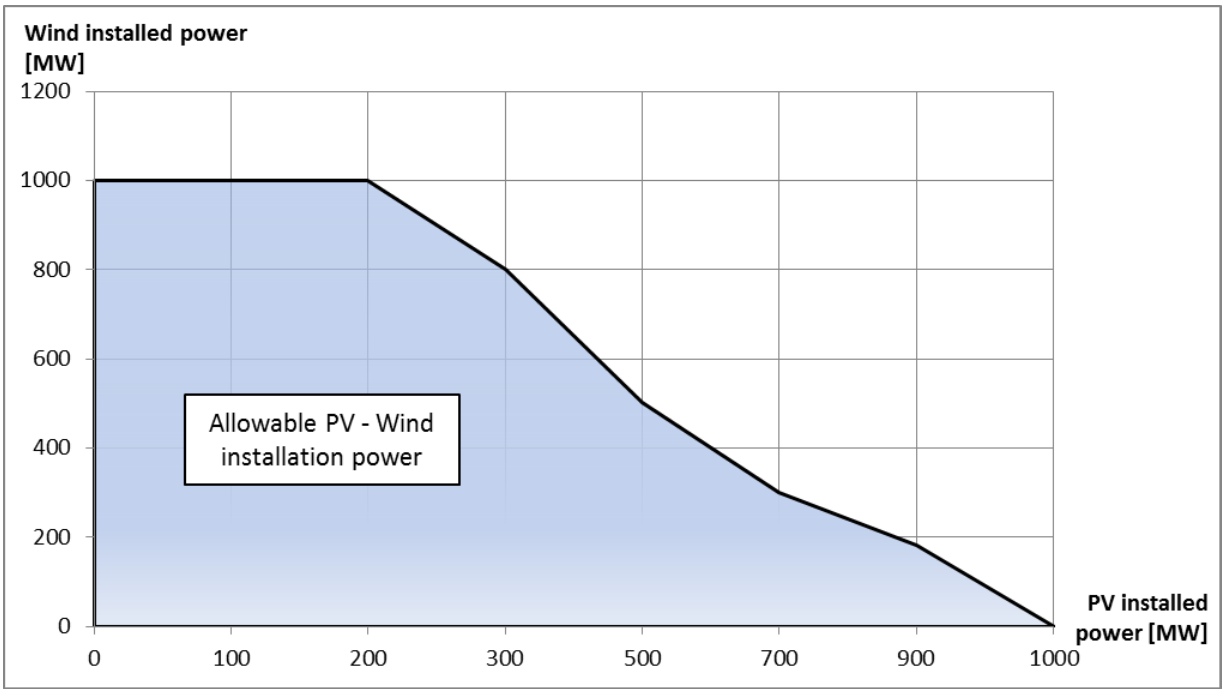


Figure 1 – Theoretical example of the allowable area on the PV/Wind installed power chart

To determine the maximum amount of VRES which can be installed in the system without affecting its security, the analysis focuses on the most critical conditions, which are characterized by low load and high VRES production. It is assumed that also in these conditions the VRES do not support the system with provision of ancillary services for reserve, and their production should not be curtailed.

In this low load condition the sum of PV and wind production covers a large amount of the load. The residual load is supplied by traditional hydroelectric and thermal plants. These traditional plants operate therefore near their minimum output, although they have to provide the system with all the downward secondary and tertiary reserve required in order to cope with the uncertainty of load and VRES production, guaranteeing the stability and security of the whole system.

A further element that must be taken into account is that the unit commitment of the traditional power plants in the low load condition is not completely free. In fact it must be suitable to provide services to the system such as voltage regulation, inertia, etc. In other words, there is a minimum number of traditional power generation that must be in service.

Also the production of plants such as run of the river and biomass cannot be neglected even in low load condition.

The need to guarantee a suitable amount of downward reserve on the traditional plants is then the factor that limits the amount of VRES installed.

The calculation is performed in two steps for wind and for PV power plants.

The maximum wind power production is assessed considering the 10^{th} percentile of the load and no PV production, condition which can happen during the night. The selection of the 10^{th} percentile of the load instead of the absolute minimum is proposed because the acceptance of a risk margin is a common practice during the planning process.

The calculation is performed evaluating the maximum wind power production admissible in the system which does not affect the fulfilment of the reserve constraint. Since the reserve requirements depend also on the amount of wind power production, this maximization is calculated with an iterative method. The corresponding maximum admissible installation of VRES is then calculated assuming a contemporaneity factor which is also commonly adopted as the probability that the wind power plants run at full power all together is pretty low.
The procedure is depicted in the Figure 2.

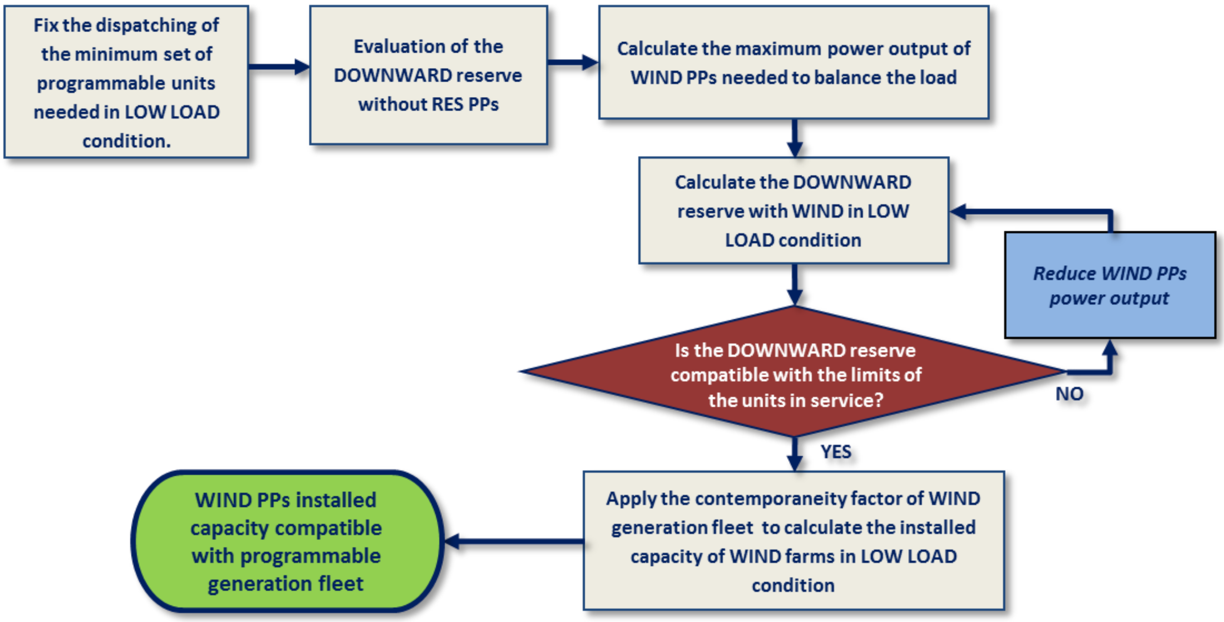


Figure 2 - iterative calculation of max installation of wind power plants

Once the maximum installed wind power is defined, a similar approach is followed to evaluate the maximum allowable PV production which does not require any curtailment due to reserve requirements. Also in this case a low load condition is analysed, selected among the hours in which the PV production is high. In particular, the 10th percentile of the loads that occur during the hours of maximum solar radiation is considered. The calculation of the maximum PV production is performed for different levels of wind production, from the maximum value calculated in the previous step to 0 MW, in order to define the allowable PV/Wind installed power area as depicted in Figure 1.
The points of the upper bound of the area are calculated assuming an installed value for one technology (i.e. Wind) and calculating the corresponding maximum amount of admissible installed power for the other technology (i.e. PV). Four conditions are analysed:

- Calculation of maximum PV installable power in presence of the maximum wind installable power defined in the first step
- Calculation of maximum wind installable power in presence of an amount of PV installed power equal to the target defined for each Country at 2030 or at the closest year before 2030 for which this target is available; if not possible, the today situation is taken as reference
- Calculation of maximum PV installable power in presence of an amount of wind installed power equal to the target defined for each Country at 2030 or at the closest year before 2030 for which this target is available; if not possible, the today situation is taken as reference

- Calculation of maximum PV installable power in presence of no wind installed power

To maximize the installed power of a VRES source means to find the maximum amount of production that can assure the presence of the reserve requirements on the traditional unit. Since the reserve requirements depend also on the amount of solar PV and wind farms, this maximization is calculated with an iterative method (Figure 3 and Figure 4)

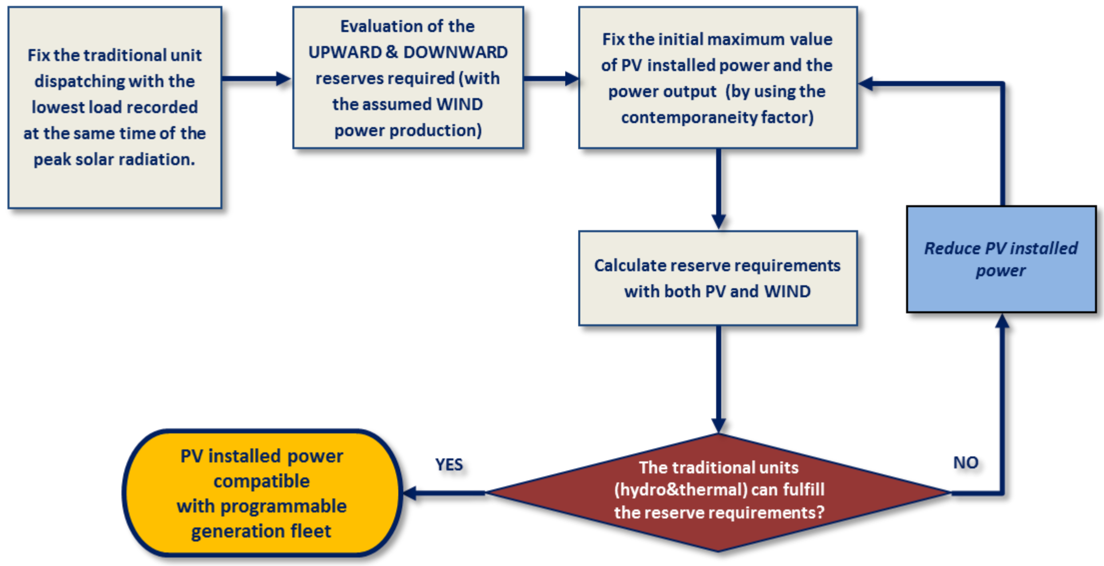


Figure 3 - iterative calculation of max installation of PV once assumed a fixed value of Wind

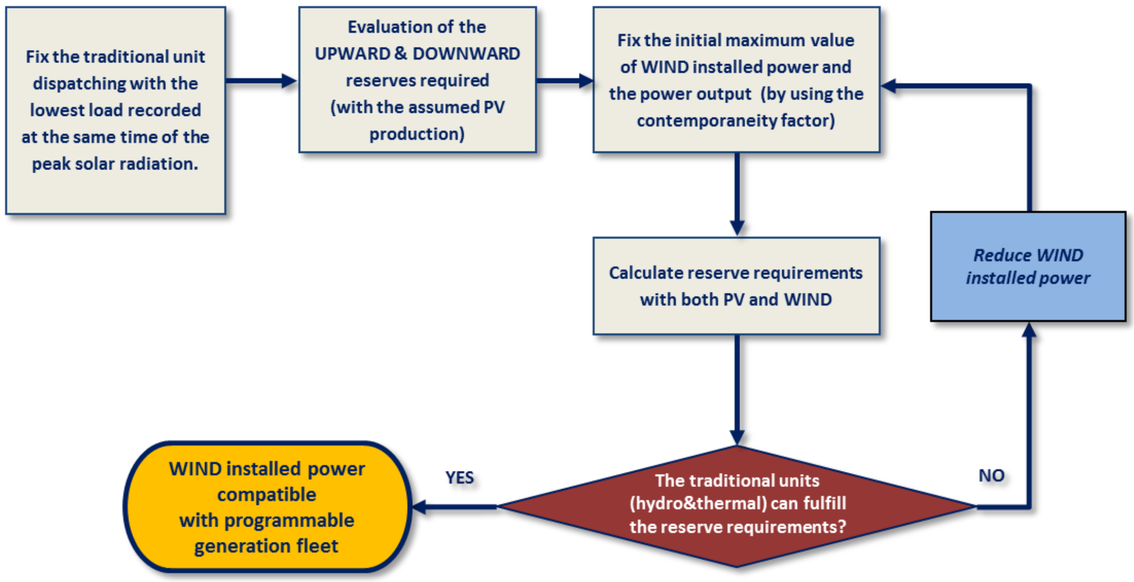


Figure 4 - iterative calculation of max installation of WIND once assumed a fixed value of PV

The results section will report a snapshot of the power system in low load condition considered in the above described methodology,

When considering different areas in case of Argentina, for each pair of values calculated for the whole system on the single bus-bar model, the presence of possible constraints due to the inter-area limited

net transfer capacity is checked. The amount of load and VRES additional generation defined for the whole system is divided in the different areas assuming at first a distribution which respect in percentage the distribution assumed for the VRES generation present in the planned values closest to 2030 available, as reported in the Inception Report [1]. This distribution reflects in a good way the allocation of the new VRES power plants in the areas according to their relevant potential.
With this new generation scenario the reserve requirements for each area and the power flows between them are calculated. Each area must fulfil its reserve requirements using its own generation or using the interconnection with other areas. In this case, the sum of the actual power flow plus the needed reserve should not exceed the net transfer capacity of the section.

2.2.2 Assumptions

2.2.2.1 Load

The low load conditions are calculated using for both the countries the data presented in the Inception Report. The available hourly profiles (referred to 2016) have been rescaled in order to have the 2030 foreseen peak value and annual energy demand.

Low load during night

The load used to analyse the most binding condition during the night hours (useful to calculate the absolute maximum wind installation, regardless the PV) is calculated as the 10^{th} percentile of loads of all the year.

Low load condition during solar radiation peak

The load used to analyse the most binding condition during the solar radiation peak hours (useful to calculate the maximum combined installable power of PV and wind) is calculated as the 10^{th} percentile of loads that occurs during these hours in the rescaled trends.

For both the analysed situations the most binding condition for wind and PV exploitation is the absolute minimum load, nevertheless, the absolute minimum load is a too strict condition since it occurs only once a year and the probability of having very high production of VRES power plants during the absolute minimum load is very low. The acceptance of a risk margin is a common practice during the planning process; in fact, with a deterministic approach, 10% of probability of RES curtailment is acceptable. Therefore in both the analysed extreme scenario the 10^{th} percentile of load can be used for this preliminary analysis. In this way the VRES curtailment could occur only when the load will be lower than the 10th percentile.
In the Table 1 are depicted the load values used for the countries.

Table 1 - Low load value in most binding condition [MW]

[MW]	Argentina				Brazil					Uruguay
	PAT	NEC	NWE	Total	N	NE	SE/CO	S	Total	Total
Low load during night	675	15,700	4,975	21,350	8,500	15,400	50,250	14,350	88,500	1,230
Low load condition during solar radiation peak	700	16,175	5,125	22,000	8,450	15,550	55,100	15,000	94,100	1,450

2.2.2.2 PV and WIND contemporaneity factor and uncertainty

As a general definition, the contemporaneity factor is the ratio between the maximum actual power production of a given set of power plants and the sum of their nominal power. It summarizes the fact that not all the power plants are producing at full power at the same time, so the sum of the maximum actual production of the plants is lower than the sum of the installed power; or vice versa it can be seen as the factor to be considered to evaluate which installed power is necessary to obtain a maximum power production.

The contemporaneity factor is used in this activity in this last way, to estimate the amount of MW which can be installed for the PV or the wind technology which can inject in the system the maximum power production which does not affect the fulfilment of the reserve requirements. Given a specific power production, the relevant installed power can be obtained dividing it by the estimated contemporaneity factor.

The contemporaneity factors used in this study are shown in Table 2.

Table 2 - Contemporaneity factor for solar PV and Wind farms [%]

[%]	Argentina				Brazil					Uruguay
	PAT	NEC	NWE	Total	N	NE	SE/CO	S	Total	Total
Wind farms	80	70	65	73.9	85	65	-	70	66.2	70
Solar PV	70	70	70	70	70	70	70	-	70	70

The secondary and tertiary reserve requirements with PV and wind farms are calculated in accordance to the description provided in the Inception Report.

As described there, one of the main factors for the assessment of upward and downward reserve is the standard deviation of load and VRES production. This standard deviation represents how the actual load and VRES production are statistically distributed around the foreseen values. In other words, it provides an indication about the possible discrepancy between the forecasted values of load or generation (which determine how the operation of the power system is planned), and their actual values. This difference must be compensated by available dispatchable generation with higher or lower production, to keep the balance of the whole system.

The standard deviations used in the analysis related to load and PV and wind production are shown in Table 3.

Table 3 - Standard deviation of load, PV and wind production [%]

	[%]
Load	2.92
Solar PV	10
Wind farms	20

2.2.2.3 Net transfer capacity between countries and between areas inside each country

For all the analysed countries, the interconnection with neighbouring power systems have not been considered. Only for Argentina, a division in some areas is considered and the possibility to exchange energy between them is taken into account, after the analysis of the isolated country as a whole is completed.

The transfer capacity between the areas depends on the expected network reinforcements in the 2030 scenario (as described in the Inception Report).

When Argentina is analysed divided in different areas, the maximum power exchanges between them have been taken into account as depicted in Figure 5.

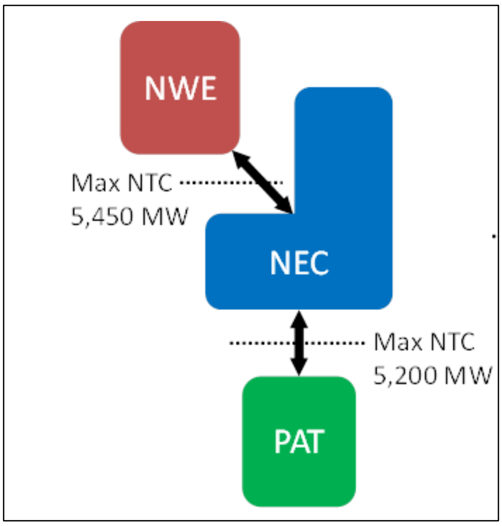


Figure 5 - Transfer capacity between Argentinian areas

As explained above, this simplified approach per areas is not applied to Brazil because due to the complexity of the network even the bus-bar model results in a meshed system. The detailed assessment of the optimal VRES installable power in each area will be then performed during the following task, where the transmission network is considered.

2.2.2.4 “Must run” and traditional units needed in low load condition

In the most binding low load scenarios used to determine the maximum amount of VRES installable capacity, an important hypothesis is related to the “must run” units and to the minimum set of hydraulic and thermal units that must be kept in service (even in very low load conditions) in the system. These power plants are usually required in order to provide services such as voltage regulation or rotating inertia as well as a proper margin of primary reserve and cannot be shut down even when the load is low to ensure the system is operating in a secure way.

This set of generators introduces a constraint of minimum power output which must remain in service, reducing the space for other VRES generation.

2.3 Results of performed analysis

This section describes the results of the assessment of the limit of VRES due to system operation constraints considering a single bus-bar modelling of the countries, i.e. neglecting the possible internal network constraints. After the analysis of the whole country power system, also the results considering the internal macro-areas are presented for Argentina in order to evaluate potential limitations due to the internal cross-area NTC foreseen in the reference scenario.

2.3.1 Argentina

Figure 6 shows the maximum VRES installed capacity considering different combination of Wind and PV generation. The blue line represents the values obtained considering Argentina as isolated system (i.e.: “*Analysis considering the Transmission System in the Reference Scenario*”). The grey line is calculated assuming the usage of the interconnections between Argentina and Brazil and Uruguay for a total amount of 3,000 MW[2] (i.e.: “*Analysis considering the Transmission System with the possible reinforcements defined in the Inception Report*”). It probably does not represent a possible operational condition, but provides a clear indication about a maximum value beyond which a significant part of new VRES should be curtailed for operational constraints. In the figure the actual VRES installed capacity is also indicated as well as the installed capacity target set for 2025.

[2] As described in [1], with Brazil there is the back-to-back solution in Garabì plus the additional interconnection at the Foz de Iguacu and towards Uruguay two 500 kV lines are considered

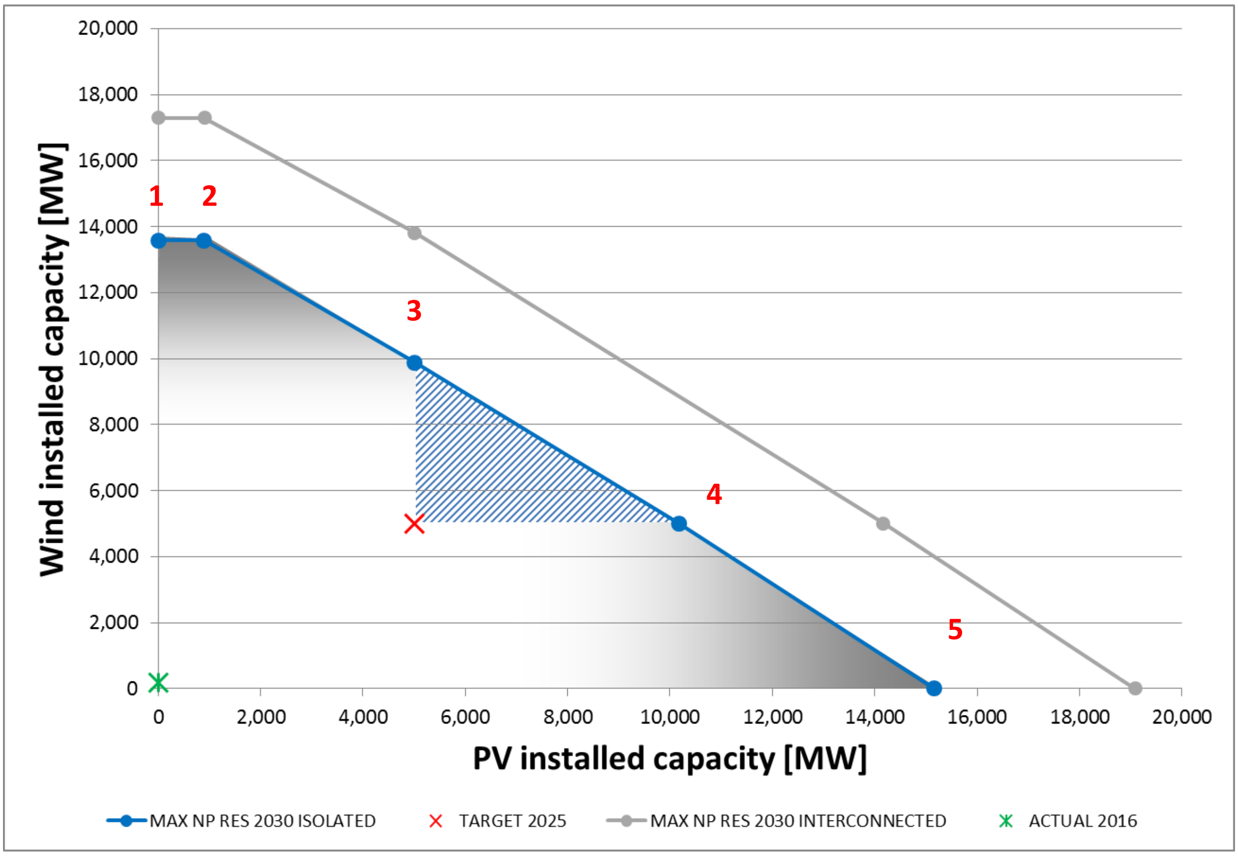


Figure 6 - VRES installed capacity limits due to system operation constraints in Argentina – 2030

As described in paragraph 2.2.1, the boundary lines are obtained by the interpolation of the following PV-wind combination according the methodology shown in Figure 2, Figure 3 and Figure 4:

- maximum wind installed capacity in low load scenario (point 1 in the previous picture)
- maximum PV installed capacity corresponding to the maximum installed wind generation calculated during solar radiation peak (point 2)
- maximum wind installed capacity meeting PV target at 2025 in low load and high VRES scenario (point 3)
- maximum PV installed capacity meeting wind target at 2025 in low load and high VRES scenario (point 4)
- maximum PV installed capacity in low load and high VRES scenario with no wind installed power (point 5)

Points 1, 2 and 5 do not represent situations which are likely to happen, because the planned development of VRES generation in Argentina foresees a growth of both PV and wind power installed plants, so at 2030 it is expected that there will be a balanced mix of PV and wind installed capacity and not the predominance of only one technology, as indicated by these points. Even if it is not probable that the system will operate in these conditions, they have been anyway evaluated in order to provide a general overview of the boundaries due to the system constraints.

The most interesting results are related to the maximum penetration of wind and PV in Argentina when the other two technologies are set to the value considered in 2025 target (point 3 and point 4):

- when the PV target is 5,016 MW, the analysis shows a potential wind installed capacity limit of 9,800 MW in case of isolated system (blue point 3 in Figure 6) and additional 4,000 MW in case the interconnection with Brazil and Uruguay are fully available for up to 3,000 MW export (grey point 3 in Figure 6). Further installation of wind over these limits should determine an unacceptable curtailment of VRES in low load conditions.
- when the wind target is 5,000 MW, the analysis shows a potential PV installed capacity limit of 10,200 MW in case of isolated system (blue point 4 in Figure 6) and about additional 4,000 MW in case the interconnection with Brazil and Uruguay are fully available for up to 3,000 MW export (grey point 4 in Figure 6). Further installation of PV over these limits should determine an unacceptable curtailment of VRES in low load conditions.

The area highlighted with the blue represent amount of PV and wind installed power most likely to happen, as aligned with the 2025 targets and with a balanced development which does not harm the system.
In fact, if a technology is developed much more than the other (grey areas in the graph) concentrated in the limited portion of the transmission system where there is the best natural resource, local problems might appear due to the constraints in the evacuation capacity and technical minimum.

Finally, it is important to underline how the values provided considering the export capacity towards neighboring countries are indicative, as it is not sure that the other systems are able to absorb the exported energy which would be in excess in Argentina.
In Chapter 3 detailed calculations will be performed in order to quantify the real risk of VRES curtailment considering simulating the expected operation of the systems with a detailed model of generation and transmission network.

2.3.2 Brazil

The assessment of the maximum installable PV and wind power in the Brazilian system as a whole provides the results shown in Figure 7. As described in previous Chapters, it represents the relationship between PV and wind installed power which allows to keep the risk of possible VRES curtailments low, considering the reserve requirements and the minimum amount of generation which cannot be shut down.

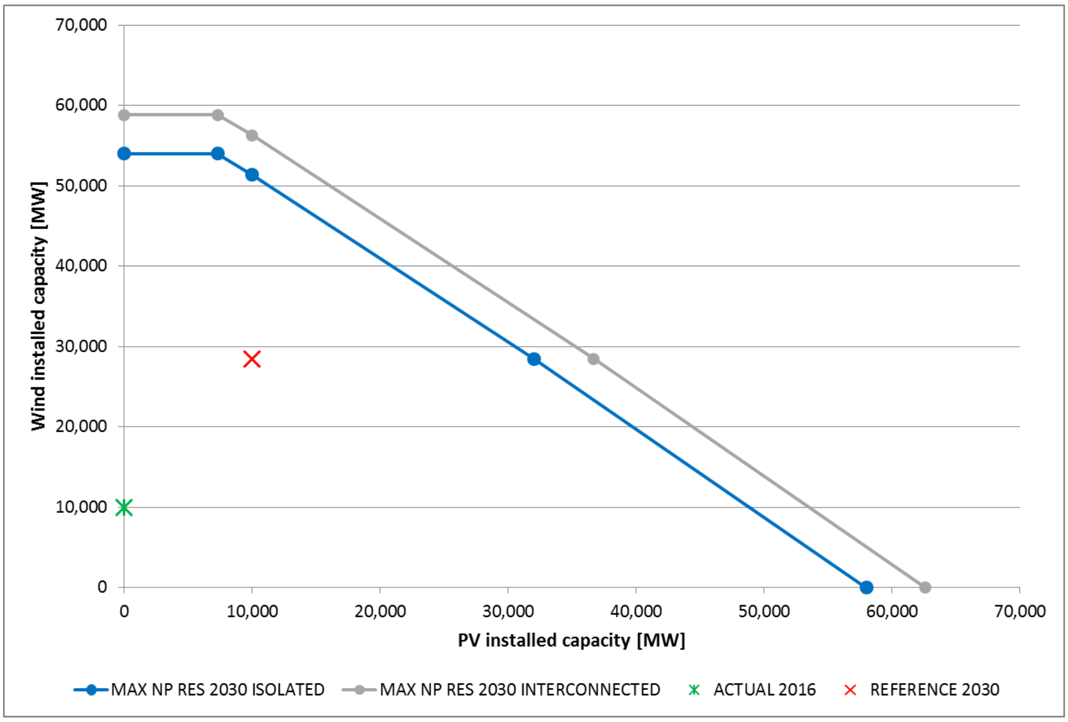


Figure 7 - VRES installed capacity limits due to system operation constraints in Brazil – 2030

For the Brazilian case it is necessary to underline how the minimum amount of generation not by VRES is subject to high possible variation, depending on the assumptions about the hydropower production which represents a very big portion of the overall production in the system (currently, about 2/3 of the electricity in Brazil is generated by hydropower plants). In fact, modulation capacity of big hydropower plants has a big impact on the risk of VRES production curtailment, because if the hydro generation can be reduced temporary for a short period, curtailments can be avoided. But if this condition happens too often or for too long time, it might result in the need of wasting water (especially for RoR hydropower plants), and in this case VRES production wouldn't be acceptable and should be curtailed.

Most of the hydropower plants, and especially the big ones, have basins ensuring a significant modulation capacity. Even RoR ones can modulate for a limited time before wasting water.

In order to estimate the real minimum amount of hydropower production that should not be reduced, reference was made to historical data, looking at values in the lowest range recorded during real operation and rescaling them with respect to the expected installed power. The resulting value considered as minimum production by the hydroelectric plants is then around 37 GW.

Figure 7 shows that there is a huge potential for the installation of additional VRES plants in the Brazilian system before reaching critical conditions with respect to the system operational constraints. It is worth underlining that most of this room for additional installations is due to the increase of the load which can be covered by VRES plants without affecting the operation of the system and the minimum power and reserve demand. From the picture it is possible to estimate that more than 22 GW of VRES plants (shared between PV or wind technologies) can be added to the values assumed as 2030 targets, which correspond to the values defined by EPE for 2026 in the PDE2026 [2].

This amount reduces to about 7 GW when considering the equivalent low load condition foreseen at 2026, which is around 13 GW lower than the 2030 case.

As explained in the previous paragraphs, due to the complexity of the network and the necessity to consider a meshed grid even when the areas are modelled as bus-bars systems, the calculation of the maximum installable power is not performed at regional level. Inter-area interconnections in the meshed network will be considered in detail in the analysis performed in Chapter 3, where detailed models of transmission system and the generation fleet are considered. The results on the optimal penetration of PV and wind power plants in the different areas will be then available at the end of the relevant analysis which will investigate the best mix of technologies to be installed and the location in the power system, evaluating the most promising areas for their installation.

2.3.3 Uruguay

The Uruguayan power system is very small compared to the Argentinean and Brazilian ones, and it is characterized by an already high penetration of wind power plants and a very strong interconnection capacity with the neighbouring countries compared to the internal peak load demand. Moreover, more than half of the demand is supplied by hydropower plants (considering also the production by Salto Grande dam). For these reasons, the Uruguayan system has an extremely high flexibility which makes it able to support considerable variations of VRES production without facing critical problems. Thermal production is available to support in case of low VRES production and to provide regulation capacity together with the hydropower plants, but also does not constitute a strong constraint with its minimum production, as it can be in critical cases completely shut down. Only the new CCGT plant under construction in Punta del Tigre might introduce some limitation in this context, which however can be managed with a proper advance production planning.

When defining the maximum installable VREs power in Uruguay, amount which is mainly limited by the inflexibility constraint of the system, a first evaluation has been done assuming the country as isolated with no minimum technical limit of thermal and hydro generation, due to the specific power system conditions described above. In this context, the resulting values (blue line in Figure 8) show a limited space for additional VRES installations with respect to the installed power at 2016[3], before reaching critical situations in which risk of VRES curtailments becomes not negligible.

[3] This gap has been already covered by installations in 2017

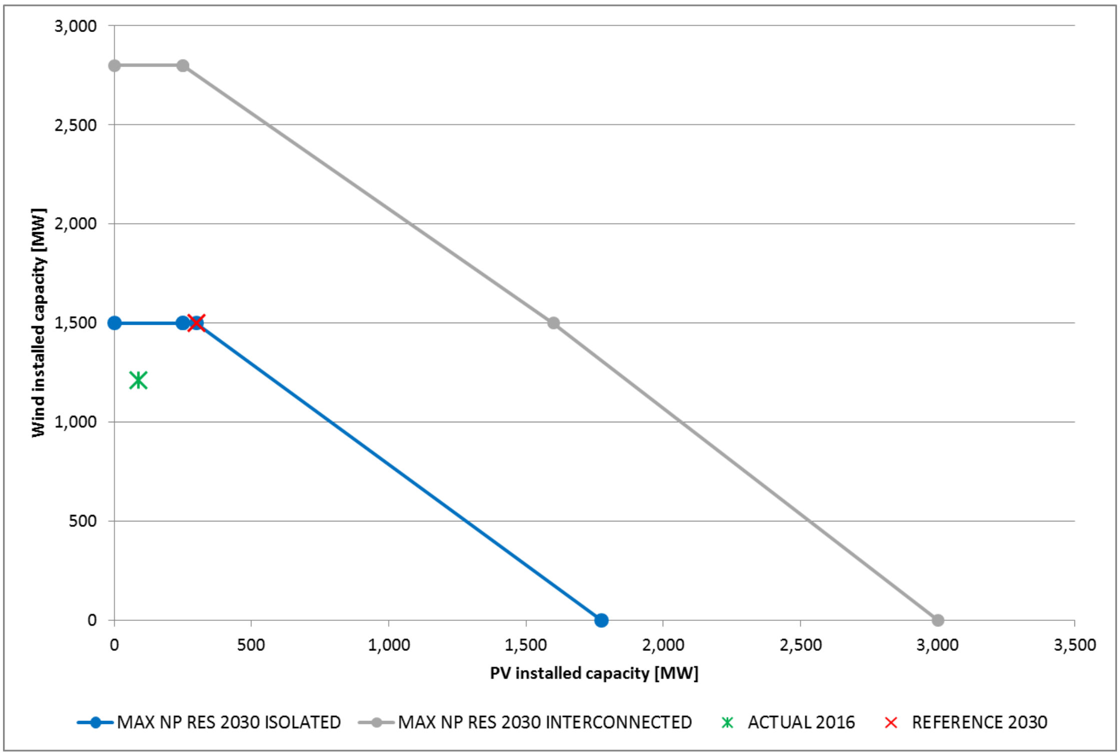


Figure 8 - VRES installed capacity limits due to system operation constraints in Uruguay – 2030

However, the situation is not critical thanks to the presence of the strong interconnection capacity, which ensures that the frequency control is properly maintained in the system and that reserve is available to face possible quick variations of VRES production.

For example, assuming an interconnection capacity equal to 1,000 MW towards the neighbouring countries, the maximum installable VRES power increases considerably, leaving space for additional power plants. In periods with high VRES production due in particular to strong wind, the Uruguayan system will have enough renewable power to cover its load and export towards the other countries, keeping a low risk of production curtailments and without affecting security of supply.

3 ECONOMIC AND TECHNICAL ANALYSES TO EVALUATE OPTIMAL AMOUNT OF ADDITIONAL VRES

3.1 Introduction

The objective of these analyses is to assess the impact of the expected renewable generation on the operation of the power system taking into account a detailed model of the transmission network. Power flows internally to the country and between the countries under examination are evaluated, investigating also the existing constraints.

A detailed generation and transmission model is set up and simulations of one year of operation with a probabilistic approach based on Monte Carlo method are performed increasing the amount of VRES and calculating the main technical and economic figures to allow the evaluation of the optimal solution.

The computational tool used for the simulation is GRARE (Grid Reliability and Adequacy Risk Evaluator) developed by CESI on behalf of Terna (the Italian Transmission System Operator) and widely used for reliability analyses in presence of substantial penetration of RES generation.

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, the results depict the expected operation of the whole system, obtained analysing many real operational states, and evaluating detailed information of each system component.

The most interesting results are the expected benefits for the system in terms of lower generation costs, taking into account the variation of the Expected Energy Not Supplied (EENS[4]), but also the expected production of the VRES plants, considering possible curtailments due to system or transmission constraints. These curtailments, which might become necessary to solve overloads that cannot be resolved by a different dispatching of the traditional generation or to meet very low load conditions when the thermal generation is already at the minimum production, reduce the production of the new VRES plants, reducing their profitability.

Thanks to the comparison of the main results obtained by the simulations of scenarios with different amount of VRES, it is possible to define the optimal amount of additional VRES power plants and to split the different technologies or areas, looking at the configurations which provide the highest benefits to the system, taking into account also the relevant costs.

The detailed methodology applied in the study is presented in the following paragraph.

3.2 Methodology

In this paragraph, the methodology applied to assess the optimal economic RES penetration accounting for possible network reinforcements is presented.

It is based on the calculation of the benefits generated for the system by the investment of the same amount of money in different technologies, and proposing investments in VRES supporting the one

[4] 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)

which provides higher benefits. The procedure adopted is illustrated in Figure 9 and is made by different steps and iterations that will be described in the next paragraphs.

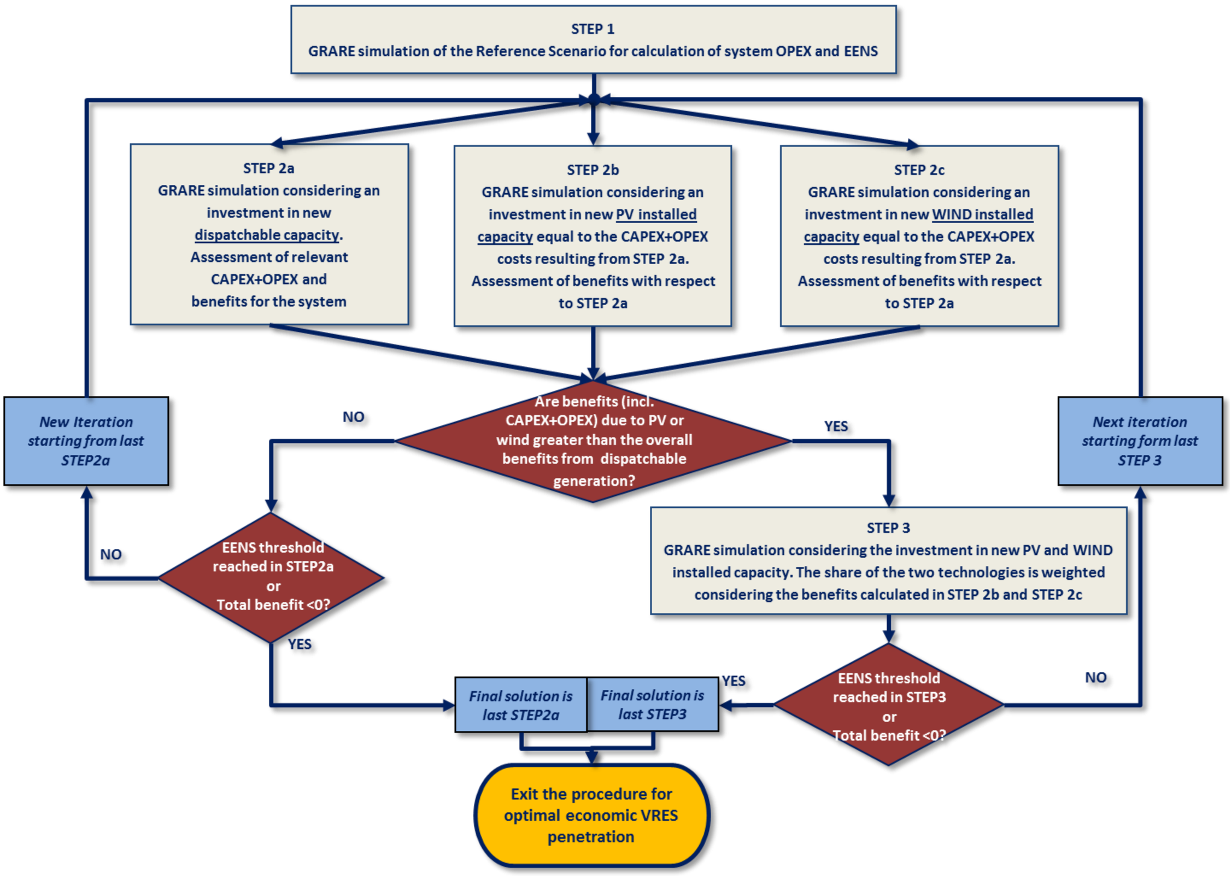


Figure 9 - Procedure for the calculation of the optimal economic VRES penetration

3.2.1 STEP 1 - GRARE simulation of the Reference Scenario for calculation of system OPEX and EENS

The first step of the analysis consists in the construction of the model to be analysed and the assessment of the corresponding operational conditions.

The power systems of the countries are initially set up as isolated systems, and after optimal development of VRES are defined for each country they will be interconnected in order to evaluate the effect of the international power exchange on the operation of the systems.

The construction of the Reference Scenario is based on the information described the Inception Report. For some Countries, it might turns out that there is an inadequate installed generation for peak demand supply due to the misalignment between the year considered for the development of the generation and the one considered for the load. For instance, the generation in Argentina is compliant with 2025 demand target and in Brazil it corresponds to the planning done by EPE at 2026, while the load in the analysed scenario refers to 2030. In this case the demand increase from the year relevant for the generation to 2030 needs to be compensated by further installed generation.

Local congestions on transmission lines, due to concentrated load increase, are identified and eliminated, including local network reinforcements which are required to supply the load. Such

reinforcements are not the object of the present study, which is focused on the improvement of transmission system to ensure the optimal exploitation of VRES.
The whole transmission network is modelled to ensure a correct calculation of the power flows on the lines, but only constraint on Extreme HV lines (500 kV and above) are considered. It means that overloads are evaluated only on these voltage levels which are responsible of the power flows over long distances and between different areas, since the lines with lower voltage have a limited capacity and a more local effect. Constraints on 220 kV and 150kV are taken into account when deemed appropriate.
Once the Reference Scenario to be simulated is defined, a run is carried out to evaluate the operation of the system in this starting condition.
The main information taken from the results are related to:

- System operational costs
- Energy production of the planned VRES plants
- Energy exchanges among areas
- Expected Energy Not Supplied (EENS)
- Line overloads
- Amount of VRES curtailments due to overgeneration or needed redispatching because of transmission line overloads

This preliminary simulation with GRARE might show very high values of EENS due to a general lack of installed power, and high operational costs due to the utilization also of expensive generation when available to cover the load and the high cost of EENS.

3.2.2 STEP 2 - Simulation of the power system considering investment in new dispatchable, wind and PV generation separately

In the second step, simulations are carried out to determine the best economic generation mix which ensures the minimization of the system operational costs, taking into account also the cost of EENS and aiming at an adequate level of generation adequacy.
The main parameters considered to calculate the amount of new generation capacity to be added in the systems are the annual costs of the system, including OPEX and CAPEX of the new power plants and the EENS. In order to find the best mix of new generation, three different simulations will be performed to compare different technologies, assuming that an equal amount of money is invested in dispatchable or PV or wind plants.
As shown in Figure 9, the first simulation of the second step (Step 2a) will consider the introduction of an amount of new dispatchable generators, defined case by case for each country depending on the lack of power and energy resulting from Step 1. The outcome of this first run will be the evaluation of the benefit for the system and the costs (CAPEX[5] and OPEX) of the new added plants. This cost will be taken

[5] The economic evaluations are performed comparing annual values. For this reason CAPEX is considered in its annuity (amount of money equal for every year of the lifetime which corresponds to the investment done at the first year, taking into account interest rate), calculated with the formula

$$EAC_{i,t} = \frac{(Discount\ Rate) * (CAPEX_i)}{1 - \frac{1}{(1 + Discount\ Rate)^n}}$$

Where n is the economic life of the plant.

as reference for the amount of money which is possible to invest in PV and wind technologies in the following steps.
When introducing new dispatchable generation, the main reference will be combined cycles gas turbines (CCGTs) with an assumed installation cost equal to 800 USD/kW.
For generation adequacy purpose any equivalent dispatchable generation (e.g. Biomass or Concentrated Solar Power) of the same capital cost could be selected provided that the new installed capacity is sufficient to contain the EENS within the maximum acceptable value. Also different technologies such as open cycle gas turbine (OCGT) might be considered when EENS is only concentrated in few hours where higher availbility of generation would be needed. The choice should finally be made by optimizing parameters such as flexibility, efficiency, carbon emissions and costs.
The dispatchable power plants are added in different areas of the countries, looking at the problems of lack of power highlighted in Step 1.

Once the amount of money which can be invested in new generation is available, calculated as CAPEX+OPEX of the dispatchable generation analysed in Step 2a, simulations in Step 2b and Step 2c are carried out, assuming respectively that an equivalent investment is done in PV or wind technologies. In both cases, part of the investment will be assigned to the introduction of storage devices which allows the VRES technologies to provide active support to the operation of the systems, on one hand reducing the reserve need to cope with their variations, and on the other increasing the dispatchability of their production, with positive benefit on the exploitation of the renewable source and on the system adequacy. The PV and wind plants are supposed to be installed in the different regions in a way which reflects the distribution foreseen in the available generation expansion plans: this allows to take into account the preference for areas with higher availability of resource and with an easier feasibility of the plants also in terms of permissions or accessibility. This approach is maintained until critical network problems appear, which require to increase the installations in areas with lower producibility but less constraints.
The economic benefits for the system are assessed both at the end of Step 2b and Step 2c, and compared with the one obtained with the dispatchable generation (Step 2a).
When the benefits[6] resulting from the introduction of VRES are higher than the ones due to dispatchable generation, the results of the of Step 2b and Step 2c simulations are used to define the best combination of the technologies, weighting the investments in PV or wind by the respective benefits provided to the system with respect to Step 1. Thanks to this approach, the resulting optimal mix considers an investment in both PV and wind, and not only in the most effective generation technology, to diversify the resources, reducing uncertainty and risks, but keeping an economic merit order.

As can be seen in Figure 9, the Step 2 is part of an iterative process which considers progressive increase of generation until it is economically viable or a proper adequacy level is reached.

As far as OPEX are concerned for dispatchable generation, the sum of the fuel costs of all the new added power plants is considered.

[6] As the simulations carried out in Step 2a, Step 2b and Step 2c are performed assuming an equal investment in the different technologies, the comparison of the benefits can be done considering only the following formula: Benefits = Δ OPEX (dispatching costs) – Δ EENS * 2000 USD/MWh

3.2.3 STEP 3 - Simulation of the power system considering an effective combined investment in WIND and PV technology

The benefits for a total investment in each of the two technologies separately can be measured as a reduction of system operational costs ($Benefits_{PV}$ and $Benefits_{wind}$) and it is calculated based on the results of the simulations carried out in Step 2.
The final simulation of each iteration is performed in the Step 3 considering the combined investment in PV and wind calculated in a proportional way with respect to the benefits brought to the system, i.e. if wind has twice benefits than PV, the investment in VRES in the Step 3 scenario will be 2/3 in wind generation 1/3 in PV generation. In this way it is kept the same investments that would be required also to install and operate the new dispatchable generators and there is a diversification of the VRES technologies keeping an economic merit order between them.
As explained above, the new PV and Wind plants are installed in the area with highest potential.

3.2.4 Iterations

The steps 2a, 2b, 2c and 3 are repeated until one of the following conditions is reached:

- A proper generation adequacy is reached, able to keep the EENS at the value of 10^{-5} p.u. of the load, assumed as standard threshold for proper system planning
- The introduction of new generation does not provide positive benefits to the system, i.e. the cost of the new plants is not compensated by reduction of EENS or fuel costs

As mentioned, the amount of generation introduced in the systems in each iteration as well as the new VRES to be considered is calibrated considering the specific characteristics of the power system allowing to obtain the optimal solution in a limited number of iterations.
When the process ends the following information about the optimal economic VRES penetration can be obtained and compared with the outcomes of the reference case:

- System operational cost
- Operational costs of the new added CCGTs
- Energy production of the planned VRES plants
- Energy exchanges among areas
- Expected Energy Not Supplied (EENS)
- Line overloads
- Costs and VRES curtailments related to dispatching caused by transmission line overloads
- LCOE of Renewable resources

3.2.5 LCOE of Renewable Energy Sources

The levelised cost of electricity (LCOE) is a parameter adopted for the comparison of different generation technologies and their economic viability. The LCOE is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of a renewable plant including all the costs over its lifetime, namely:

- Capital costs
- Operations and Maintenance cost

In this study, the LCOE is calculated using the cost per year of owning and operating an asset over its entire lifespan (CAPEX annuity + OPEX) using the assumed discount rates. These equivalent annual costs are then divided by the expected yearly production of the plants, resulting from the simulations.
More in detail the formula that describes the LCOE is given here below:

$$LCOE = \frac{CAPEX\ annuity + OPEX}{Yearly\ energy\ generated\ in\ the\ simulation}$$

3.2.6 Role of Transmission

Starting from the results of previous activities (optimum PV and Wind installation in isolated countries, with defined NTC between areas), the possible impact of investments on transmission lines, both inter-area and inter-countries will be evaluated.
The analysis is done based on the evaluation of the benefit in terms of system costs' reduction, determined by the network reinforcements.

3.2.6.1 Inter-Area transmission lines in isolated country

The first step consists in considering the inter-area reinforcement, still with isolated countries.
This has to be performed only in case critical congestions happen on inter-area sections or close to them, which cause high redispatching costs or RES curtailments. In case there are no congestions and in case the country limit for VRES installation has been reached, no new line is needed.

To perform this analysis, the most loaded lines in the optimal scenario are identified for each section, and network reinforcements are defined in order to enhance the transmission capacity and reduce congestions. The type of network reinforcement and the increase of the transfer capacity have to be determined case by case depending on the type of the network element which causes the congestion.
Starting from the optimal scenario a further GRARE simulation is performed as sensitivity in order to assess the impact of the new grid reinforcements evaluating energy not supplied, generation costs and VRES curtailment. The results section will show a monetization of the benefits for each reinforcement, in particular the value of the maximum limit for the investment in the reinforcement in order to have a benefit for the system can be used as a parameter for investment decisions. If the cost of the project is known, the planned reinforcement is viable if the cost is lower than the maximum limit for the investment (over this limit the benefits will not pay back the investment).

3.2.6.2 International Interconnection lines

After internal reinforcements have been identified, the focus is moved on international interconnection lines.
A GRARE simulation will be run on the interconnected countries considering the planned international interconnection lines.
The main outcomes of the analysis of the cross-border transmission lines are the following:

- Reduction of costs for the whole system (costs increase in exporting area, decrease in importing area)
- Power flows and possible congestion rent on the international interconnection lines

3.3 Results of Base Case Scenario

This Chapter illustrates the results of the assessment of the optimal amount of PV and Wind power plants for the isolated systems and for the interconnected case.

The Reference Scenario for each isolated country is represented by the condition defined in [1]. The optimal amount of additional VRES plants is calculated for each country, and this amount is also considered during the assessment of the interconnected system.

All the results are obtained by simulations performed with Monte Carlo method and are summarized in one resulting operational year, which can be deemed as the expected operation of the system, taking into account uncertainties in the availability of the system components and variability of load and variable generation.

The evaluation of the results is based mainly on the comparison of the following key information:

- average annual value of Expected Energy Not Supplied (EENS), assigned to the relevant cause (lack of power, lack of interconnection, lines and transformers overload) and for each area. It is reported because the introduction of VRES in a system suffering high EENS might reduce this risk, with related benefits (different generation technologies have different impact on the EENS depending on their dispatchability and on the production pattern, and simulations with GRARE provide exact assessment of this aspect);
- solar and wind power plants production and curtailments due to overgeneration and overloads;
- generation costs for each area;
- a synthesis of energy exchanges and saturation hours for each interconnection.

The evaluation of the benefits introduced by some variation in the generation fleet or in the network is performed comparing the operational costs (which are mainly the thermal generation costs and the penalization related to the EENS) with the investment costs required by the introduced change (for instance, cost of the investment needed for the installation and operation of the new VRES power plants, or avoided costs for the not needed thermal power plants replaced by VRES ones).

The evaluation is carried out on an annual basis, calculating the annuity of the investments as defined in 3.2.1 (footnote 5). This method allows the comparison of the benefits obtained from different scenario and the selection of the most convenient one.

The key information described above are reported in many tables. The following glossary explains the meaning of some words and enables a correct interpretation of the values included in the tables.

General information:

- Before redispatching: it means that the result refers to the system operation obtained after a first optimized dispatching which considers the limits of power exchanges between areas but does not consider the detailed transmission network model within the areas. It corresponds to the supply of the load in every area with the hydro, VRES and imposed generation plus the cheapest thermal power plants, fulfilling power exchange constraints between areas.
- After redispatching: it means that the result refers to the system operation obtained after the changes in the power generation dispatching with respect to the first optimized one (the one "before redispatching"), required to solve overloads on transmission lines which might be present when the detailed transmission network is considered. In general, it corresponds to a

more expensive operation because cheap generation selected in the first optimized dispatching must be replaced by more expensive one, in case network congestions are present. During redispatching, thermal generation can be increased or decreased within its technical limits, while imposed and VRES generation can only be reduced and replaced by more expensive thermal one.

Tables with information relevant to the Expected Energy Not Supplied

- Lack of Power: this value provides the information about the amount of load which cannot be supplied due to lack of generation available in that moment in the whole system. This can be caused for instance by unavailability of plants because of maintenance or faults.
- Line Overload: this value expresses the amount of load which must be curtailed to solve overloads which cannot be resolved with the redispatching of the generators. Load is curtailed in the nodes which have highest impact on the power flow through the overloaded line.
- Lack of interconnection: this value shows the amount of load which must be curtailed in an area due to not enough interconnection capacity with other areas. It differs from the lack of power because some power would be available in the system in other areas, but cannot be transferred to the area with missing generation due to interconnection limits.

Tables with information relevant to generation production and costs:

- Reduction Min. Tec. Gen.: the results reported under this label show the variation of the hydro, imposed and VRES generation which is necessary in conditions of low load and overgeneration. When all the required thermal power plants are already operating at the minimum power, but the production, including imposed, hydro and VRES one, remains higher than the load, it is necessary that these latter generation are also reduced, to meet the load level.
- DP: it indicates the Delta Production which a generator is required to apply during the redispatching process. "DP>0" means that the generator increases its production with respect to the first optimized dispatching (valid only for thermal power plants), "DP<0" means that the generator reduces its production.

3.3.1 Argentina

In this Chapter the main results regard the Argentinean power system are presented. First of all the results of Reference scenario are illustrated; then scenario with optimal economic amount of additional VRES is analyzed and compared with the reference one. Some further cases aimed at evaluating the possible benefits gained removing some network constraints are then presented and discussed.

3.3.1.1 Reference scenario

The simulation of the ***Reference scenario*** shows:

- ***An inadequacy*** of the analyzed system, with EENS equal to around 1.3×10^{-3} of the total load.
- Overall ***generation costs*** are about ***9,800 M$***, which include the costs due to redispatching to solve curtailments equal to 1 M$. This corresponds to an average cost of generation equal to about 42.2 $/MWh[7].
- Expected ***generation by PV*** power plants around 12,300 GWh (2,450 EOH) without generation curtailment.
- Expected ***generation by wind*** power plants close to 20,000 GWh (about 4,030 EOH) without generation curtailment.
- Nearly no cases where the power flows through the ***sections*** between areas are at the NTC limit.

The operation of the Argentinian system in the Reference scenario, isolated from the neighboring countries, has been simulated. Due to the fact that the study includes also Uruguay and will analyze also the operation of the interconnected systems, the Salto Grande hydroelectric power plant which is shared between Uruguay and Argentina and inject power in both systems is represented as a standalone area and will appear in the tables and figures with its production.

The main results are presented in this paragraph.

From Table 4, which shows the EENS expressed as MWh/year and split by area and reason, it can be seen that the Argentinian power system presents an inadequacy of the installed generation, indeed the greatest part of EENS is due to the lack of power. Line overloads that are not solved with a redispatching of the generation produce 5.8 GWh/year of EENS, mainly concentrated in NEC area.

Table 4 - Expected Energy Not Supplied - Argentinian Reference scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
TOTAL NEC	153,329	5,364	9	158,702
TOTAL NWE	137,830	459	33	138,322
TOTAL PAT	4	9	0	13
TOTAL	**291,163**	**5,832**	**42**	**297,037**

[7] This value does not represent the average price at which the energy is sold, which is higher, as determined in every condition by the cost of the unit which is marginal. It indicates the average costs of the energy production.

Table 5 shows the total energy produced in each area and the related costs, which are only due to thermal power plants. In this reference scenario total costs are around 9,800 M$/year, of which only a very small part due to redispatching costs (1 M$/year).

Table 5 - Total production and fuel costs - Argentinian Reference scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NEC	165,920	7,583	0	-60	164	6
NWE	46,730	2,037	0	-160	64	-5
PAT	19,510	180	0	-8	1	0
TOTAL	**232,160**	**9,800**	**0**	**-228**	**229**	**1**

As regard PV generation (Table 6), total production is around 12,300 GWh/year and it is mainly concentrated in NWE. Considering that the total installed capacity is 5 GW, the equivalent operating hours (EOH) are approximately 2,450 h/year. No PV energy curtailment is present in this scenario.

Table 6 - Total production of PV plants - Argentinian Reference scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NEC	44	0	0	0	2,458
NWE	12,274	0	0	0	2,456
PAT	0	0	0	0	-
TOTAL PHOTOV. GENER.	**12,318**	**0**	**0**	**0**	**2,456**

As regard wind generation (Table 7), total production is around 19,900 GWh/year and it is almost equally divided between NEC and PAT; only a small part of the production (less than 4%) is in NWE. Considering that the total installed capacity is 5 GW, the equivalent operating hours are a bit higher than 4,000 h/year. The wind energy curtailed is null.

Table 7 - Total production of Wind plants - Argentinian Reference scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NEC	9,092	0	0	0	3,699
NWE	773	0	0	0	2,560
PAT	10,042	0	0	0	4,604
TOTAL WIND GENER.	**19,907**	**0**	**0**	**0**	**4,029**

Table 8 summarizes energy exchanges through the defined areas. Power flow is mainly from PAT to NEC and from NEC to NWE. The interconnections are not saturated during the year. The loading of interconnections, evaluated as energy/limit is the following:

- from PAT to NEC: 28%; from NEC to PAT: 0%
- from NEC to NWE: 30%; from NWE to NEC: 6%.

Table 8 - Interconnections - Argentinian Reference scenario

AREA A	AREA B	NTC [MW]		ENERGY EXCHANGES [GWh/year]				SECTION LIMIT REACHED [h/year]	
				BEFORE RE-DISPATCHING		AFTER RE-DISPATCHING			
		A -> B	A <- B	A -> B	A <- B	A -> B	A <- B	A -> B	A <- B
PAT	NEC	4,250	4,250	10,373	3	10,361	14	0	0
NEC	NWE	4,300	4,300	11,408	2,424	11,404	2,324	0	0

The following Figure 10 provides a visual summary of the operation of the Argentinian system in the reference scenario, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

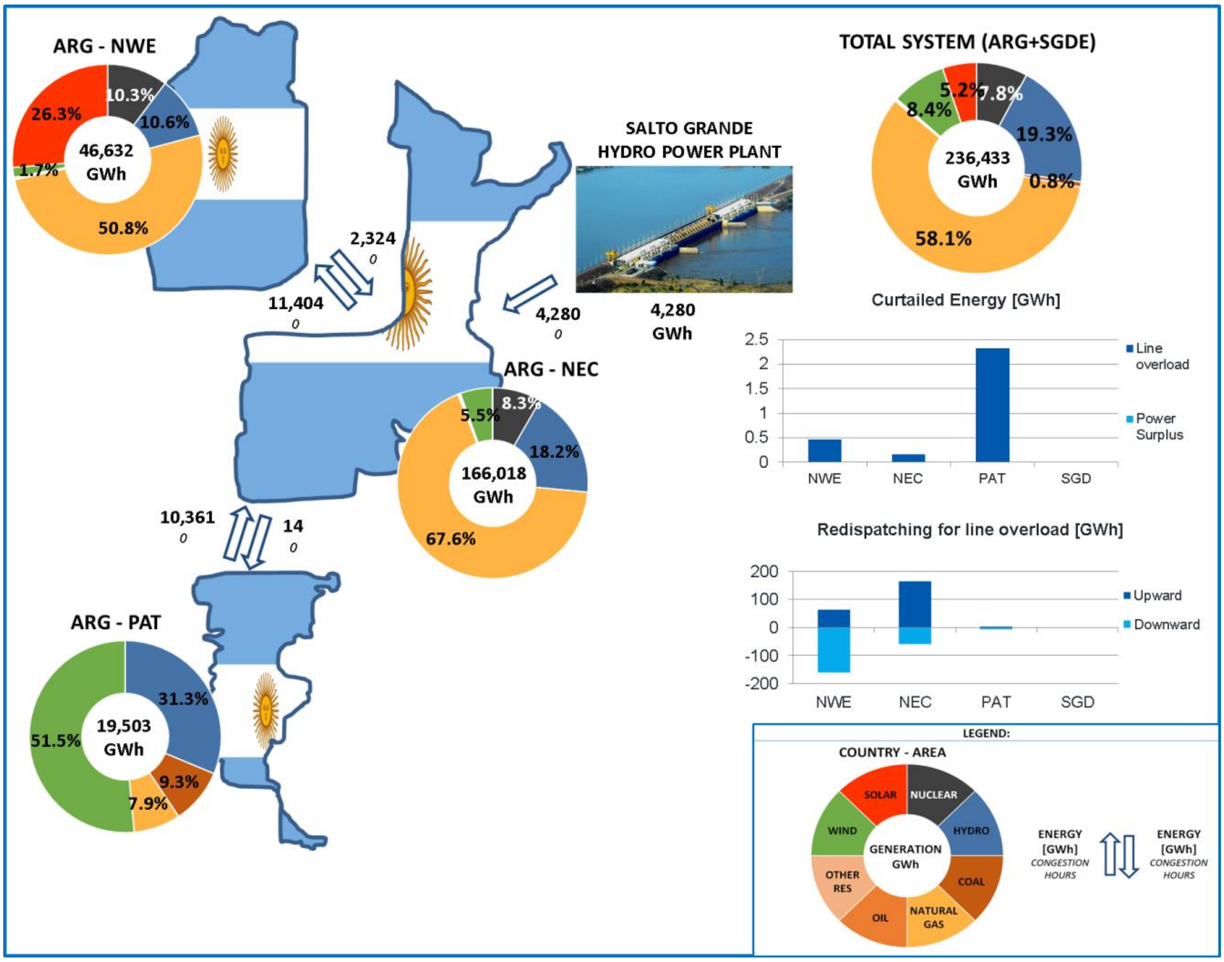


Figure 10 - Total production and energy exchanges – Argentinian Reference scenario

3.3.1.2 Scenario with optimal economic amount of additional VRES and additional CCGT

At the end of the computational process depicted in Figure 9, the ***optimal amount of additional VRES*** with respect to the installed power already considered in the Reference scenario is about ***5,000 MW of PV*** and ***9,000 MW of wind*** power plants, with a total of installed ***storage*** of about ***2,000 MW***.

Additional ***3,000 MW of new CCGT*** power plants has been considered in order to reach a ***good adequacy*** of the power system with a value of EENS around 0.9×10^{-5} of the total demand.

The investment in such technologies provides benefits for the system higher than 1,310 M$/year (thanks to savings in the generation costs and in EENS higher than investment costs).

In this scenario an increased transmission capacity for some selected lines has been considered. These reinforcements are deemed to be possible with low investments costs because the constraint is actually due to low rating of equipment such as measurement transformers, series capacitors or breaking equipment while the conductors are already able to transport the increased power considered as new limit.

The ***expected LCOE*** for PV is 45.4 $/MWh, and for wind 43.7 $/MWh.

The amount of additional power turns out to be quite balanced between the VRES technologies because in general wind power plants have a lower LCOE and higher production but PV is cheaper in terms of annuity per installed MW, so more power plants can be installed with a lower amount of money.

In this new scenario:

- The ***EENS*** due to lack of power or line overload reaches 1.3 GWh, equal to around 0.6×10^{-5} of the total load.
- Overall ***generation costs*** decrease to 6,736 M$ thanks to the VRES production which replaces thermal generation. The part of costs due to the presence of network congestions increases to 35 M$ (+34 M$ with respect to the Reference scenario), due to higher expected overloads. The overall costs correspond to an average production cost equal to 28.6 $/MWh.
- Expected ***generation by PV*** plants higher than 23,000 GWh, but the EOH decreases below 2,400h due to curtailments which increase up to 380 GWh (about 1.6% of total PV production).
- Expected ***generation by wind*** power plants higher than 58,000 GWh (more than 4140 EOH) and a curtailment of about 1,000 GWh (2.7% of the total wind generation).
- The ***NTC limits of the section PAT - NEC and NWE – NEC*** are reached in some cases, summing up to about 725 hours for PAT-NEC section and about 230 hours for NWE-NEC section.

The analysis performed following the procedure described in Figure 9 provides an optimal amount of additional VRES installations in Argentina equal to about 5,000 MW in PV and 9,000 MW in wind power plants. Table 9 provides the detail of the added PV and wind installed power in each area with respect to the Reference scenario and the final resulting values.

Table 9 - Additional and total VRES installed power in the Scenario with optimal economic amount [MW]

AREA	PV installed power		Wind installed power	
	Added to reference scenario	Total	Added to reference scenario	Total
NEC	1,082	1,100	5,950	8,400
NWE	4,000	9,000	0	300
PAT	0	0	3,000	5,200

The results of the simulation of one year of operation of the system with this new amount of VRES installed power are shown in detail below.

The Argentinian power system with the increased VRES production and the additional new CCGTs reaches a good adequacy. Table 10 shows the EENS, expressed as MWh/year, split by area and cause. As for the reference scenario, the greatest part of EENS is due to lack of power.

Table 10 - Expected Energy Not Supplied - Argentinian optimal scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
TOTAL NEC	571	35	0	606
TOTAL NWE	676	7	0	683
TOTAL PAT	0	3	0	3
TOTAL	**1,247**	**45**	**0**	**1,292**

Table 11 sums up the total annual production and the thermal costs. With respect to the costs of the Reference scenario reported in Table 5, the total thermal costs decrease considerably (- 3,065 M$/year with respect to the Reference scenario, equal to a reduction of more than 30%) which is the result of a lower initial costs before redispatching (- 3,100 M$/year because part of the load is supplied by the new VRES plants and not by thermal plants, with considerable savings on the fuel costs) and a greater cost of the redispatching needed because of some network constraints and line overloads (+ 34 M$/year).

Table 11 - Total production and fuel costs - Argentinian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NEC	153,197	5,091	0	-611	1,280	47
NWE	50,981	1,518	358	-337	123	-7
PAT	31,559	92	628	-458	3	-5
TOTAL	**235,737**	**6,701**	**986**	**-1,406**	**1,406**	**35**

In Table 12 the results in term of PV generation for the optimal amount of additional RES are presented; Table 13 shows the difference of total PV production respect to Reference scenario.

There is an increase of almost 11,500 MWh/year in the annual production, so nearly twice the Reference scenario. Since the 4,000 MW of additional PV plants are deployed in NWE area, the increase is totally in this area.

The results show a solar production curtailment equal to 380 GWh (1.6% of the produced energy).

The greatest part of PV production curtailment, equal to 353 GWh, is present in conditions where the load is low and the thermal generation is operating at the minimum production and no additional power can be evacuated towards NEC area. This part due to an overgeneration is present only in NWE area. A very small part of curtailment is present after redispatching and it is equal to 27 GWh/year (equivalent to 0.1% of the produced energy).
The increase of the curtailments has the effect to reduce in the equivalent operating hours with respect to the Reference scenario (almost 133 hours).

Table 12 - Total production of PV plants - Argentinian optimal scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NEC	2,091	0	-3	0	1,899
NWE	21,769	353	-24	0	2,375
PAT	0	0	0	0	-
TOTAL PHOTOV. GENER.	**23,860**	**353**	**-27**	**0**	**2,323**

Table 13 - Difference of total production of PV plants between Argentinian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NEC	2,047	0	-3	0	-559
NWE	9,495	353	-24	0	-81
PAT	0	0	0	0	-
TOTAL PHOTOV. GENER.	**11,542**	**353**	**-27**	**0**	**-133**

In Table 14 wind production results of the optimal scenario are presented; Table 15 shows the difference of total wind production respect to Reference scenario.
The annual wind production reaches almost 58,500 MWh, also in this case nearly twice the Reference scenario. The results show a wind production curtailment equal to 1,031 GWh (1.8% of the produced energy). More than 60% of the curtailments is due to minimum production constraint (and concentrated in PAT area) while the rest is due to line overloads, and is more distributed also in NEC area.
It is interesting to point out that the equivalent operating hours globally increase if compared to the Reference scenario because the additional wind power plants are installed in areas with higher potential. The EOH reach almost 4,140 h/year with an increase of about 113 hours.

Table 14 - Total production of Wind plants - Argentinian optimal scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NEC	34,572	0	-112	0	4,099
NWE	769	5	-1	0	2,526
PAT	23,143	628	-285	0	4,306
TOTAL WIND GENER.	**58,484**	**633**	**-398**	**0**	**4,142**

Table 15 - Difference of total production of Wind plants between Argentinian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NEC	25,480	0	-112	0	400
NWE	-4	5	-1	0	-34
PAT	13,101	628	-285	0	-298
TOTAL WIND GENER.	**38,577**	**633**	**-398**	**0**	**113**

Table 16 gathers information on the interconnections in the optimal scenario. Looking at the variations with respect to the Reference scenario, it can be highlighted that there is an increase of 29% in the energy exchange from PAT to NEC area: this growth is due to the additional wind farm production in PAT which is exported to the North. As regard interconnection NEC – NWE, energy exchanges increase in both directions: from NWE to NEC the growth is significant, and it is related to the higher PV production in NWE area, while the increase from NEC to NWE is due to the absence of additional dispatchable plants in NWE, which then needs to import more energy when PV production is absent. Even if it happens a limited time in the year, it is worth highlighting that the power exchanges across the PAT-NEC and NEW-NEC section reach the limit defined with the NTC.

The average loading of interconnections is the following:

- from PAT to NEC: 57%; from NEC to PAT: 0%
- from NEC to NWE: 41%; from NWE to NEC: 17%.

Table 16 - Interconnections - Argentinian optimal scenario

AREA A	AREA B	NTC [MW]		ENERGY EXCHANGES [GWh/year]				SECTION LIMIT REACHED [h/year]	
				BEFORE RE-DISPATCHING		AFTER RE-DISPATCHING			
		A -> B	A <- B	A -> B	A <- B	A -> B	A <- B	A -> B	A <- B
PAT	NEC	4,250	4,250	21,545	6	21,085	10	727	0
NEC	NWE	4,300	4,300	12,079	6,942	12,080	6,730	9	224

Figure 11 shows the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and thermal redispatching needed to solve network congestions in the scenario with the optimal amount of VRES installations. The comparison with Figure 10, which provides the same information for the Reference scenario, highlights the increase of the PV and wind production in the system and the relevant reduction of thermal generation, and an increase of the operations required to solve network constraints.

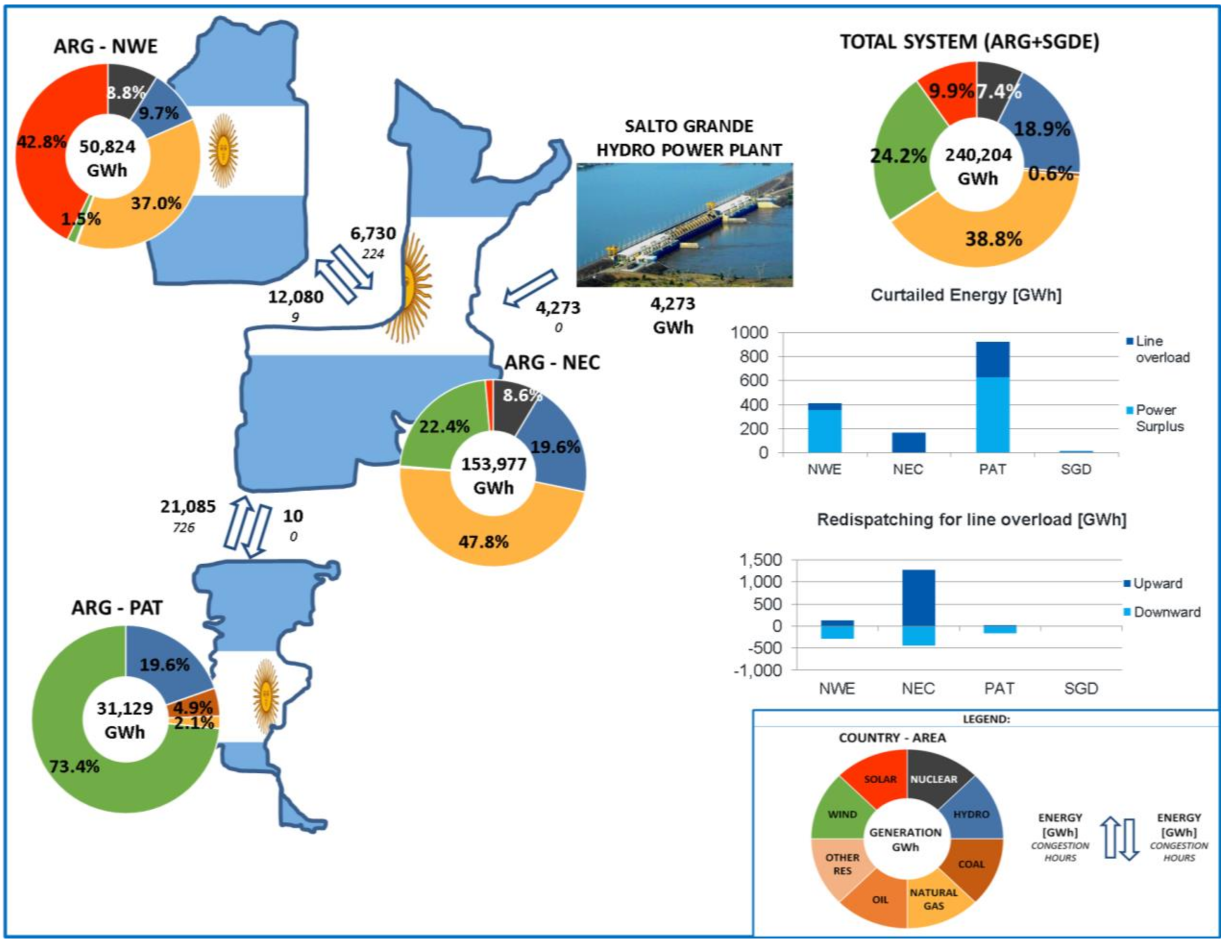


Figure 11 - Total production and energy exchanges – Argentinian scenario with optimal VRES amount

The analysis of the results obtained by the simulation of the operation of the system with the additional 14,000 MW of VRES power plants and additional 3,000 MW of thermal power plants is completed with a table that summarizes the total benefit evaluated with respect to the Reference scenario, so expressed as a difference between optimal scenario and the reference one.

The Table 17 reports the main differences in terms of:

- total thermal generation variation, already considering the needed redispatching;
- RES curtailment variation;
- EENS variation.

These values are expressed in GWh/year.

For each of the previous information, economic benefits are presented. All the savings (or costs) are evaluated calculating the relevant annuity, in order to allow a direct comparison, and include:

- the investment for the additional VRES;

- the investment for the storage;
- the investment for the additional dispatchable generation needed to reach the power system adequacy;
- total thermal generation costs variation;
- the variation of the cost of EENS.

Please note that the cost associated to VRES production curtailment is already included in total thermal generation costs variation, because during the redispatching more thermal generation is needed and paid if VRES generation is reduced. All the costs and savings are expressed in M$/year. Benefit has been evaluated for each MW of additional VRES too.

Table 17 - Total benefit – Argentinian optimal scenario with respect to Reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	14,025	-1,868
STORAGE	2,093	-197
ADDITIONAL DISPATCHABLE	3,000	-282
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-45,853	3,065
RES CURTAILMENT	1,411	-
TOTAL EENS	-296	591
TOTAL BENEFIT	**-**	**1,310**

BENEFIT/MW VRES [kUSD/year]	**93**

Finally, based on the results presented above, it is possible to calculate the expected LCOE for the PV and wind power plants added to the Argentinian power system.
Considering the assumed CAPEX and OPEX, the resulting values are:

- LCOE for PV power plants: 45.4 $/MWh
- LCOE for wind power plants: 43.7 $/MWh

The following table shows the transmission capacity of the lines which were increased during the analysis. As explained above, they are existing lines with a transmission capacity actually limited not by the conductor capacity but by other equipment constraints, such as limited rating of the Current Transformer or the Series Capacitors for long lines. For this reason, it has been decided to consider in the simulations the real thermal limit assuming that the cost for the removal of the constraint is limited.

Table 18 - Network reinforcements

BUS 1	BUS 2	Reference Scenario Imax [A]	Scenario whit RES Imax [A]
MALVINAS	RECREO	1251	1762
RECREO	LAVALLE	1000	1562
ROMANG	S. TOME	1251	1931
ROMANG	RESISTENCIA	1400	1929
SANTA CRUZ NORTE	COMODORO	1000	1840
SANTA CRUZ NORTE	RIO SANTA CRUZ	1000	2800
CERRITO DE LA COSTA	P. BANDERITA	1500	2000

3.3.1.3 Optimal scenario without the new additional CCGT power plants

The scenario with the optimal amount of additional VRES has been investigated also without considering the installation of the new additional 3,000 MW of CCGT power plants, in order to evaluate which is the impact on the adequacy of the system and on the total benefit.

The simulation of this scenario shows:

- An ***increased inadequacy*** of the system, with EENS higher than 1x10^{-4} of the total load.
- The ***total generation costs*** increase by 147 M$ due to the absence of the new cheaper plants.
- Total ***PV production*** and the ***Wind production*** remain aligned with the optimal scenario.

The scenario without the new additional CCGT power plants presents an EENS around 24 GWh/year, therefore respect to the previous one there is a strong increase by nearly 20 times. EENS is equal to 10^{-4} p.u with respect to the load, underlining the lower adequacy. The greatest part of EENS is due to the lack of power in the NWE and NEC areas. The EENS due to line overload increased from 0.05 GWh/year of the previous case to 1.3 GWh/year. Table 19 shows the EENS, expressed as MWh/year, split by area and cause.

Table 19 - Expected Energy Not Supplied - Argentinian scenario without new additional CCGTs

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
TOTAL NEC	8,685	886	1	9,572
TOTAL NWE	13,866	450	37	14,353
TOTAL PAT	0	7	0	7
TOTAL	**22,551**	**1,343**	**38**	**23,932**

The total thermal costs increases of 147 M$/year with respect to the scenario with new additional CCGTs, mainly due to the increase of fuel cost before redispatching (increment of 2%).

Table 20 - Total production and fuel costs - Argentinian scenario without new additional CCGTs

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NEC	157,353	5,386	0	-721	1,110	33
NWE	46,756	1,354	376	-207	282	11
PAT	31,682	104	633	-467	4	-5
TOTAL	235,791	6,844	1,009	-1,395	1,396	39

PV and wind production remain aligned to the optimal scenario with the CCGT plants considered, with only a negligible reduction due to some unresolved overloads.

•

Table 21 reports the main differences in terms of:

- the investment for the additional dispatchable generation needed to reach the power system adequacy;
- total thermal generation variation, already considering the needed redispatching;
- RES curtailment variation;
- EENS variation.

Table 21 - Total benefit - Argentinian optimal scenario and without new additional CCGTs

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	0	0
STORAGE COST	0	0
ADDITIONAL DISPATCHABLE	-3000	282
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	27	-147
RES CURTAILMENT	30	-
TOTAL EENS	23	-45
TOTAL BENEFIT	-	90

The results reported in the Table 21 highlight that the analyzed case presents a total benefit equal to 90 M$/year higher than the previous one, due to the savings on the investment in new 3,000 MW CCGT power plants, which are higher than the fuel cost increase and the cost related to the adequacy deterioration. However, it is important to underline that an EENS equal to 10^{-4} of the total load might be not acceptable in a long term system planning, and that resources to face adverse events such as loss of generators or strong unbalances due to wrong VRES production forecasts must be available. Interconnections to other power systems able to provide the required power when needed might also improve the adequacy. This will be analyzed in chapter 3.3.4.

3.3.1.4 Optimal scenario without the storage

A simulation has been carried out on the optimal configuration described in 3.3.1.2 without considering the storage related to the additional VRES plants to assess which is the economic impact of the technical assumption that VRES plants are able to support the system without requiring additional reserve to the thermal generation. In fact, as explained in the description of the methodology, the storage is assumed as mandatory in the optimal solution because it allows the new VRES power plants to be able to support the system with additional services and limiting the reserve requirements.

The key results arising from the ***scenario without storage*** are:

- ***System Reliability***: the EENS without storage installed in the Argentinian power system increases by 6 GWh/year (+600%), reaching $3.5x10^{-5}$.
- ***Generation costs***: the generation costs increase by about 125 M$/year.
- ***PV generation*** and ***Wind generation***: without storage the PV and wind production are reduced (by 300 GWh/year and 250 GWh/year respectively), mainly due to increased number of overproduction conditions which cannot be solved without the storage.

The detailed results are reported below. The results are compared with the scenario with optimal amount of VRES.

The scenario without the storage presents an EENS around 7 GWh/year. The increment of the EENS is mainly due to the lack of power in the NWE and NEC areas. The results are reported in the Table 22.

Table 22 - Expected Energy Not Supplied - Argentinian scenario without storage

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
TOTAL NEC	2,921	44	0	2,965
TOTAL NWE	4,369	11	8	4,388
TOTAL PAT	0	4	0	4
TOTAL	**7,290**	**59**	**8**	**7,357**

The difference of total PV and wind production between the two cases is reported in the Table 23 and Table 24.

Table 23 - Difference of total production of PV plants between Argentinian optimal scenario and without storage

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NEC	0	0	-1	0	-1
NWE	-286	286	-25	0	-66
PAT	0	0	0	0	-
TOTAL PHOTOV. GENER.	**-286**	**286**	**-26**	**0**	**-59**

Table 24 - Difference of total production of Wind plants between Argentinian optimal scenario and without storage

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NEC	0	1	4	0	0
NWE	-4	4	-2	0	-33
PAT	-221	221	13	0	-84
TOTAL WIND GENER.	**-225**	**226**	**15**	**0**	**-32**

The Table 25 reports the main differences in terms of:

- the investment for the additional dispatchable generation needed to reach the power system adequacy;
- total thermal generation variation, already considering the needed redispatching;
- RES curtailment variation;
- EENS variation.

Table 25 - Total benefit - Argentinian optimal scenario and without storage

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	0	0
STORAGE COST	-2093	197
ADDITIONAL DISPATCHABLE	0	0
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	268	-123
RES CURTAILMENT	523	-
TOTAL EENS	6	-12
TOTAL BENEFIT	-	62

As expected, the storage constitute an economic cost for the system, but is necessary to ensure that the new VRES plants can support the system, not requiring high reserve margin to thermal generation, this reaching the high penetration considered. In fact, the case without it presents respect to the optimal scenario a total benefit equal to 62 M$/year, thanks to the saving of the investment, but the EENS is higher than the target threshold. Investments in some other technological solution would be needed to keep the same adequacy and allow a correct comparison.

The increase of VRES curtailment (more than 500 GWh/year higher than in the previous case) and of the thermal generation cost (about 125 M$/year more than before) together with the EENS increase demonstrate that the operation of the system with the high amount of VRES plant but without proper mitigation of their variability is subject to technical limitations and not optimized.

3.3.1.5 *Optimal scenario without the reinforcements of the transmission lines*

Finally, the scenario with the optimal amount of additional VRES and storage has been investigated also without considering the reinforcements of transmission lines listed in Table 18, which were considered in the final scenario.

The simulations of this scenario shows:

- ***System Reliability***: the EENS when the reinforcements of transmission lines are not considered remains aligned with the optimal case (around 1.3 GWh/year), with only a slight increase of EENS due to line overload.
- ***Generation costs***: the generation cost increase by 63 M$/year due to additional redispatching.
- ***PV*** and ***wind generation***: without network reinforcement, the VRES production must be curtailed for more than 1 TWh, distributed in similar proportion between PV in NEW and wind in PAT.

Table 26 shows the EENS when the reinforcement of the Santa Cruz Norte-Comodoro-Puerto Madryn line is not considered. The EENS is a bit above 1.3 GWh/year, aligned with the optimal scenario.

Table 26 - Expected Energy Not Supplied - Argentinian scenario without network reinforcements

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
TOTAL NEC	571	77	0	648
TOTAL NWE	676	8	0	684
TOTAL PAT	0	4	0	4
TOTAL	**1,247**	**89**	**0**	**1,336**

The difference of total PV and wind production between the two cases is reported in the Table 27 and Table 28.

Table 27 - Difference of total production of PV plants between Argentinian optimal scenario and scenario without network reinforcements

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NEC	0	0	2	0	2
NWE	-9	8	-500	0	-58
PAT	0	0	0	0	-
TOTAL PHOTOV. GENER.	**-9**	**8**	**-498**	**0**	**-51**

Table 28 - Difference of total production of Wind plants between Argentinian optimal scenario and scenario without network reinforcements

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NEC	0	0	22	0	3
NWE	0	0	-32	0	-105
PAT	-6	6	-594	0	-118
TOTAL WIND GENER.	**-6**	**6**	**-604**	**0**	**-45**

The Table 29 reports the summary of the main figures which allow to evaluate the possible benefits deriving from the network reinforcements. Due to the fact that there are no changes in the investment costs for generation and storage and in the EENS, the whole amount of the additional generation costs caused by required redispatching (equal to 63 M$/year) can be considered as the amount of money which is possible to save thank to the improvement of the transmission capacity.

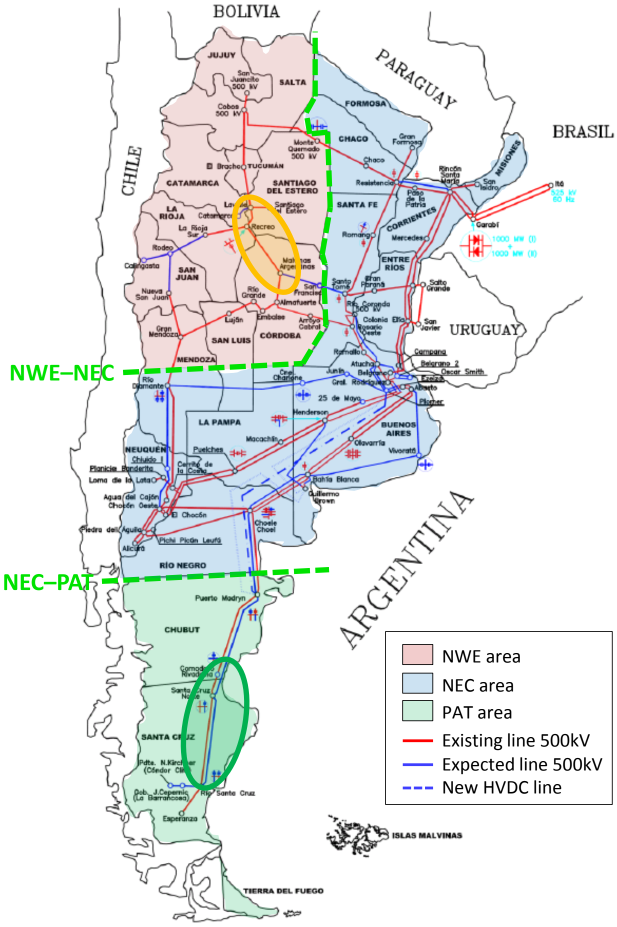
Table 29 - Total benefit - Argentinian optimal scenario and without network reinforcements

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	0	0
STORAGE COST	0	0
ADDITIONAL DISPATCHABLE	0	0
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	1021	-63
RES CURTAILMENT	1116	-
TOTAL EENS	0	0
TOTAL BENEFIT	-	**-63**

Table 30 shows the expected overloads for the most critical lines in case the reinforcements are not considered. It is possible to see that there are two lines belonging to the backbone which connects PAT and NEC (and their overload causes the reduction of the wind production) and two lines close to the section between NEW and NEC (which are responsible for the reduction of the PV plants).

Table 30 - Network reinforcements

BUS 1	BUS 2	Expected Overload [h/year]
SANTA CRUZ NORTE	COMODORO	3750
SANTA CRUZ NORTE	RIO SANTA CRUZ	3500
MALVINAS	RECREO	1800
RECREO	LAVALLE	540



3.3.1.6 Final considerations on Argentinian isolated system

The optimal solution for additional VRES installations defined in 3.3.1.3, able to ensure a proper adequacy of the Argentinian system, includes 5,000 MW of PV , 9,000 MW of wind power plants and storage of about 2,000 MW, plus additional dispatchable power plants which are necessary to keep the EENS below the 10^{-5} p.u. threshold. Without the additional CCGTs in fact the EENS would increase considerably, and with minor extend this happens also in case the storage systems are not considered.

Dispatchability of the energy sources is essential to reach an elevate level of system adequacy, and can be obtained and improved thanks to the integration of different technologies and the usage of storage systems. Investment in storage systems might be not economically profitable if they are considered as stand-alone systems, but it is necessary to ensure proper conditions for a considerable growth of the VRES penetration.

Concerning the transmission system, the new lines currently planned and assumed in the analyzed scenario allow a good development of VRES plants in the areas with higher potential. Some upgrades of capabilities of existing lines are proposed, where the conductors seems to be already able to transport higher amount of power but the capacity is limited by some other equipment. These improvements should require a relatively low investment, allowing a better exploitation of PV resource in NEW and wind one in PAT.

The presence of storage systems and the improvement of some transmission capacity introduce a high level of flexibility for the system which is then able to accept higher amount of VRES plants also concentrated in limited areas where the best resources are present.
As installation of storage systems and investments in transmission lines provide similar benefit on the system, and in some way compete one against the other, during the detailed planning of the system (network and generation) it is necessary to evaluate actual opportunities and constraints for each project in order to select the best solution for every different case.

3.3.2 *Brazil*

Expected operation of Brazilian system has been simulated without considering interconnections to the neighboring countries. As described in [1], it is characterized by a very huge extension and it is divided in four main areas: Norte (N), Nordeste (NE), Sudeste/Centro (SE/CO) and Sul (S). Each area is again divided in different States.

The simulations have been carried out considering the detailed model of the generation fleet and the transmission network, looking for possible overloads on the EHV lines (equal or above 500 kV) between different states and between the areas.

3.3.2.1 Reference Scenario

The simulation of the ***Reference scenario*** for Brazil shows:

- ***An inadequacy*** of the analyzed system, with EENS equal to around $3x10^{-4}$ of the total load.
- Overall ***generation costs*** are about ***13,000 M$***, which include the costs due to redispatching to solve curtailments equal to 41 M$.
- Expected ***generation by PV*** power plants around 18 TWh (about 1,850 EOH) without generation curtailment.
- Expected ***generation by wind*** power plants close to 112 TWh (nearly 3,900 EOH) with the presence of some overproduction conditions.
- Nearly no cases where the power flows through the ***sections*** between areas are at the NTC limit.

In the Reference scenario, the Brazilian system shows a generation inadequacy due to the fact that the generation fleet in this scenario is the one foreseen by EPE at 2026 while the load has been increased up to the value expected at 2030. The total EENS is nearly 250 GWh, which is about $3x10^{-4}$p.u. of the load. The main reason for EENS is lack of available power, and in minor part a lack of interconnections between areas. This suggests that the lack of power is distributed in all the areas and that the interconnections are well sized.

Table 31 - Expected Energy Not Supplied – Brazilian Reference scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
N	14,378	59	3,690	18,127
NE	47,088	7,131	3,636	57,855
SE/CO	169,104	0	1,418	170,522
S	0	0	0	0
EENS TOTAL	**230,570**	**7,190**	**8,744**	**246,504**

In this context, the generation costs are high (about 13,000 M$/year) due to the usage of also expensive plants which are often required to cover the peak demand. On the other hand, it is possible to observe that there are conditions with overgeneration, due to the presence of a big amount of hydropower plants, the presence of an already considerable amount of VRES plants and the need to keep in service many thermal plants needed for the high demand hours. However, these conditions cause some curtailments of the hydro and VRES generation, which in the real operation of the system might be reduced with a more optimized short term planning of the power plants. It is anyway important to highlight that the curtailments due to overproduction might become the limiting factor for the installation of big amount of VRES plants.

Table 32 - Total production and fuel costs - Brazilian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
N	136,645	1,116	1,344	-1	25	10
NE	203,918	2,297	1,315	-285	48	-18
SE/CO	468,021	6,740	0	-26	142	23
S	218,042	2,745	0	-5	103	26
TOTAL	**1,026,626**	**12,898**	**2,659**	**-317**	**318**	**41**

Concerning VRES production, Table 33 and Table 34 show the main figures related to PV and wind plants respectively. Also for them curtailments due to overgeneration conditions are already present, especially for wind which is present also during low load periods in the night.

Table 33 - Total production of PV plants - Brazilian Reference scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
N	192	11	0	0	1,899
NE	3,673	49	0	0	2,070
SE/CO	14,124	0	0	0	1,812
S	0	0	0	0	-
TOTAL PHOTOV. GENER.	**17,989**	**60**	**0**	**0**	**1,859**

Table 34 - Total production of Wind plants - Brazilian Reference scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
N	884	43	0	0	3,500
NE	94,797	1,266	0	0	3,934
SE/CO	102	0	0	0	3,636
S	16,062	0	0	0	3,626
TOTAL WIND GENER.	**111,845**	**1,309**	**0**	**0**	**3,882**

Table 35 summarizes the energy exchanges between the areas. There is a clear energy flow from the Norte, Nordeste and Sul areas to the central one (equal to nearly 105 TWh), where most of the load is concentrated. But thanks to the high NTC values, the limits are almost never reached.

Table 35 - Interconnections - Brazilian Reference scenario

AREA A	AREA B	NTC [MW]		ENERGY EXCHANGES [GWh/year]				SECTION LIMIT REACHED [h/year]	
				BEFORE RE-DISPATCHING		AFTER RE-DISPATCHING			
		A -> B	A <- B	A -> B	A <- B	A -> B	A <- B	A -> B	A <- B
N	NE	8,246	8,246	6,774	13,022	7,373	13,300	0	0
NE	SE/CO	7,900	6,000	30,216	1,248	30,297	1,246	0	0
N	SE/CO	17,510	11,900	44,041	609	43,777	643	0	0
N-NE	SE/CO	20,850	19,800	72,984	1,138	72,776	1,145	42	0
SE/CO	S	11,300	9,800	751	31,745	750	31,842	0	29

Figure 12 below provides a visual summary of the operation of the Brazilian system in the reference scenario, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

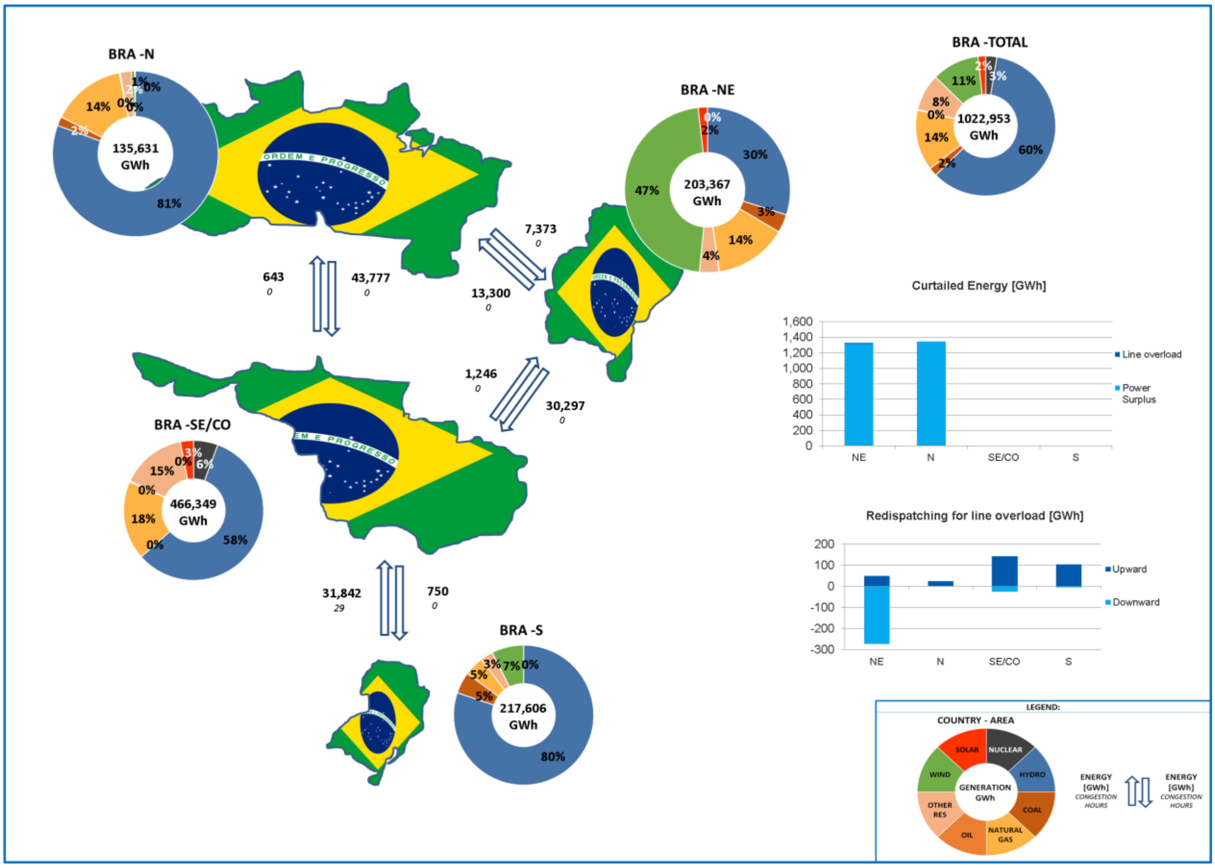


Figure 12 - Total production and energy exchanges – Brazilian Reference scenario

3.3.2.2 Scenario with optimal economic amount of additional VRES

At the end of the computational process depicted in Figure 9, the ***optimal amount of additional VRES*** with respect to the installed power already considered in the Reference scenario is about ***11,000 MW of PV*** and ***10,000 MW of wind*** power plants, with a total of installed ***storage*** of about ***3,400 MW***. The total amount reaches nearly 60 GW, divided 35% PV and 65% wind. The ***expected LCOE*** for PV is 44.7 $/MWh, and for wind 49.6 $/MWh.

There is **no need for new thermal generation**, and the load increase from 2026 to 2030 can be covered with VRES plants only.

With these additional VRES power plants the system reaches a ***good adequacy*** with a value of EENS around 0.7×10^{-5} of the total demand.

The investment in PV, wind and relevant storage provides benefits for the system around 3,200 M$/year (thanks to savings in the generation costs and reduction of EENS).

The amount of additional power turns out to be quite balanced between the VRES technologies because in general wind power plants have higher production but PV is cheaper in terms of annuity per installed MW, so more power plants can be installed with a lower amount of money.

In this new scenario:

- The total ***EENS*** reaches 6.6 GWh, equal to around 0.7×10^{-5} of the total load.
- Overall ***generation costs*** decrease to 7,370 M$ thanks to the VRES production which replaces thermal expensive generation. The part of costs due to the presence of network congestions remains around 50 M$.
- Expected ***generation by PV*** plants is almost 40 TWh, with curtailments increasing up to 1.5 TWh (about 3.8% of total PV production).
- Expected ***generation by wind*** power plants higher than 145 TWh (more than 3600 EOH) and a curtailment of about 5,900 GWh (about 3.9% of the total wind generation).
- The ***energy exchanges between areas*** increase, with the SE/CO area receiving about 130 TWh from the neighboring ones. The sections reach the NTC limits less than 200 hours.

At the end of the calculation of the optimal economic amount of additional VRES plants with respect to the Reference scenario, the resulting values are the ones listed in Table 36.

Table 36 - Additional and total VRES installed power in the Scenario with optimal economic amount [MW]

AREA	PV installed power		Wind installed power	
	Added to reference scenario	Total	Added to reference scenario	Total
N	1,360	1,460	430	670
NE	6,720	8,470	5,220	28,990
S	0	0	4,480	8,910
SE/CO	2,790	10,590	0	30
TOTAL	**10,870**	**20,520**	**10,130**	**38,600**

There is no need to introduce additional thermal generation to ensure the system adequacy which can be obtained thanks to the new energy produced by the VRES plants and a different utilization of the

hydro resource, which can be more concentrated in the periods when VRES plants show a lower production.
PV installed power becomes more than double the one in the Reference scenario, reaching more than 20 GW, mainly concentrated in NE (where the best resource is available) and in SE/CO, where already in the Reference scenario about 7 GW are present.
Wind installed power increased by more than 10 GW, mostly distributed in the NE and S.
NE is the area with highest increase of installed power, because the best available resource, even if the curtailments due to the increasing overproduction conditions become significant and represent a limiting factor for further growth.
The total amount of PV and wind installation reaches nearly 60 GW. With this amount of additional VRES power the EENS reduces considerably down to about 6.6 GWh, corresponding to 0.7x 10^{-5} p.u. of the load.

Table 37 - Expected Energy Not Supplied - Brazilian optimal scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
N	119	5	578	702
NE	655	488	890	2,033
SE/CO	2,716	0	1,146	3,862
S	0	44	0	44
EENS TOTAL	**3,490**	**537**	**2,614**	**6,641**

The generation costs are strongly reduced by the presence of new VRES plants. As usual in power systems with increasing penetration of VRES, the need for redispatching increases but the relevant costs remain a small part of the total. The amount of curtailed production due to minimum production constraint increases up to nearly 10 TWh, about 1% of the total production. This amount might be reduced in the real operation of the system thanks to a more detailed short term planning of the thermal fleet and a coordination in the operation of the VRES and the hydroelectric plants.

Table 38 - Total production and fuel costs - Brazilian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
N	134,643	904	3,332	-74	34	1
NE	223,206	1,498	6,557	-312	111	1
SE/CO	441,755	3,791	1	-28	575	35
S	226,218	1,129	13	-376	71	12
TOTAL	**1,025,822**	**7,322**	**9,903**	**-790**	**791**	**49**

Table 39 shows the new production of the PV power plants, with the total amount that becomes more than double than the Reference scenario, up to almost 40 TWh. The curtailments due to overproduction conditions account for 1.5 TWh that means about 7% of the new plants. Table 40 highlights the differences with respect to the Reference scenario, where it is possible to see the impact of the curtailments due to overgeneration on the additional production.

Table 39 - Total production of PV plants - Brazilian optimal scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
N	2,655	444	0	0	1,519
NE	16,975	1,029	-71	0	1,874
SE/CO	19,851	1	0	0	1,875
S	0	0	0	0	-
TOTAL PHOTOV. GENER.	**39,481**	**1,474**	**-71**	**0**	**1,849**

Table 40 - Difference of total production of PV plants between Brazilian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
N	2,463	433	0	0	-380
NE	13,302	980	-71	0	-196
SE/CO	5,727	1	0	0	63
S	0	0	0	0	-
TOTAL PHOTOV. GENER.	**21,492**	**1,414**	**-71**	**0**	**-10**

As far as wind power plants are concerned, Table 41 and Table 42 report the main figures. They produce more than 145 TWh, with an increase of 34.5 TWh with respect to the Reference scenario. The curtailments also reach 5.8 TWh, four times the amount estimated in the Reference scenario, corresponding to a bit more than 10% of the new plants.

Table 41 - Total production of Wind plants - Brazilian optimal scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
N	2,323	264	0	0	3,069
NE	111,610	5,528	-76	0	3,657
SE/CO	102	0	0	0	3,636
S	32,290	13	0	0	3,623
TOTAL WIND GENER.	**146,325**	**5,805**	**-76**	**0**	**3,638**

Table 42 - Difference of total production of Wind plants between Brazilian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
N	1,439	221	0	0	-431
NE	16,813	4,262	-76	0	-277
SE/CO	0	0	0	0	0
S	16,228	13	0	0	-3
TOTAL WIND GENER.	**34,480**	**4,496**	**-76**	**0**	**-244**

Finally, Table 43 reports the energy exchanges between the areas. The import of the SE/CO area is equal to more than 130 TWh as most of the VRES plants are installed in NE and Sul areas and the load is concentrated in the SE/CO. However, notwithstanding the high amount of energy exchanged between the areas, the sections are not saturated, and reach their limit less than 200 hours in a year.

Table 43 - Interconnections - Brazilian optimal scenario

AREA A	AREA B	NTC [MW]		ENERGY EXCHANGES [GWh/year]				SECTION LIMIT REACHED [h/year]	
				BEFORE RE-DISPATCHING		AFTER RE-DISPATCHING			
		A -> B	A <- B	A -> B	A <- B	A -> B	A <- B	A -> B	A <- B
N	NE	8,246	8,246	4,902	18,205	5,111	19,016	0	164
NE	SE/CO	7,900	6,000	42,044	572	41,225	556	164	0
N	SE/CO	17,510	11,900	49,025	249	49,601	263	0	0
N-NE	SE/CO	20,850	19,800	90,216	516	89,976	518	126	0
SE/CO	S	11,300	9,800	311	39,766	311	39,461	0	100

Table 44 shows the main figures in terms of costs and benefits for the system which summarize the difference between the Reference scenario and the one with the optimal amount of VRES. It is possible to see that the advantages for the system are significant, mainly thanks to the replacement of expensive thermal generation.

Table 44 - Total benefit – Brazilian optimal scenario with respect to Reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	21,000	-2,660
NEW STORAGE	3,400	-190
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-54,707	5,567
RES CURTAILMENT	6,123	-
TOTAL EENS	-240	480
TOTAL BENEFIT	-	**3,197**

BENEFIT/MW VRES [kUSD/year]	**152**

The following Figure 13 provides a visual summary of the operation of the Brazilian system in the optimal scenario, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions. With respect to the Reference scenario (Figure 12) the wind production increases from 11% to 15% mainly replacing energy generated by Natural Gas plants, which decrease from 14% to 10%. PV, due to lower installed power and lower equivalent hours, has a more marginal part in the energy mix of the country. Energy exchanges between the areas increase, and this cause also an increase of the network losses, so part of the benefit due to the new VRES generation (more than 6 TWh) is lost.

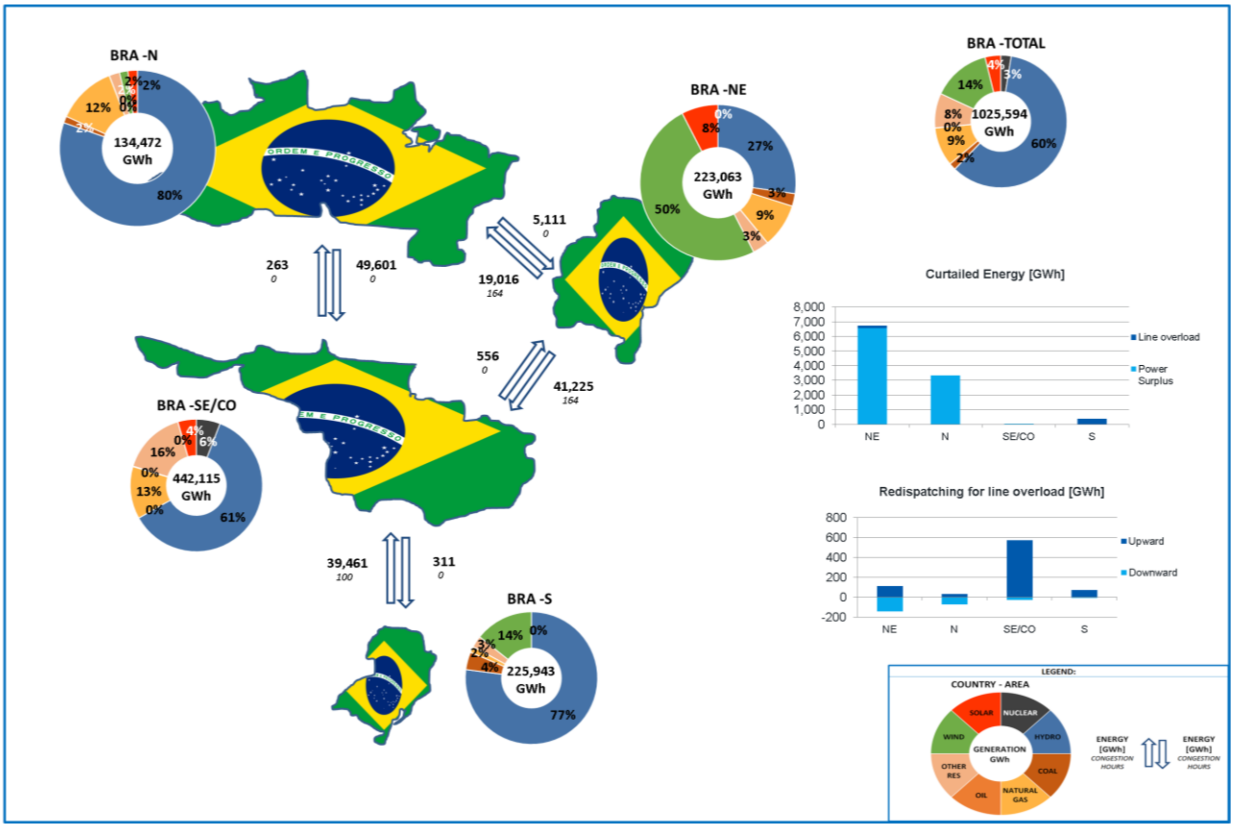


Figure 13 - Total production and energy exchanges – Brazilian optimal scenario

3.3.2.3 Optimal scenario without the storage

Due to the special configuration of the Brazilian system with a massive presence of hydropower plants often with considerable modulation and reserve capacity, a simulation has been carried out without considering the investment in storage systems along with the new VRES power plants.

The main results are reported in Table 45: in absence of additional storage plants, EENS and generation costs increase only slightly because a different utilization of the hydro resource can avoid lack of power without requiring very expensive thermal generation. This means that the storage resources already present in the system in the hydropower plants can be useful for the development of the VRES in the system.

In fact electric storage was inserted in the system to facilitate the dispatchability of the new VRES power plants, avoiding that high reserve needs should be compensated by other technologies. However, in

systems where reserve is significantly provided also by hydropower plants with a limited cost, the storage associated to the VRES plants might be partially reduced relying on storage and modulation resources already existing in the system. In this case, the hydropower plants must be operated in a more flexible way and well-harmonized with VRES plants, in order to cope with wide variations of VRES generation and avoid degradation of the system adequacy. A deeper coordination of the system resource and agreements between different power plants owners must be also required to keep high performances of the whole system. This coordinated operation of different technologies should be managed by system operator who is in charge to ensure the reliable dispatching of the resources coping with possible load and generation variations. It might have impact on commercial agreements, in case system needs require modification of power production contracted by generation plants, and must be also addressed in a proper regulatory framework. Clear rules, rights and duties of the different involved parties have to be defined, taking into account costs and advantages in which they incur in case an improved coordination and different reserve management are required as services for the system.
The investment in localized storage systems placed close to the VRES power plants is anyway useful to facilitate the insertion of new plants also in remote locations of the power system, because the operation can be optimized locally.

Table 45 - Total benefit – Impact of Storage in the Brazilian optimal scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	0	0
NEW STORAGE AVOIDED	3,400	190
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	406	-46
RES CURTAILMENT	338	-
TOTAL EENS	1	-2
TOTAL BENEFIT	**-**	**142**

3.3.2.4 Sensitivity with increased installed power in selected hydropower plants

A sensitivity case of the optimal scenario has been performed considering an increase of the installed power in some selected hydropower plants, as indicated in the SRG/ANEEL Technical Note No. 026/2011. This note provides an analysis to estimate the amount of energy and peak generation possible in selected power plants provided that water is available. Table 46 reports the hydroelectric power with the expansion capacity expressed in MW.

Table 46 - Hydroelectric power plants with expansion capacity

Hydropower plants	Expansion capacity [MW]
São Simão	1075
Três Marias	123
Jaguara	213
Porto Primavera	440
Luiz Gonzaga	1000
Gov. Bento Munhoz	838
Taquaruçu	105
Rosana	89
Curuá – Uma	10
Cachoeira Dourada	105
Salto Santiago	710

In the simulation carried out with GRARE tool, the amount of water available during the year in these hydropower plants has been kept equal to the previous cases (i.e. the maximum amount of energy which can be produced remains the same), but thanks to the different installed power, the production can be concentrated more in periods when higher generation is needed, and wasted water (if any) can be reduced. In other words, the increase of the installed power allows a more flexible operation of the plants, and higher focus on peak demand periods.

The main results of this simulation are summarized in Table 47: as expected, with the considered increased hydroelectric capacity there is reduction of the thermal generation costs and a slightly reduction of the EENS. In this case the overall system present a total economic benefit equal to 15 M$/year.

Table 47 - Total benefit – Sensitivity scenario with increased installed power in selected hydropower plants

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	0	0
NEW STORAGE	0	0
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-123	14
RES CURTAILMENT	22	-
TOTAL EENS	-0.5	1
TOTAL BENEFIT	**-**	**15**

The Brazilian system obtains a benefit from the presence of higher installed power in some hydroelectric plants in terms of reduced thermal costs thanks to the possibility to shave peaks and avoid the usage of expensive generation. In the real time operation, benefits might become even higher thanks to the contribution that additional installed hydroelectric power can give to frequency regulation, reserve provision and other ancillary services that otherwise should be bought from other generators and might require additional expenses to keep dispatchable generation available.

No significant variation in the curtailment of VRES and hydropower generation is observed, meaning that no impact on the optimal amount of VRES power plants can be expected, as the main economics (generation costs, EENS, production curtailments) remain very similar.

3.3.2.5 Final considerations on Brazilian isolated system

The optimal solution for additional VRES installations defined in 3.3.2.2, able to ensure a proper adequacy of the Brazilian power system, includes 20,520 MW of PV, 38,600 MW of wind power plants and storage of about 3,400 MW. With these additional VRES power plants the system reaches a ***good adequacy*** with a value of EENS around 0.7x 10^{-5} of the total demand.

It's worth highlighting that no need for new thermal generation emerges for the coverage of the load increase from 2026 to 2030, and that the generation planned by EPE at 2026 plus the additional wind and PV plants individuated in this study is enough to ensure a good adequacy of the system. Also the transmission system defined in the PDE2026 [2] shows adequate exchange capacities between the areas and the states. Local network reinforcements might be needed to connect the huge amount of new plants resulting from the performed analysis, and the definition of the specific projects must be evaluated with detailed studies focused on the real requests for connections, identifying for each case the best solution.

The simulations showed an already high level of flexibility for the system thanks to the massive presence of hydroelectric power plants with regulation capacity. This characteristic allows a high penetration of the VRES plants (wind and PV reach in the optimal scenario 25% of the installed capacity and supply more than 20% of the load). The high share of hydroelectric generation is on the other hand also the limiting factor for further VRES penetration, as the introduction of additional generation would cause an increase in the risk of curtailments due to the overproduction situations, making the construction of new plants not convenient from the economic point of view.

In presence of high VRES penetration, the operation of the system might require an increase of the coordination between dispatchable hydroelectric power plant and the variable ones in the short term planning and in the real time operation, in order to ensure that proper reserve is available in the system to face possible variation in the production which become significant in absolute values. This improved coordination, needed as a new system service to be provided by generation plants, must be clearly identified and addressed through a proper regulatory framework, which should take into account technical constraints and also advantages and disadvantages which the system and the generation companies might incur when required to be operated in a different manner.

3.3.3 Uruguay

In this Chapter the main results related to the isolated Uruguayan power system are presented. First of all the results of Reference scenario are illustrated. Then a simulation with increased amount of PV production is reported, concluding that when considered isolated, the Uruguayan system with the generation fleet planned at 2023 is already adequate and it is not convenient to install additional plants.

3.3.3.1 Reference scenario

The simulation of the ***Reference scenario*** of the Uruguayan system shows:

- ***Good adequacy***, with EENS due to lack of power or line overload around 0.4 GWh, equal to around 2.7×10^{-5} of the total load.
- Expected ***generation by PV*** power plants around 344 GWh (1,500 EOH) with a negligible curtailment.
- Expected ***generation by wind*** power plants close to 4,300 GWh (about 2,770 EOH) and a limited curtailment of 25 GWh, due to overgeneration conditions.

The operation of the Uruguayan system in the Reference scenario, isolated from the neighboring countries, has been simulated. The energy production by Salto Grande hydroelectric plant has been included in the system for an amount slightly lower than half of the expected energy produced, according historical values, in order to take into account the expected energy balance in the real interconnected system.

The main results are presented in this paragraph.

From Table 48, it can be seen that the Uruguayan power system has a good generation adequacy even when considered isolated. This is due to the considerable presence of hydropower plants, the strong penetration of the wind and the operation of the new CCGT in Punta del Tigre, currently under construction. EENS is mainly due to line overload and lack of power, both generating about 0.2 GWh/year of EENS.

Table 48 - Expected Energy Not Supplied – Uruguayan Reference scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
TOTAL UTE	15	204	199	418

Costs for generation are evaluated about 140 M$/year.

The following tables show the results of the Reference scenario for the Wind and PV production.

As regard PV generation (Table 49), the total production is around 340 GWh/year, no significant need of PV production curtailments is required. The equivalent operating hour is 1,500 h/year.

Table 49 - Total production of PV plants – Uruguayan Reference scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
TOTAL UTE	344	0.5	-0.03	0	1497

As regard wind generation (Table 50), the total production is a bit higher than 4,300 GWh/year with an equivalent operating hour approximately of 2,770 h/year. Some wind energy curtailments due to overgeneration are already present in this condition, even if in a limited amount, and estimated around 25 GWh/year. This value can be reduced during operation with a more flexible management of hydropower plants and in the real conditions also thanks to the strong interconnection capacity with other countries.

Table 50 - Total production of Wind plants – Uruguayan Reference scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
TOTAL UTE	4,336	25	-0.4	0	2771

In Uruguay, there are sites with wind resource availability which can reach capacity factors up to 40% and higher, but during the operation in the last years they had to be curtailed due to overgeneration conditions. The introduction of the Punta del Tigre CCGT can further stress this critical conditions as this new power plant introduces in the system additional minimum power generation constraints, and will compete against other generation facilities.
LCOE of PV and wind plants is expected to be about 58.5 $/MWh and 60.3 $/MWh respectively, in case curtailments similar to the ones happened in the past have to be maintained also in the future. In case EOH for wind generation can increase up to 3500 h (corresponding to a 40% capacity factor) thanks to reduction of curtailments, the corresponding LCOE would decrease to values around 48 $/MWh.

3.3.3.2 Scenario with optimal economic amount of additional VRES

The results of computational process depicted in Figure 9 shows that the optimal amount of VRES installations is already reached in the reference scenario, where the installed capacity is about 230 MW of PV and 1550 MW for wind.
To show the non–convenience to install additional VRES plants, in this paragraph the results obtained considering an additional 100 MW of wind power plant are reported.

- The ***EENS*** remains equal to the previous case.
- Expected ***generation by PV*** remains the same, while ***generation by wind*** increases due to the additional plants. Curtailments also increase due to a bigger number of overgeneration conditions.
- The ***generation costs*** decrease by 10 M$ thanks to the VRES production which replaces thermal generation but the investment needed to install 100 MW new wind power plus the related storage system is nearly the double, so it means that there is no advantage for such installation.

The following Figure 14 provides a visual summary of the operation of the Uruguayan system in the identified scenario, highlighting the generation mix, the curtailed production and the amount of thermal energy to be redispatched to solve network congestions.

It is possible to see that a part of the energy coming from the Salto Grande hydroelectric plant is curtailed due to overproduction (in periods with low load or also high wind and PV production). In the real operation of the Uruguayan system, this energy can be saved with a more detailed production planning also based on short term forecasts, but above all thanks to the interconnections with neighboring countries, not considered in this isolated analysis, which allow the export of the energy surplus. In particular, the Salto Grande production can be better modulated with proper agreements with Argentina, exploiting the interconnection capacity made available by two 500 kV lines. This case will be better analyzed in Chapter 3.3.4, focused on the operation of the interconnected systems.
However, when the interconnection capacity with neigbouring countries in not exploited in a significant way, the Uruguayan system shows an already sufficient generation fleet with economic resources such as hydro and VRES, which makes no profitable the introduction of additional VRES plants.

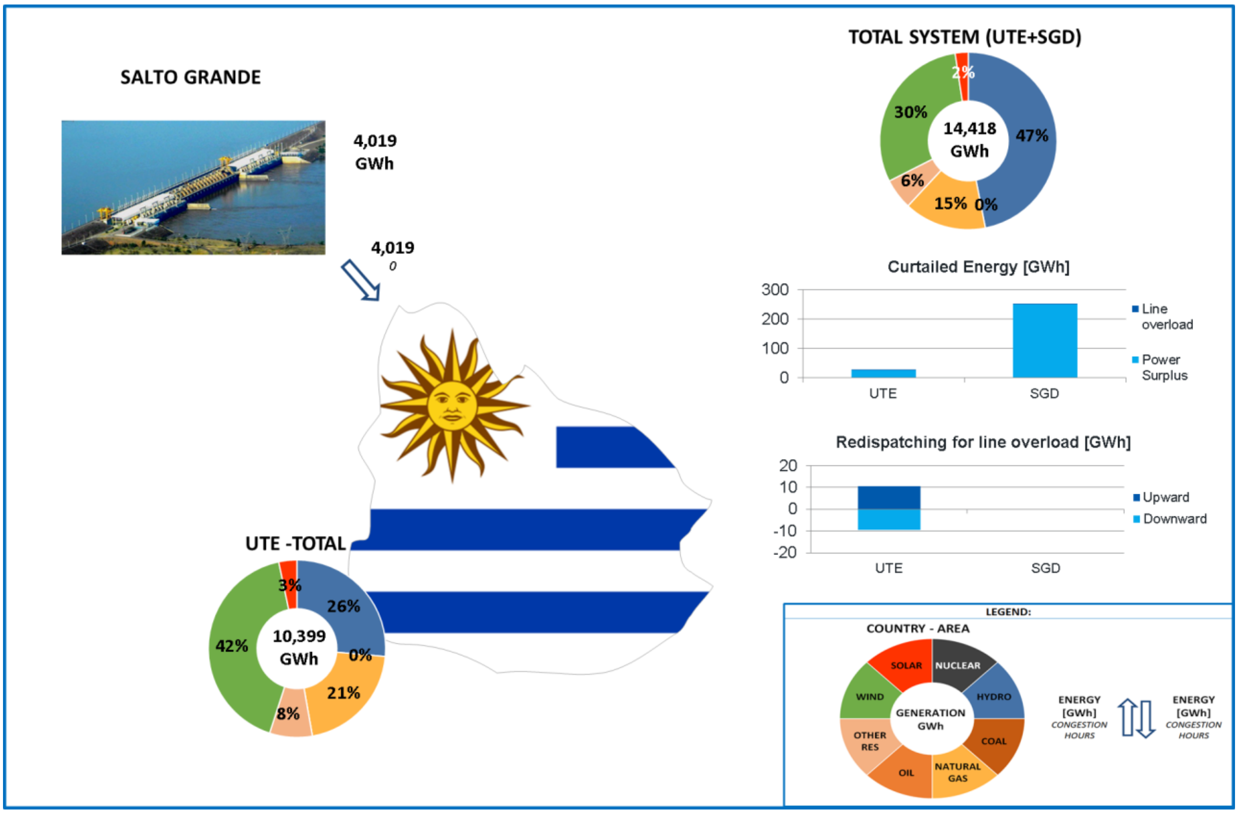


Figure 14 - Total production and energy exchanges – Uruguayan scenario

3.3.3.3 Final considerations on Uruguayan isolated system

Uruguayan generation fleet has been improving for the last years with the introduction of a considerable amount of wind power and the construction of the new CCGT plant in Punta del Tigre. Also some important improvements of the Uruguayan transmission system are foreseen in the next years and simulations show that the risk of lack of power and overloads is mitigated.
Simulations show that the current amount of wind power plants is already the optimal economic one when considering the system as isolated, so with high risk of production curtailment in case of overproduction (as already happened in significant way in the past years) due to impossibility to evacuate the power in excess towards neighboring countries.

Due to the high interconnection capacity compared to the dimension of the Uruguayan power system, different conclusions might appear when the system is considered connected to others, as the VRES production might be exploited with lower curtailments.

3.3.4 Interconnected countries

Following the analysis of the Argentinian, Brazilian and Uruguayan systems considered as isolated, in which the optimal economic amount of VRES power plants that each country individually can accept without jeopardizing the security of the power system has been evaluated, in this paragraph the results of the analysis of the interconnected systems are presented.

The evaluation of the operation of the systems together and the assessment of the benefits that an additional amount of VRES plants can bring to the whole system is carried out starting from the configurations obtained at the end of the analysis of the isolated systems, i.e. including the VRES plants resulting at the end of the previous optimizations.

When two systems are interconnected, a new simulation is required imposing an energy exchange equal to zero (i.e. simulating again the systems as they were isolated): this new simulation becomes the reference against which all the following ones will be compared. It is necessary because of the simulation method, which, based on Montecarlo approach, analyses thousands of different configuration of the system extracted randomly according their likelihood to happen. When the configuration of the system changes (from two single countries to one single scenario), new sets of system configurations are extracted, and small differences can appear with respect to the ones utilized during the analysis of the isolated cases. For this reason, a new reference scenario is necessary, which contains both the systems and that can become the starting point for the comparison when the interconnections are introduced, ensuring that the results obtained for the scenarios with the interconnections are based exactly on the same sets of configurations used as reference. Because of the change of the system conditions considered during the probabilistic analysis, this new simulation can show some minor variations with respect to the results presented for the single isolated countries.

When this new reference scenario with the interconnected countries is available, further simulations can be carried out considering the possibility to exchange energy between the different systems. The simulations identify the expected behavior of the interconnected system minimizing the production costs, i. e. sharing the generation when convenient. From the comparison between this scenario and the sum of the isolated cases, it is possible to assess the maximum advantages which the whole system can experience from the interconnections.

In the real operation, the energy exchanges between the countries are subject to bilateral agreements between the governments and require also proper regulatory framework. The more a flexible coordination of the whole system is allowed exploiting the interconnection to the maximum level, the closer the benefits will be to the ideal case.

Due to the complexity of the system which includes portion of the network with different frequency (Argentina and Uruguay are operated at 50 Hz, while Brazil is at 60 Hz, so in real operation they are coupled through AC-DC-AC converters which introduce different control parameters which influence the power flows on the network), the interconnection of the countries has been carried out in two steps, starting from the 50 Hz countries and adding Brazil afterwards.

3.3.4.1 Reference scenario for Argentina and Uruguay interconnected systems (50 Hz countries)

A new Reference scenario has been analyzed including both the Argentinian and the Uruguayan systems, without considering any interconnection between the countries[8]. As regard PV and wind installed power, the values established in the previous simulations, corresponding to the optimal amount of VRES installations, have been considered. The installed capacity in the different areas is reported in the following table.

Table 51 - Total VRES installed capacity in Reference scenario for ARG and UY interconnected [MW]

AREA	PV installed power	Wind installed power
NEC	1,100	8,400
NWE	9,000	300
PAT	0	5,200
UTE	230	1,550

The simulation of this scenario, which becomes the reference for the evaluation of the benefits introduced by the interconnection, shows results in line with the sum of the results obtained for the two isolated countries independently:

- ***EENS*** is around 1.3 GWh; it is about $0.8x10^{-5}$ of the total load.
- ***Overall generation costs*** are close to 6,970 M$; of which 60 M$ due to presence of network congestions.
- Expected ***generation by PV*** power plants around 23,500 GWh (2,270 EOH) with a curtailment of 559 GWh, corresponding to 2.3% of the total PV production
- Expected ***generation by wind*** power plants close to 61,300 GWh (about 3,970 EOH) with a curtailment of nearly 1,300 GWh, corresponding to 2% of the total wind production

These values become the reference for the quantitative evaluation of the benefits generated by the interconnection between the countries.

The detailed results of the simulations of Argentinian and Uruguayan systems together but not interconnected are reported below. The system configuration and the generation fleet are the ones resulting from the evaluation of the optimal amount of additional VRES carried out on the isolated countries (3.3.1.2 and 3.3.3.2).
Results are aligned with the ones obtained with the simulations of single countries, but some small differences can appear due to different probabilistic simulations applied to both countries together and due to the fact that the hydroelectric power plants of Salto Grande is now connected to both countries simultaneously. The new Reference scenario for the evaluation of the benefits resulting from the interconnection is then briefly presented.

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[8] Even if no interconnections are considered between Argentina and Uruguay, the countries are not completely independent as the Salto Grande hydroelectric power plant is shared between them. This fact introduces some differences with respect to the isolated cases because the optimization of the production is performed taking into account the demand in both countries and not only in one of them.

The following table shows the EENS, expressed as MWh/year, split by area and reason. The greatest part of EENS is concentrated in Argentina, in NWE area, and it is mainly due to lack of interconnection. This lack of interconnection mostly correspond to the lack of power found in the simulations of the single country, which are now counted as interconnection problems because some power would be available in the other country if there were an interconnection available. Line overloads not solved after redispatching cause 170 MWh/year of EENS.

Table 52 - Expected Energy Not Supplied – ARG and UY interconnected Reference scenario (NTC=0)

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NEC	84	33	22	139
NWE	78	8	854	940
PAT	0	1	0	1
UTE	0	128	87	215
TOTAL	162	170	963	1,295

Table 53 shows the total energy produced in each area and the related costs. These costs are only due to thermal power plants. In reference scenario overall generation costs including redispatching are around 6,828 M$/year in the entire system (Argentina and Uruguay).

Table 53 - Total production and fuel costs - ARG and UY interconnected Reference scenario (NTC=0)

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NEC	152,807	5,102	0	-1,173	2,048	67
NWE	51,457	1,583	500	-552	208	-10
PAT	31,369	91	772	-484	27	-5
SALTO GRANDE	8,412	0	142	-349	0	0
UTE	10,351	132	56	-593	870	8
TOTAL	254,396	6,908	1,470	-3,151	3,153	60

The following table shows PV generation before redispatching and PV curtailments after redispatching for each area of the system. Total production is around 23,500 GWh/year. The energy curtailed after the redispatching phase is negligible, only 64 GWh/year that is less than 0.3% of total production, concentrated in NWE as expected.

Table 54 - Total production of PV plants - ARG and UY interconnected Reference scenario (NTC=0)

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NEC	2,089	0	-4	0	1,895
NWE	21,611	493	-57	0	2,337
PAT	0	0	0	0	-
UTE	343	2	-3	0	1,475
TOTAL PHOTOV. GENER.	**24,043**	**495**	**-64**	**0**	**2,271**

As regard wind generation, total production is around 61,300 GWh/year, as illustrated in Table 55. The production is mainly concentrated in Argentina. The energy curtailed after redispatching phase is 461 GWh/year, that is less than 0.8% of total production.

Table 55 - Total production of Wind plants - ARG and UY interconnected reference scenario (NTC=0)

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NEC	34,567	0	-115	0	4,097
NWE	767	7	-3	0	2,523
PAT	22,997	772	-268	0	4,237
UTE	4,307	54	-75	0	2,686
TOTAL WIND GENER.	**62,638**	**833**	**-461**	**0**	**3,971**

As shown in Table 56, there are no exchanges between Argentina and Uruguay as expected. It can be observed a stronger reduction of the Salto Grande production towards Uruguay with respect to the value obtained in the isolated case (the final energy exchange is 3,857 GWh against 4,019 GWh), because of a different production profile resulting when considering the whole system.

Table 56 - Interconnections - ARG and UY interconnected reference scenario (NTC=0)

AREA A	AREA B	NTC [MW]		ENERGY EXCHANGES [GWh/year]				SECTION LIMIT REACHED [h/year]	
				BEFORE RE-DISPATCHING		AFTER RE-DISPATCHING			
		A -> B	A <- B	A -> B	A <- B	A -> B	A <- B	A -> B	A <- B
PAT	NEC	4,250	4,250	21,387	8	20,926	14	710	0
NEC	NWE	4,300	4,300	11,669	7,029	11,765	6780	5	243
Salto Grande	NEC	1,000	10	4,206	0	4,206	0	1,321	2,257
Salto Grande	UTE	1,000	10	4,206	0	3,857	0	755	312
NEC	UTE	0	0	-	-	-	-	-	-

Once the new reference scenario with the two isolated countries is ready, a simulation to assess the effects of the interconnection and the possibility to exchange energy between the countries is run: the operation of the two systems together, with exactly the same generation fleet, is evaluated to quantify the amount of energy flowing through the interconnections and the possible fuel costs savings.
Finally, the simulation with the additional VRES power plants, which becomes acceptable by the systems thanks to the interconnection, is performed, and the benefits provided by the new plants are also assessed.

3.3.4.2 Argentina and Uruguay interconnected

Simulations with different values of NTC between Argentina and Uruguay have been carried out to define the impact of this constraint on the optimal economic operation of the interconnected system. Due to the fact that the interconnection is composed mainly by two 500 kV lines, the maximum value applied to the section is 2000 MW. The cases with 1000 MW and 500 MW NTCs are also analyzed and briefly presented.

NTC = 2000 MW

This scenario represents the *Argentinian and Uruguayan power systems interconnected* with the possibility to *exchange up to 2,000 MW*, limit which corresponds nearly to the sum of the capabilities of the lines belonging to the cutset.
The presence of the interconnection provides the following main variations with respect to the Reference scenario:

- A complete *reduction of the EENS* from more than 1.3 GWh to 0.08 GWh (-94%). The final EENS corresponds to about 2.8×10^{-6} of the total load.
- *Overall generation costs* are reduced by 172 M$. Salto Grande also needs a lower curtailment because the produced energy can be exchanged between the countries.
- Expected *generation by PV* increases respect to the Reference scenario; PV curtailment of 323 GWh with a reduction of 230 GWh (-42%) with respect to the Reference scenario.
- Expected *generation by wind* increases respect to the Reference scenario; Wind curtailment of 968 GWh with a reduction of 316 GWh (-24%) with respect to the Reference scenario.
- *Energy exchanges between the countries* equal to 2.32 TWh from Argentina to Uruguay and 2.26 TWh from Uruguay to Argentina, therefore the section between Argentina and Uruguay is balanced (the loading of this interconnection is 13% in both directions).

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 174 M$.

NTC = 1000 MW

The Argentina and Uruguay interconnected scenario has been studied *reducing the NTC limit to 1000 MW.*
The main results of this scenario with respect to the reference scenario are:

- A *reduction of the EENS* from more than 1.3 GWh to 0.36 GWh (-72%). The final EENS corresponds to about 3.2×10^{-6} of the total load.
- *Overall generation costs* are reduced by 168 M$.

- Expected *generation by PV* increases respect to the Reference scenario; PV curtailment of 324 GWh with a reduction of 235 GWh with respect to the Reference scenario.
- Expected *generation by wind* increases respect to the Reference scenario; Wind curtailment of 988 GWh with a reduction of 306 GWh with respect to the Reference scenario.
- *Energy exchanges between the countries* equal to 2.26 TWh from Argentina to Uruguay and 2.16 TWh from Uruguay to Argentina, therefore the section between Argentina and Uruguay is balanced (the loading of this interconnection is 26% in both directions).

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 170 M$.

NTC = 500 MW

The last scenario considers *the Argentina and Uruguay power systems interconnected* with a *NTC limit equal to 500 MW.*

The following main variations with respect to the reference scenario are present:

- A *reduction of the EENS* from more than 1.3 GWh to 0.49 GWh (-62%). The final EENS corresponds to about 4.5×10^{-6} of the total load.
- *Overall generation costs* are reduced by 153 M$.
- Expected *generation by PV* increases respect to the Reference scenario; PV curtailment of 346 GWh with a reduction of 213 GWh (-38%) with respect to the Reference scenario.
- Expected *generation by wind* increases respect to the Reference scenario; Wind curtailment of 1,036 GWh with a reduction of 258 GWh (-20%) with respect to the Reference scenario.
- *Energy exchanges between the countries* equal to 1.59 TWh from Argentina to Uruguay and 1.56 TWh from Uruguay to Argentina, therefore the section between Argentina and Uruguay is balanced (the loading of this interconnection is 36% in both directions).

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 155 M$.

The following Table 57 compares the main results.

Table 57 - Main results for different NTC values between Argentina and Uruguay [MW]

	Reference scenario	NTC 2,000 MW	NTC 1,000 MW	NTC 500 MW
EENS [GWh]	1.9	0.08	0.36	0.49
Total generation costs [M€/year]	6,970	6,798	6,802	6,817
PV production [GWh]	23,500	23,735	23,735	23,710
Wind production [GWh]	61,300	61,616	61,606	61,560
Exchanges [TWh]				
ARG--> UY	-	2.3	2.3	1.6
ARG <-- UY	-	2.3	2.2	1.6

It is possible to note that the results in case the NTCs is set at 2,000 MW or 1,000 MW are very similar. The reason is that the interconnection capacity is very high compared to the peak load in Uruguay, and it is not fully used also because hydropower plants, VRES and thermal power plants with their technical minimum are already supplying most of the demand. Interconnections are needed only in case of unbalances due to high variation of VRES plants and errors in the load and production forecasts, and the required amount is not higher than 1000 MW. On the contrary, it is possible to see that setting the limit at 500 MW can introduce some constraints which impede the operation of the interconnected systems at the optimal conditions.

For this reason, the limit of 1,000 MW has been selected as basis for the following simulations. As explained, this value does not affect the economics of the system, ensuring that form technical point of view there are no issues also in case one of the interconnection lines trips. In fact, the 1000 MW power flow can be maintained also with only one line without exceeding its temporary capability.

It is important to underline that the definition of an NTC value does not depend only on technical issues, but often is more determined by political or strategic decisions, which must be supported by technical possibilities but which might differ significantly from the optimal solution.

The resulting conditions and energy exchanges are depicted in Figure 15

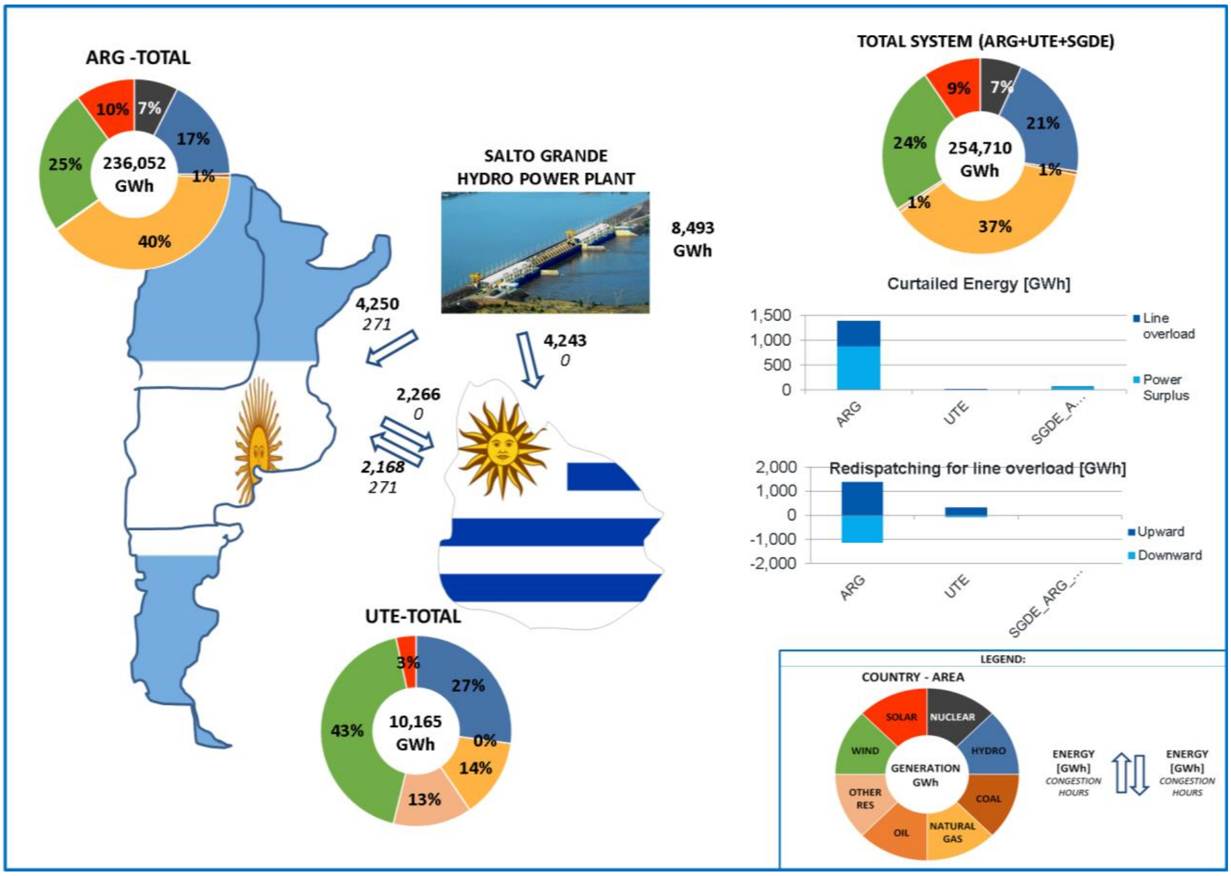

Figure 15 - Total production and energy exchanges – Argentina and Uruguay interconnected NTC=1,000 MW

3.3.4.3 Additional VRES in Argentinean and Uruguayan interconnected systems

In order to verify whether the interconnection of the Argentinian and Uruguayan power systems allows the ***introduction of further VRES power plants***, two additional cases have been analyzed: considering an NTC value equal to 1000 MW:

- additional 100 MW of wind power plant installed in Argentina.
- additional 100 MW of wind power plant installed in Uruguay.

The results show that the optimal amount of VRES installation is already reached in the isolated scenario and that the presence of the interconnection between Argentina and Uruguay does not modify significantly the optimal values found. The investment in new wind power plant is lower than the benefits generated for the interconnected power system.
The presence of the interconnection lines in fact on one hand reduces the overgeneration conditions, limiting the curtailed energy and thus allowing a higher number of equivalent hours for the new installed plants, fostering the relevant investments. But on the other hand, the interconnection reduces also the conditions with lack of power, energy not supplied or with the usage of expensive thermal generation: in this way, the interconnection contributes to flatten the price profiles thanks to the possibility to share economic generation between the countries, and for this reason the energy produced by VRES plants generates less benefits because replaces cheaper generation. The result of these two opposite effects is that the investment in new plants is not profitable.

Table 58 and Table 59 illustrate the benefits introduced for the whole system by the additional 100 MW wind power plant installed in Argentina and in Uruguay respectively. In both cases it is possible to note that the cost for the installation of new wind plants and relevant storage is higher than the savings in the thermal generation costs, meaning that the investments is not profitable from a system point of view and there is no advantage in the construction of new plants.

Table 58 - Total benefit – Additional 100 MW wind power plant in Argentina with respect to NTC=1,000 scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	100	-19
STORAGE	12	-1
ADDITIONAL DISPATCHABLE	0	0
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-272	14
RES CURTAILMENT	126	-
TOTAL EENS	0	0
TOTAL BENEFIT	-	-6

Table 59 - Total benefit – Additional 100 MW wind power plant in Uruguay with respect to NTC=1,000 scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	100	-16
STORAGE	12	-1
ADDITIONAL DISPATCHABLE	0	0
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-249	12
RES CURTAILMENT	17	-
TOTAL EENS	0	0
TOTAL BENEFIT	-	-5

Looking at the small negative benefit resulting from the installation of additional plants in the two countries, it might be that the optimal solution in the interconnected case is an amount of plants lower than the one defined for the isolated cases.

This condition has not been investigated in detail because in the long term system planning every country tends to define its own targets for the generation expansion and in particular for VRES power plants, without assuming as main input the future generation expansion of the neighboring countries, especially when huge investments are foreseen and might be subject to delays. Interconnections offer the possibility to improve reliability of the power system and reduce costs avoiding situation with lack of power or overgeneration, but it is not convenient to plan a massive energy import from other countries when the natural resources available on own territory are good enough to allow the installation of VRES plants and obtain cheap energy.

It is then reasonable that each country will try to exploit its own resource as much as possible and avoiding strong dependency, where possible, form energy provided by other countries.

3.3.4.4 Reference scenario for Argentina, Brazil and Uruguay interconnected systems

A new Reference scenario has been analyzed including the Argentinian, Brazilian and Uruguayan power systems together without considering any interconnection between the countries[9]. As regard PV and wind installed power, the values established in the previous simulations, corresponding to the optimal amount of VRES installations, have been considered. The installed capacity in the different areas is reported in the following table.

Table 60 - Total VRES installed capacity in Reference scenario for ARG, BRA and UY interconnected [MW]

COUNTRY	AREA	PV installed power [MW]	Wind installed power [MW]
ARGENTINA	NEC	1,100	8,400
	NWE	9,000	300
	PAT	0	5,200
URUGUAY	UTE	230	1,550
BRAZIL	N	1,460	670
	NE	8,470	28,990
	SE/CO	10,590	30
	S	0	8,910

The simulation of this scenario, which becomes the reference for the evaluation of the benefits introduced by the interconnection, shows results in line with the sum of the results obtained for the two isolated countries independently:

- ***EENS*** is around 5.5 GWh; it is about 0.5x10^{-5} of the total load.
- ***Overall generation costs*** are close to 14,210 M$; of which 82 M$ due to presence of network congestions.
- Expected ***generation by PV*** power plants around 63,500 GWh (2,000 EOH) with a curtailment higher than 1,900 GWh, corresponding to 2.9% of the total PV production.
- Expected ***generation by wind*** power plants close to 209,000 GWh (about 3,750 EOH) with a curtailment of nearly 6,900 GWh, corresponding to 3% of the total wind production.

These values become the reference for the quantitative evaluation of the benefits generated by the interconnection between the countries.

The detailed results of the simulations of the Argentinian, Brazilian and Uruguayan power systems together but not interconnected are reported below. The system configuration and the generation fleet are the ones resulting from the evaluation of the optimal amount of additional VRES carried out on the isolated countries (3.3.1.2, 3.3.2.2 and 3.3.3.2).

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[9] Even if no interconnections are considered, Argentina and Uruguay are not completely independent as the Salto Grande hydroelectric power plant is shared between them. This fact introduces some differences with respect to the isolated cases because the optimization of the production is performed taking into account the demand in both countries and not only in one of them.

Results are aligned with the ones obtained with the simulations of single countries, but some small differences can appear due to different probabilistic simulations applied to the countries together and due to the fact that the hydroelectric power plants of Salto Grande is now connected to Argentina and Uruguay simultaneously. The new Reference scenario for the evaluation of the benefits resulting from the interconnection is then briefly presented.

The following table shows the EENS, expressed as MWh/year, split by area and reason. The greatest part of EENS is concentrated in Brazil, in SE/CO area, and it is mainly due to lack of interconnection. This lack of interconnection mostly correspond to the lack of power found in the simulations of the single country, which are now counted as interconnection problems because some power would be available in the other country if there were an interconnection available. Line overloads that are not solved after redispatching produce about 300 MWh/year of EENS.

Table 61 - Expected Energy Not Supplied – ARG, BRA and UY interconnected Reference scenario (NTC=0)

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	0	0	605	605
NEC	0	72	1	73
PAT	0	0	0	0
N	0	4	521	525
NE	0	155	628	783
SE/CO	0	5	3,268	3,273
S	0	61	0	61
UTE	0	0	190	190
TOTAL	**0**	**297**	**5,213**	**5,510**

Table 62 shows the total energy produced in each area and the related costs. These costs are only due to thermal power plants. In Reference scenario overall generation costs including redispatching are around 14,210 M$/year in the whole system (Argentina, Brazil and Uruguay).

Table 62 - Total production and fuel costs – ARG, BRA and UY interconnected Reference scenario (NTC=0)

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NWE	50,971	1,521	356	-248	67	-5
NEC	153,801	5,116	0	-451	891	40
PAT	31,492	90	670	-470	1	-5
N	134,760	907	3,280	-6	93	5
NE	223,107	1,486	6,482	-412	117	-6
SE/CO	441,843	3,796	0	-2	512	38
S	226,123	1,122	8	-372	73	14
UTE	9,789	90	31	-17	224	1
SALTO GRANDE	8,451	0	95	0	0	0
TOTAL	**1,280,337**	**14,128**	**10,922**	**-1,978**	**1,978**	**82**

The following table shows PV generation before redispatching and PV curtailments after redispatching for each area of the system. Total production is around 65,500 GWh/year. The energy curtailed after the redispatching phase is negligible, only 82 GWh/year that is about 0.1% of total production.

Table 63 - Total production of PV plants – ARG, BRA and UY interconnected Reference scenario (NTC=0)

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	21,634	351	-25	0	2,360
NEC	2,083	0	-3	0	1,892
PAT	0	0	0	0	-
N	2,665	450	0	0	1,522
NE	17,011	1,039	-54	0	1,879
SE/CO	19,820	0	0	0	1,872
S	0	0	0	0	-
UTE	344	1	0	0	1,497
TOTAL PHOTOV. GENER.	**63,557**	**1,841**	**-82**	**0**	1,998

As regard wind generation, total production is around 216,000 GWh/year, as illustrated in Table 64. The energy curtailed after redispatching phase is 479 GWh/year that is less than 0.2% of total production.

Table 64 - Total production of Wind plants – ARG, BRA and UY interconnected Reference scenario (NTC=0)

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	771	5	-1	0	2,533
NEC	34,572	0	-125	0	4,097
PAT	23,085	670	-289	0	4,285
N	2,325	262	0	0	3,075
NE	111,666	5,443	-63	0	3,662
SE/CO	102	0	0	0	3,636
S	32,302	8	0	0	3,625
UTE	4,329	30	-1	0	2,763
TOTAL WIND GENER.	**209,152**	**6,418**	**-479**	**0**	3,744

The following Figure 16 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system together without power exchanges (as the simulation has been carried out without the possibility for the countries to exchange energy), highlighting the generation mix per countries, the energy exchanges, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

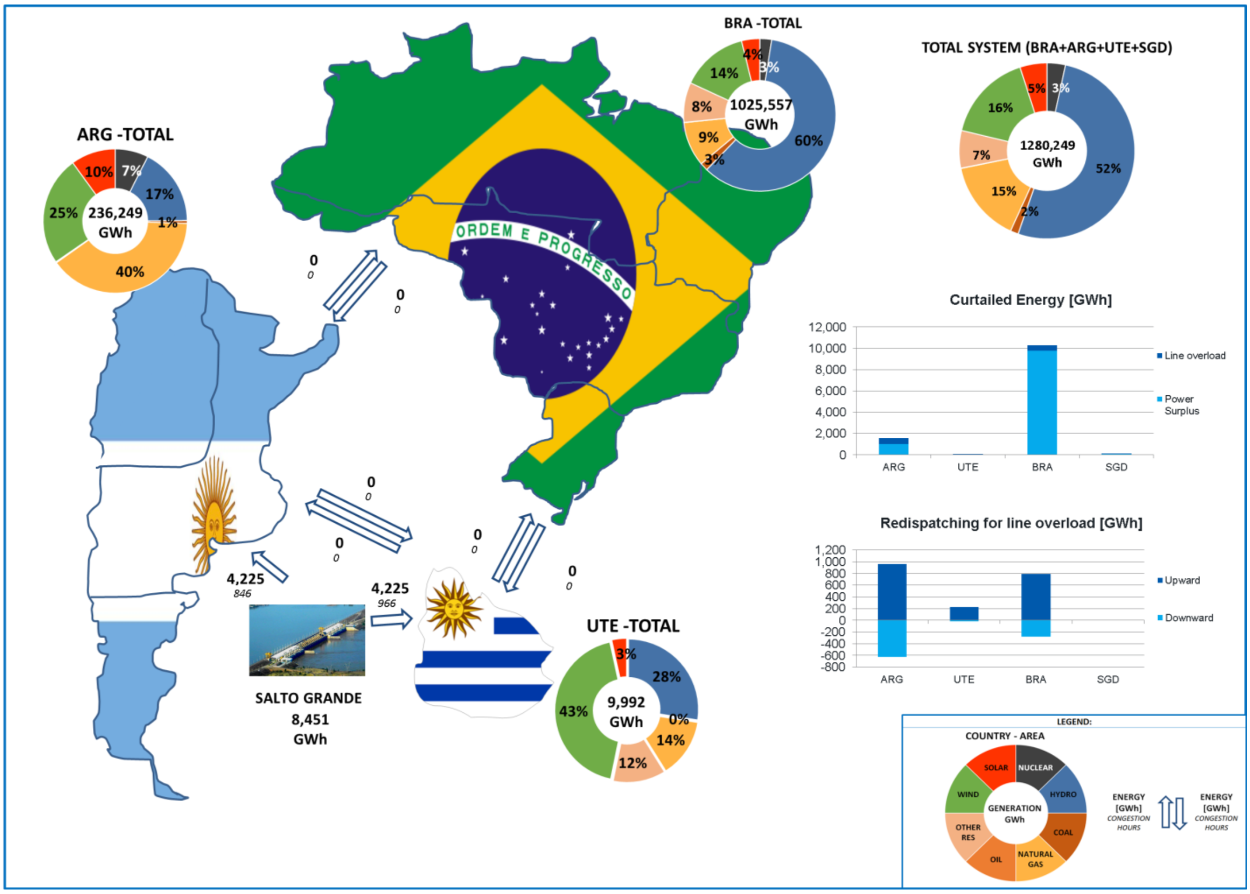

Figure 16 - Total production and energy exchanges – ARG, BRA and UY Reference scenario (NTC=0)

Once the new reference scenario with the three isolated countries is ready, simulations to assess the effects of the interconnection and the possibility to exchange energy between the countries are run. The first ones are focused on the definition of the best NTC between the countries, the following ones evaluate the effects that interconnections have on the VRES penetration and on other operational conditions.

3.3.4.5 Argentina, Brazil and Uruguay interconnected

Simulations with different values of NTC between the three considered countries have been carried out to define the impact of this constraint on the optimal economic operation of the interconnected system. Four different cases have been simulated as reported in the Table 65.

The first case (*Case 1*) considers as NTC between two countries the sum of the capabilities of the lines connecting them, so it corresponds to the theoretical maximum value of power that can be exchange. The detailed calculations based on the assumption in [1] are reported below:

- the interconnection between Argentina and Uruguay is composed mainly by two 500 kV lines, so the maximum value applied to the section is 2,000 MW[10];
- the interconnection between Argentina and Brazil is composed by two HVDC with rated power of 2,000 MW and 1,000 MW respectively, so an NTC equal to 3,000 MW has been considered;
- the interconnection between Brazil and Uruguay is composed by two HVDC with rated power of 500 MW and 70 MW respectively, so an NTC equal to 570 MW has been considered.

In the other cases (*Case 2, Case 3 and Case 4*), the values of NTCs have been reduced in order to study the interconnected power systems without a fully exploitation of the interconnections, for example to ensure that in case one of the line trips during the operation there are no technical issues to the exporting and importing countries (N-1 criterion). The margin with respect to the maximum theoretical value can become also a useful resource to face other technical issues such as unbalances due to high variation of VRES plants or errors in the load and production forecasts, which would be not available or available to a minor extent in case the interconnections were already loaded at their maximum capacity with energy exchanges resulting only from an economic optimization.

For these reasons, the *Case 2* considers for the interconnection between Argentina and Uruguay the optimal value of NTC obtained by the previous analysis (paragraph 3.3.4.2), for the interconnection between Uruguay and Brazil considers 500 MW and for the interconnection between Argentina and Brazil considers an NTC equal to 2,500 MW.

In *Case 3* the NTC between Argentina and Brazil and the NTC between Uruguay and Brazil are reduced again, and the last *Case 4* represents the case with the minimum value of NTCs.

It is important also to underline that the interconnection with Brazil are obtained through the usage of static converters due to the different frequency (50 Hz in Argentina and Uruguay, 60 Hz in Brazil), and this introduces the possibility to actively control the power flows more than in an AC interconnection, better exploiting the transmission capacity and reacting in case of technical issues.

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[10] The simulations of the Argentina and Uruguay interconnected scenario (paragraph **Errore. L'origine riferimento non è stata trovata.**) show that the results obtained with NTSC equal to 2,000 MW or 1,000 MW are very similar and the interconnection between the two countries is not fully used therefore the lower value of NTC (1,000 MW) has been selected. In this new scenario where there is the interconnection with the Brazil the power flows between countries change and the interconnections could be more used.

Table 65 - Considered cases for the interconnected scenario [MW]

CASES	NTC ARG-UY	NTC ARG-BRA	NTC UY-BRA
1	2,000	3,000	570
2	1,000	2,500	500
3	1,000	2,000	400
4	500	1,000	200

The results of the different cases are briefly reported below.

Case 1

This case represents the *Argentinian, Brazilian and Uruguayan power systems interconnected* with the possibility to *exchange the maximum power (2000 MW between ARG-UY, 3000 MW between ARG-BRA and 570 MW between UY-BRA).*

The presence of the interconnection provides the following main variations with respect to the Reference scenario:

- A *reduction of the EENS* from more than 5.5 GWh to 1.3 GWh (-76%). The final EENS corresponds to about $0.1x10^{-5}$ of the total load.
- *Overall generation costs* are reduced by 860 M$.
- Expected *generation by PV* increases 530 GWh with respect to the Reference scenario thanks to lower curtailments, which in this case account for 1.4 TWh.
- Expected *generation by wind* increases 1.8 TWh with respect to the Reference scenario; total curtailment equal to 5.1 TWh.
- *Energy exchanges* equal to:
  - 2 TWh from Argentina to Uruguay and 1.5 TWh from Uruguay to Argentina. The loading of interconnections, evaluated as energy/limit, is 12% for ARG to UY and 9% for UY to ARG.
  - 13.5 TWh from Argentina to Brazil and 6.7 TWh from Brazil to Argentina. The loading of interconnections, evaluated as energy/limit, is 51% for ARG to BRA and 26% for BRA to ARG.
  - 1.8 TWh from Uruguay to Brazil and 1.4 TWh from Brazil to Uruguay. The loading of interconnections, evaluated as energy/limit, is 35% for UY to BRA and 29% for BRA to UY.

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 868 M$.

Case 2

In this case the following main variations with respect to the reference scenario are present:

- A *reduction of the EENS* from more than 5.5 GWh to 1.2 GWh (-78%). The final EENS corresponds to about $0.1x10^{-5}$ of the total load.
- *Overall generation costs* are reduced by 777 M$.
- Expected *generation by PV* increases by 480 GWh with respect to the Reference scenario; total curtailments are equal to 1.4 TWh.
- Expected *generation by wind* increases respect to the Reference scenario by more than 1.6 TWh; curtailment equal to 5.2 TWh.
- *Energy exchanges* equal to:
  - 2.1 TWh from Argentina to Uruguay and 1.2 TWh from Uruguay to Argentina. The loading of interconnections, evaluated as energy/limit, is 24% for ARG to UY and 14% for UY to ARG.

- 11.7 TWh from Argentina to Brazil and 6.1 TWh from Brazil to Argentina. The loading of interconnections, evaluated as energy/limit, is 54% for ARG to BRA and 28% for BRA to ARG.
- 1.8 TWh from Uruguay to Brazil and 1.2 TWh from Brazil to Uruguay. The loading of interconnections, evaluated as energy/limit, is 40% for UY to BRA and 27% for BRA to UY.

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 786 M$.

<u>Case 3</u>

In this the value of NTCs between Argentinian, Brazilian and Uruguayan power systems are: 1,000 MW between ARG-UY, 2,000 MW between ARG-BRA and 400 MW between UY-BRA.

The following main variations with respect to the reference scenario are present:

- A *reduction of the EENS* from more than 5.5 GWh to 1.3 GWh (-76%). The final EENS corresponds to about $0.1x10^{-5}$ of the total load.
- *Overall generation costs* are reduced by 675 M$.
- Expected *generation by PV* increases 430 GWh with respect to the Reference scenario and curtailments are equal to nearly 1.5 TWh.
- Expected *generation by wind* increases respect to the Reference scenario by 1.4 TWh; wind curtailment account for nearly 5.5 TWh.
- *Energy exchanges* equal to:
  - 2.1 TWh from Argentina to Uruguay and 1 TWh from Uruguay to Argentina. The loading of interconnections, evaluated as energy/limit, is 24% for ARG to UY and 12% for UY to ARG.
  - 9.7 TWh from Argentina to Brazil and 5.2 TWh from Brazil to Argentina. The loading of interconnections, evaluated as energy/limit, is 55% for ARG to BRA and 30% for BRA to ARG.
  - 1.6 TWh from Uruguay to Brazil and 1 TWh from Brazil to Uruguay. The loading of interconnections, evaluated as energy/limit, is 46% for UY to BRA and 28% for BRA to UY.

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 683 M$.

<u>Case 4</u>

The last case represents the *Argentinian, Brazilian and Uruguayan power systems interconnected* with the possibility to *exchange the minimum power (500 MW between ARG-UY, 1000 MW between ARG-BRA and 200 MW between UY-BRA).*

The following main variations with respect to the reference scenario are present:

- A *reduction of the EENS* from more than 5.5 GWh to 2.1 GWh (-62%). The final EENS corresponds to about $0.2x10^{-5}$ of the total load.
- *Overall generation costs* are reduced by 422 M$.
- Expected *generation by PV* increases 250 GWh with respect to the Reference scenario; PV curtailments are about 1.7 TWh.
- Expected *generation by wind* increases respect to the Reference scenario by more than 800 GWh; and relevant curtailments are higher than 6 TWh.
- *Energy exchanges* equal to:
  - 1.7 TWh from Argentina to Uruguay and 0.7 TWh from Uruguay to Argentina. The loading of interconnections, evaluated as energy/limit, is 39% for ARG to UY and 16% for UY to ARG.
  - 5.1 TWh from Argentina to Brazil and 2.9 TWh from Brazil to Argentina. The loading of interconnections, evaluated as energy/limit, is 58% for ARG to BRA and 33% for BRA to ARG.

- 0.9 TWh from Uruguay to Brazil and 0.5 TWh from Brazil to Uruguay. The loading of interconnections, evaluated as energy/limit, is 53% for UY to BRA and 30% for BRA to UY.

The presence of the interconnection provides *benefits for the whole system* evaluated equal to 429 M$.

In all the cases, it is present also an amount of curtailed energy of hydroelectric power plants caused by overgeneration conditions, which is considered in the performed analysis. As already explained in other situations, this amount of energy might be reduced during real operation of the system with a better short term planning of the resources. To this aim, it is necessary to ensure a good coordination among all the different energy sources, which might become more complex whit an increased amount of VRES power plants.

The following Table 66 compares the results.

Table 66 - Main results for different NTC values between Argentina, Brazil and Uruguay [MW]

	Reference scenario	Case 1	Case 2	Case 3	Case 4
EENS [GWh]	5.5	1.3	1.2	1.3	2.1
Total generation costs [M€/year]	14,210	13,350	13,430	13,535	13,788
PV production [TWh]	63.5	64.0	64.0	63.9	63.7
Wind production [TWh]	208.7	210.5	210.3	210.1	209.5
RES Curtailments [TWh]	8.9	6.5	6.7	7.0	7.8
Total benefit [M€/year]	-	868	786	683	429

It is possible to note that the results of the considered cases with different values of NTCs are very similar. The case with the higher total benefit is the one with the maximum values of NTCs (Case 1). Indeed, this case presents the lower generation costs and the maximum production of renewable power plants.

However, the operation of the system with the possibility to saturate completely the interconnections can bring to some critical conditions for instance in case an interconnection line trips or some generators are unavailable, because when the interconnections are saturated, there is a reduced flexibility for the system to face adverse events. This can be observed in the EENS value, which is slightly reduced when a margin in the interconnections is kept with respect to the maximum capability.

For this reason, the Case 2 has been selected as basis for the following simulations. It is important to underline that the definition of an NTC value does not depend only on technical issues, but often is more determined by political or strategic decisions, which must be supported by technical possibilities but which might differ significantly from the optimal solution.

The resulting conditions and energy exchanges corresponding to the Case 2 are depicted in Figure 17.

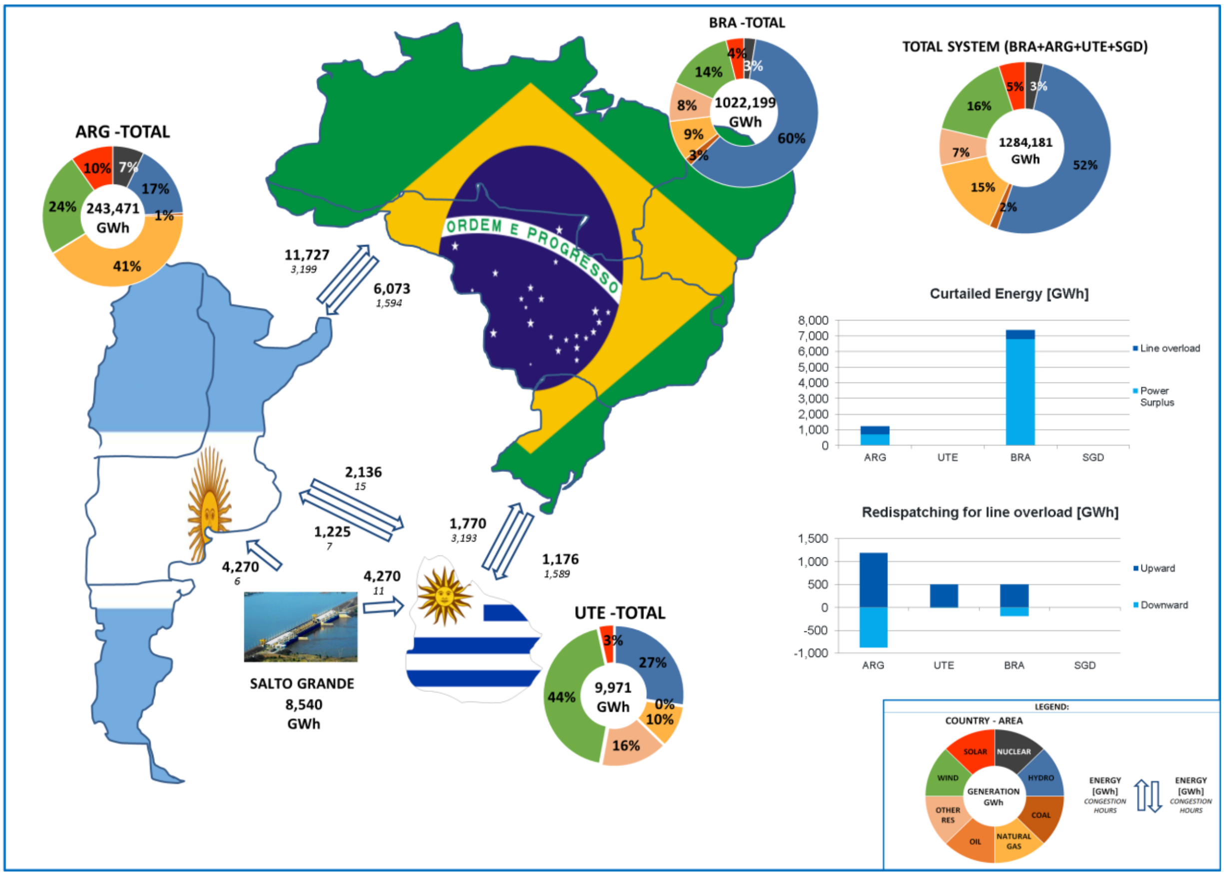

Figure 17 - Total production and energy exchanges – Argentina, Brazil and Uruguay interconnected Case 2

3.3.4.6 Final optimal configuration Argentina, Brazil, Uruguay interconnected system

The presence of the interconnections between the countries improves the adequacy of the systems, because the generation resources can be shared when necessary, further reducing the EENS and exploiting the cheap generation in a better way.

The possibility to import energy when needed cancels the need of the additional dispatchable generation introduced in the Argentinean isolated system to ensure the generation adequacy and keep the EENS below the 10^{-5} threshold. Thanks to the interconnections, the Argentinean system maintains the adequacy even without considering the 3,000 MW CCGTs proposed in NEC and NWE areas, saving the related investment costs which were higher than 280 M$/year and the fuel costs necessary to produce about 15 TWh.

This money can be invested in VRES in the areas which take advantage from the presence of the interconnections, i.e. NEC in Argentina, Sul in Brazil and Uruguay. In these areas, the main VRES resource is the wind, so a new optimal scenario has been identified increasing the wind installed power by the values listed in Table 67 looking to the benefits for the system and the technical constraints.

Table 67 - Additional wind installed power in final optimal interconnected scenario

	Additional wind installed power [MW]
NEC	1,000
S	3,000
UTE	500
TOTAL	**4,500**

Table 68 reports the final amount of PV and wind installed power in the resulting optimal scenario.

Table 68 - Total VRES installed capacity in final optimal scenario for ARG, BRA and UY interconnected [MW]

COUNTRY	AREA	PV installed power [MW]	Wind installed power [MW]	Total VRES [MW]
ARGENTINA	NEC	1,100	9,400	*10,500*
	NWE	9,000	300	*9,300*
	PAT	0	5,200	*5,200*
	Total	***10,100***	***14,900***	***25,000***
URUGUAY	UTE	230	2,050	*2,280*
	Total	***230***	***2,050***	***2,280***
BRAZIL	N	1,460	670	*2,130*
	NE	8,470	28,990	*37,460*
	SE/CO	10,590	30	*10,620*
	S	0	11,910	*11,910*
	Total	***20,520***	***41,600***	***62,120***
Whole power system	***Total***	***30,850***	***58,550***	***89,400***

EENS remains very limited, equal to about 1.4 GWh. Due to the removal of a CCGT in NWE, a slight increase in this area can be observed, as reported in Table 69.

Table 69 - Expected Energy Not Supplied in the final optimal scenario for ARG, BRA and UY interconnected [MWh]

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	0	0	80	80
NEC	0	71	0	71
PAT	0	0	0	0
N	0	1	61	62
NE	0	91	542	633
SE/CO	0	0	491	491
S	0	0	0	0
UTE	0	22	0	22
TOTAL	**0**	**185**	**1,174**	**1,359**

The total benefit for the system resulting in the optimal scenario with respect to the case presented in Chapter 3.3.4.5, where the optimal generation fleet calculated for each isolated country was considered, are reported in the Table 70.

Table 70 - Total benefit of the final optimal scenario for ARG, BRA and UY interconnected

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	4,500	-775
STORAGE	540	-35
ADDITIONAL DISPATCHABLE	-3,000	282
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-14,464	745
RES CURTAILMENT	1,481	-
TOTAL EENS	1	0
TOTAL BENEFIT	**-**	**216**

The main advantage is the avoided investment in new CCGTs. Moreover, the energy produced by the additional wind plants corresponds to an amount of energy similar to the one which was produced by the dispatchable generators removed in Argentina and which would have been produced by more expensive plants if the additional wind plants had not been considered. In conclusion, the optimal scenario provides benefits for the whole system evaluated equal to 216 M$, respect to the case explained in Chapter 3.3.4.5.

The following Figure 18 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system in the final optimal scenario. With the new added wind plants, Uruguay exports part of the produced energy mainly towards Argentina, for an amount equal to about 1.5 TWh. Argentina is quite balanced, and most of the energy imported from Uruguay is then exported towards Brazil.

In the whole system, wind energy covers almost 20% and PV 5% of the total production.

The introduction of a considerable amount of additional PV and wind plants increases the situations with overgeneration, and the need for curtailments. This amount is significant in Brazil, where there is the risk to curtail more than 8 TWh, and in Argentina, where the risk is relevant for about 1 TWh. Transmission network does not introduce strong limitations but requires some curtailments which must be compensated with dispatchable generation.

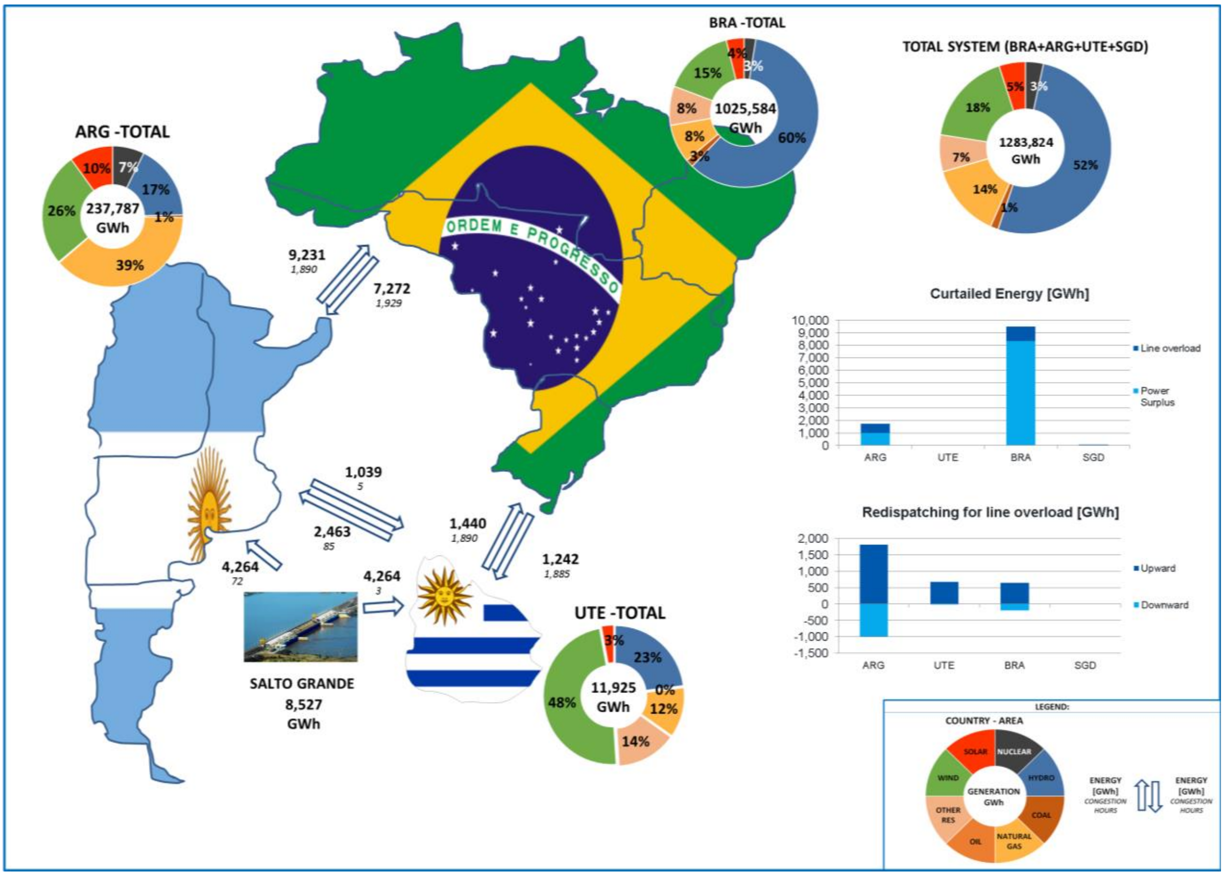

Figure 18 - Total production and energy exchanges – ARG, BRA and UY interconnected final optimal scenario

3.3.4.7 Final considerations on Argentina, Brazil and Uruguay interconnected system

The operation of the interconnected system brings significant advantages in terms of adequacy and generation costs with respect to the results obtained considering the three power systems isolated. All the cheap energy sources, even the not dispatchable ones, are better exploited reducing their curtailments, and the demand is also better supplied thanks to the availability of a wider generation fleet which can be used even if located in other countries.

The advantages which can be obtained strongly depend on the constraints which are assumed for the energy exchanges between the countries. The higher the power which can be transferred through the interconnections, the higher the economic benefit, but when this value gets too close to the maximum capability of the interconnections there is the risk that the operation of the system becomes constrained and some flexibility to face adverse events is lost.

A set of NTCs between the countries has been defined to ensure a good balance between the economic advantages and the technical adequacy. The selected values are:

- 1,000 MW between ARG and UY
- 2,500 MW between ARG and BRA
- 500 MW between UY and BRA

The NTCs towards Brazil are close to the sum of the capabilities of the interconnection links thanks to the presence of static converters (necessary to allow the connection of 50 Hz and 60 Hz systems) which ensure the possibility of an active control of the power flows and thanks to the dimension of the systems (ARG and UY on one side and BRA on the other) which are able to face power variations in case one of the interconnections would trip. The NTC of the interconnections between Argentina and Uruguay is selected from the result of the simulations reported in the paragraph 3.3.4.2, which show that the optimal value of NTC from a technical and operational point of view is 1,000 MW.

The simulations performed considering the whole interconnected system show that the possibility for the Argentina to import energy when needed from the other countries makes the additional dispatchable generation plants not needed anymore to ensure a good adequacy and keep the EENS below the 10^{-5} threshold. Therefore the Argentinean system maintains the adequacy even without considering the 3,000 MW CCGTs proposed in NEC and NWE areas, saving the related investment costs which were higher than 280 M$/year and the fuel costs necessary to produce about 15 TWh. This money can be invested in VRES in the areas which take advantage from the presence of the interconnections, i.e. NEC in Argentina, Sul in Brazil and Uruguay. In these areas, the main VRES resource is the wind, so a new optimal scenario has been identified increasing the wind installed power.

The operation of the interconnected system is simulated allowing energy exchanges between countries every time there is an economic advantage, i.e. every time in a country is available generation cheaper than in another and the interconnections between them are not congested: in this way, the cheapest generation is dispatched in the whole system through the interconnections, and the simulations show the maximum benefit which can be obtained with the exploitation of the interconnections. It is worth recalling here that in the real operation, the energy exchanges between the countries are subject to bilateral agreements between the governments and require also proper regulatory framework. In order to exploit best the possible advantages due to the interconnections, a strong and flexible cooperation and coordination between the countries is required. If this is not possible or allowed to a limited extent, for instance because the definition of energy exchange programs between countries can be defined and fixed only many days in advance with reduced flexibility during real time operation, the advantages which can be achieved will also be limited.

In conclusion, the optimal configuration for additional VRES installations defined in the paragraph 3.3.4.6 includes a total of 30,850 MW of PV power plants and a total of 58,550 MW of wind power plants as reported in the Table 68. With these additional VRES plants and the related storage systems, the system is able to cover the load increase from 2026 to 2030 only with carbon-free generation, maintaining a good adequacy and providing economic benefit to the countries. The increase of installed power is then limited mainly by the risk of curtailments due to overgeneration conditions, which represent the most significant constraint in the areas with highest wind and PV potential.

3.4 Sensitivity analyses of optimal configuration - interconnected systems

Some sensitivity analyses have been carried out on the interconnected system resulting from the evaluation performed in chapter 3.3.4. The investigation, aimed at checking how the power systems with the amount of VRES plants defined in an average scenario operate also in different conditions, has been focused mainly on:

- variations of the transmission system, especially possible late development of important corridors between countries (such as the third interconnection between Argentina and Brazil assumed) or between areas of the same country (in particular, the HVDC Graca Aranha – Silvania connecting the Norte region to the area of Brasilia in Brazil), which seems to have an important role in the development of the VRES plants;
- variation of hydrological conditions.

3.4.1 Construction delay of the HVDC Graca Aranha – Silvania

A sensitivity simulation has been performed considering a delay on the construction of the HVDC Graca Aranha – Silvania, which connect an important 500 kV node in Maranhao (close to the cut-set between N and NE) to the center of the Brazil (as illustrated in Figure 19). This HVDC is proposed by EPE in the PDE2026 [2] to increase security of supply, fostering the expansion of VRES plants in N and NE areas and optimizing the usage of hydro and thermal generation. The aim of this simulation is to verify the impact of the significant future transmission system development on the results obtained in the previous simulation. This HVDC is able in fact to transfer 4,000 MW from N to SE/CO, improving considerably the evacuation capacity of the N and NE areas, thus reducing the overproduction problems. Without this HVDC, the NTC between N and SECO is reduced by 4,000 MW, and higher curtailments in low load/high VRES conditions and higher production costs are expected with respect to the final case considered in chapter 3.3.4.5.

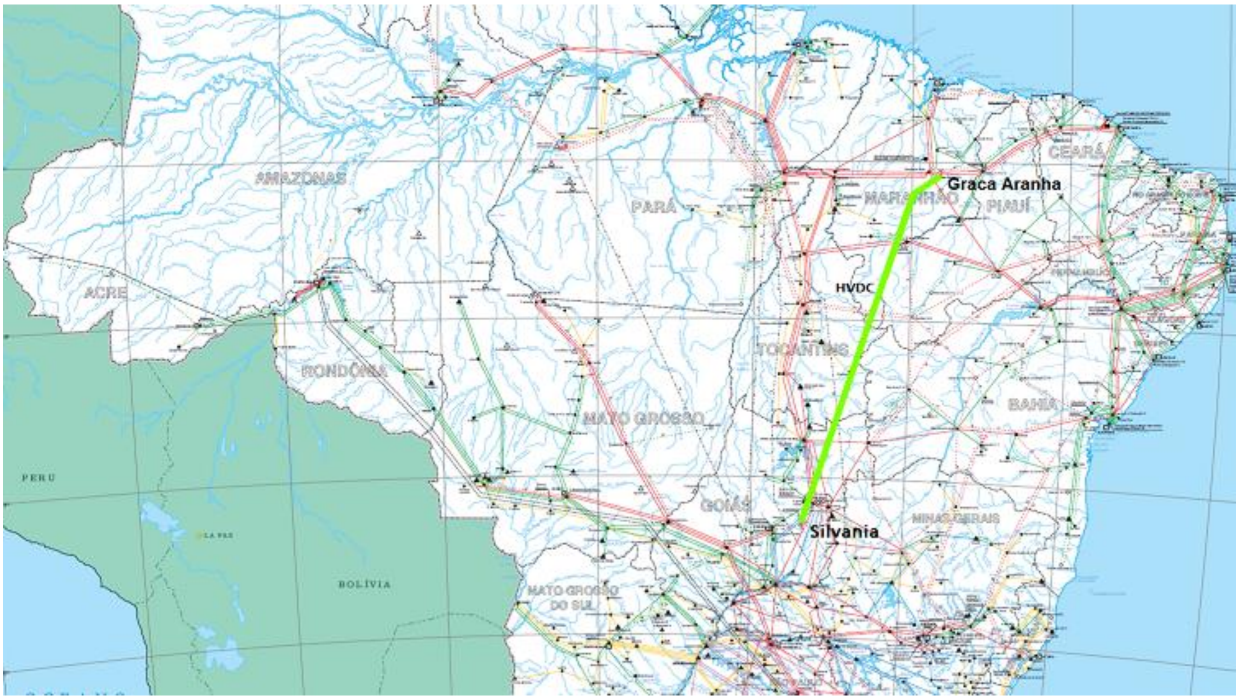

Figure 19 – HVDC Graca Aranha -Silvania

The results of the simulation show an increasing of the VRES curtailments in the N and NE areas and confirm the capacity of the HVDC Graca Aranha – Silvania to reduce the overproduction problems, evacuating the generation from N to SE/CO. The production costs are higher with respect to the final case considered in 3.3.4.5.

The main results of this sensitivity are:

- *EENS* remains aligned with the optimal case, it is about 1.1×10^{-6} of the total load.
- *Overall generation costs* are close to 12,742 M$; therefore the generation costs increase of 54 M$.
- Expected *generation by PV and wind* power plants decrease in N and NE Brazilian areas. This is due to a problem of overgeneration caused by the limited evacuation capacity. With respect to the optimal scenario, the PV curtailment increases by about 200 GWh and the wind curtailment by about 1 TWh.

Table 71 summarizes the costs and benefits of this scenario, highlighting an overall cost for the whole power system of 54 M$ due to the need to replace the curtailed energy by VRES plants with thermal ones.

Table 71 - Total benefit of the sensitivity case construction delay of the HVDC Graca Aranha – Silvania

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	1128	-54
RES CURTAILMENT	1203	-
TOTAL EENS	0	0
TOTAL BENEFIT	**-**	**-54**

This HVDC is proposed by EPE in the PDE2026 to increase flexibility of the transmission system in order to create the conditions for a stronger development of the PV and wind installations in the N and NE areas. Moreover it allows the network operator to optimize the reserve management in the real time operation, thanks to the ability to quickly modify or even invert the power flow in case of need, ensuring that generation available in N-NE areas can support SE/CO in case of need or vice versa. It also increases the security of the transmission system and the possibility to withstand N-1 or even N-2 conditions of the AC lines or also the possible delay of the construction of other 500 kV AC lines in the same direction. These benefits must also be taken into account when evaluating the advantages which can arise from the development of this HVDC line in addition to the 54 MUSD/year calculated in the analysed sensitivity case.

3.4.2 Absence of San Isidro - Foz de Iguacu 500 kV line between Argentina and Brazil

The operation of the system without the third interconnection between Argentina and Brazil has been evaluated, keeping in service only the already existing 2,000 MW interconnection in Garabì, not considering the new San Isidro – Foz de Iguacu 500 kV line.

The absence of the interconnection requires modifying the NTC between the countries, so two simulations considering 2,000 MW and 1,500 MW limit have been carried out.

When the NTC is equal to 2,000 MW the main results are the following:

- EENS slightly increases up to 1.7 GWh.
- Overall generation costs increase by 51 M$.
- Slight reduction of the expected generation by PV and wind power plants (respectively about 68 GWh/year and260 GWh/year).

In the same way, when NTC is equal to 1,500 MW the results are the following:

- Slight increase of EENS up to 2.5 GWh.
- Overall generation costs increases by 118 M$.
- Slightly reduction of the expected generation by PV and wind power plants (respectively about 150 GWh/year and 550 GWh/year).

The following Table 72 provides a direct comparison of the results also with respect to the optimal scenario.

Table 72 - Main results for the two NTC values considered in the sensitivity case

	Optimal scenario	Absence of San Isidro – Foz de Iguacu 500 kV line	
		NTC 2000 MW	NTC 1500 MW
EENS [GWh]	1.4	1.7	2.5
Total generation costs [M€/year]	12,688	12,738	12,805
PV production [TWh]	63.7	63.7	63.6
Wind production [TWh]	22.7	22.6	22.6
Total benefit [MUSD/year]	-	-51	-120

The reduction of the exchange capacity between Argentina and Brazil has a strong impact on the overall system costs, due to the necessity to reduce the production by RES and to use more expensive thermal generation. The lower NTC has also an impact on the EENS in the system, due to the reduced possibility for mutual support between the systems when the transmission capacity is more constrained.
The technical possibility to exchange more energy between the countries is then beneficial for the whole system. On the other hand it is necessary that there are proper agreements to properly exploit this advantage and allow the different power systems to support and get supported when necessary.
2,000 MW NTC between Argentina and Brazil reflects the existing situation and allows a better security of supply with limited EENS value (1.7 GWh/year). Total production and energy exchanges of this case are highlighted in the following figure.

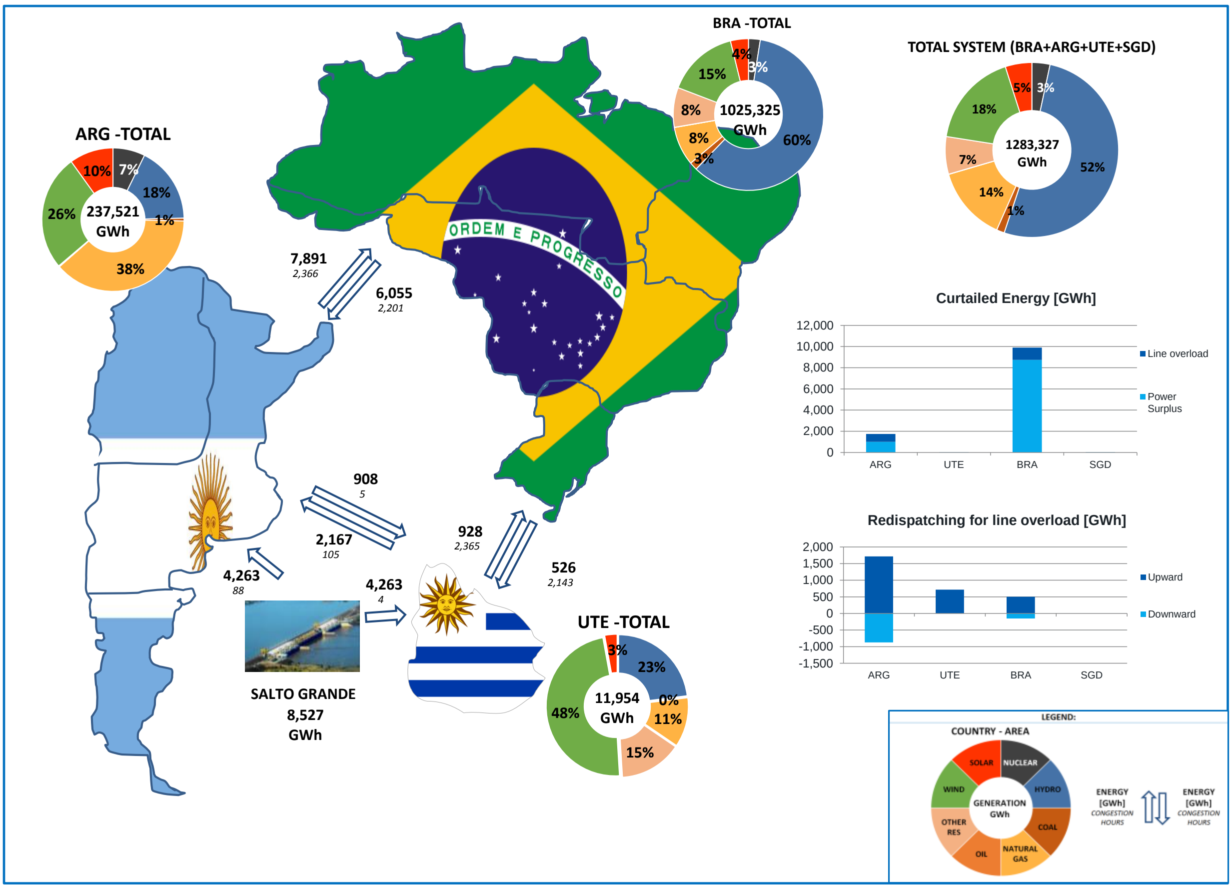

Figure 20 – Total production and energy exchanges – ARG, BRA and UY interconnected without San Isidro (ARG) – Foz de Iguacu (BRA) 500 kV line

3.4.3 Dry hydrological conditions

The scenario with dry hydrological condition presents the following main results:

- The EENS increases considerably up to 350 GWh, equal to nearly $3x10^{-4}$ of the total load. The EENS mainly increases in the Brazilian areas N, NE and SE/CO.
- Overall generation costs increases up to more than 18,500 M$, more than 45% higher with respect to the optimal scenario, due to the need to use expensive thermal generation to compensate the lower energy production by hydro.
- Both for PV and wind there are lower curtailments (there are less conditions with overproduction), and their generation increases respectively by 1.1 TWh and 3.9 TWh.

The Brazilian systems would require additional generation to ensure a better adequacy. The easiest solution would consist in the installation of some economic dispatchable plants (such as OCGT) to cover the hours with high demand when the hydro resource and the VRES would be not high enough. Other possible solutions which might improve the performance of the power system, also identified by EPE in PDE2026 [2], are the introduction of further reversible plants, the increase of installed power in selected hydropower plants, storage systems, demand response mechanism.

The optimal amount of VRES calculated in the previous Chapters has been defined considering an average production of the hydroelectric power plants, which is the correct approach when the profitability of the VRES plants is considered along their lifetime, equal to at least 20 years.
On the other hand, it is necessary to ensure that in different hydrological conditions, such as dry periods, the system has enough generation available to supply the load, avoiding a dramatic deterioration of the adequacy, which would cause a high EENS value. In these conditions, there must be other generation resources, even expensive ones, to be used to cover the demand. In case the simulation shows critical results, some countermeasures, based on thermal generation or other technologies, should be considered in the power system planning.
In order to define a “dry hydrological condition”, an analysis has been carried out on the available historical data which covers more than 80 years of hydro resource in Brazil. The typical dry year has been defined looking at the average conditions of years which present an availability of the hydro resource around about the 15th percentile of the series. The different behavior which takes place in the areas has been taken into account in the creation of the scenario: the N and NE area show a different reduction of the hydro resource availability with respect to the S and SE/CO area.
Based on the available data, the dry year has been modelled with a reduction of about 15% of the energy available from hydropower plants. N and NE area in particular have a stronger reduction with respect to SE/CO and S.
Uruguayan and Argentinean plants (including Salto Grande) have been assigned a reduction aligned to the values obtained for S and SE/CO area.

As expected, the simulation of the scenario with lower availability of hydro resource shows a strong increase of the EENS, up to 352 GWh, equal to about $2.9x10^{-4}$ of the total load. As reported in Table 73, the EENS increase is recorded in Brazil especially in the SE/CO, NE and N areas, strongly dependent on hydro. Therefore in dry hydrological conditions the Brazilian power system presents a dramatic deterioration of the adequacy since in the simulated scenario it doesn't have enough generation to cover the reduction of hydropower production. This fact suggests that the generation fleet resulting in the optimal scenario, with characterized by the high increase of VRES plants, is not enough to ensure the load coverage when there is a significant reduction of the availability of the hydro resource. To ensure a better adequacy, additional generation or ways to better exploit the existing one should be considered. Solutions already considered by EPE in PDE2026 [2] to meet peak demand and which might be useful also in this context are thermal power plants (in particular OCGT, whose installation is cheaper and which can be the optimal solution in case the power is required only for short periods and maybe with fast variations to compensate changes in the VRES production), reversible plants, additional installed power in selected hydropower plants (as examined in 3.3.2.4), introduction of additional storage plants or of a demand-response mechanism.

Table 73 - Expected Energy Not Supplied in the dry scenario for ARG, BRA and UY interconnected

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	25	0	238	263
NEC	0	101	0	101
PAT	0	0	0	0
N	5	39	40,198	40,242
NE	1,174	1,909	80,020	83,103
SE/CO	4,683	0	223,831	228,514
S	0	0	0	0
UTE	0	46	0	46
TOTAL	**5,887**	**2,095**	**344,287**	**352,269**

The produced energy by PV and Wind power plants increases due to a reduction of curtailments for overgeneration. As reported in the following tables the PV gains about 1,150 GWh while the wind improves by more than 3,900 GWh with respect to the final optimal scenario.

Table 74 - Difference of total production of PV plants between optimal scenario and dry conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NWE	175	-175	3	0	40
NEC	0	0	-1	0	-1
PAT	0	0	0	0	-
N	291	-291	0	0	399
NE	688	-688	-3	0	162
SE/CO	0	0	1	0	0
S	0	0	0	0	-
UTE	0	0	0	0	0
TOTAL PHOTOV. GENER.	**1,154**	**-1,154**	**0**	**0**	**74**

Table 75 - Difference of total production of wind plants between optimal scenario and dry conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NWE	3	-2	0	0	16
NEC	0	-1	32	0	3
PAT	221	-221	1	0	86
N	162	-162	0	0	483
NE	3,472	-3,473	5	0	240
SE/CO	0	0	0	0	0
S	19	-19	0	0	3
UTE	1	-2	6	0	4
TOTAL WIND GENER.	**3,878**	**-3,880**	**44**	**0**	**134**

In order to supply the load compensating the lower energy by hydroelectric power plants, also the thermal generation increases its production and the relevant costs reach 18,506 M$, more than 45% higher with respect to the optimal scenario.

Table 76 summarizes the main economic figures describing the operation of the system in this dry year scenario with respect to the optimal one with average hydrological conditions: there is a significant increase of the costs (6,520 M$) due to the higher thermal generation obtained also with expensive plants, and the cost associated to EENS.

Table 76 - Total benefit of the sensitivity case dry hydrological conditions

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	68,852	-5,818
RES CURTAILMENT	-5,160	-
TOTAL EENS	351	-702
TOTAL BENEFIT	**-**	**-6,520**

In Figure 21 it is possible to note that in the considered dry conditions, there is a massive import of energy in Brazil, and the sections towards Argentina and Uruguay reach their limit for more than 5,000 h/year.

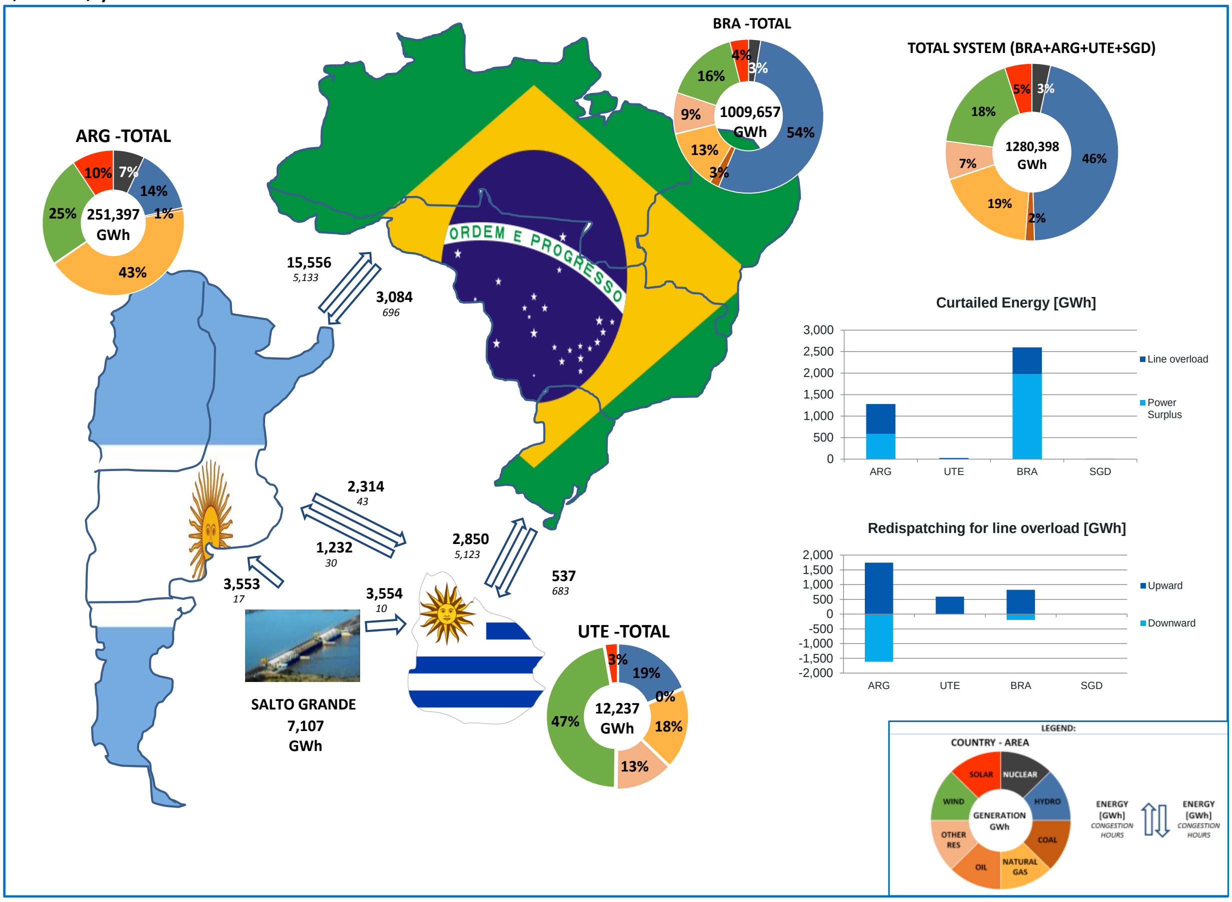

Figure 21 - Total production and energy exchanges – ARG, BRA and UY interconnected with dry hydrological conditions

3.4.4 *Wet hydrological conditions*

The operation of the power systems with wet hydrological conditions presents the following main results:

- The *EENS* nearly disappears, becoming lower than 0.1 GWh (about $1x10^{-7}$ of the total load).
- Overall *generation costs* decrease to less than 9,800 M$, -23% respect to the optimal scenario because of the higher availability of "free" generation by hydropower plants.
- Expected *generation by PV* and wind decreases due to more frequent and significant overgeneration conditions. PV must be curtailed nearly by 1.7 TWh more than in the amount in average hydrological conditions, while wind risks to be cut by nearly 7.6 TWh more.

The operation of the system in case of wet hydrological conditions is also to be analyzed, because it can lead to greater curtailments of VRES and hydropower production due to more frequent and significant overproduction conditions due to the additional availability of hydro resource. This should not affect the adequacy of the system in terms of EENS, but a huge VRES curtailment might mean that the installed VRES generation is too high and that some plants might be not exploited at their full potential along the lifetime because during the wet year have to be curtailed in a significant way. This fact might have an impact on the economic viability of the projects, constituting a possible risk for the investment. For this reason it is important to verify also that during wet years the production of VRES is not critically affected. As done for the definition of the typical dry year explained in the previous paragraph, the "typical wet year" has been defined based on historical data series of hydro resource in Brazil, looking at the conditions registered during years which had a production around the 85^{th} percentile of the series. Also in this case attention has been paid to possible different behavior in the areas.
Uruguayan and Argentinean plants (including Salto Grande) have been assigned an increase of the available energy aligned to the values obtained for S and SE/CO areas.

The simulation of the scenario with wet hydrological conditions shows that the EENS reaches very negligible values in the system (0.12 GWh, equal to about $1x10^{-7}$ of the total load). No problems are present in areas with high penetration of hydro resource. The Table 77 shows the EENS, expressed as MWh/year, split by area and cause.

Table 77 - Expected Energy Not Supplied in the wet scenario for ARG, BRA and UY interconnected

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	0	0	23	23
NEC	0	73	0	73
PAT	0	0	0	0
N	0	0	0	0
NE	0	0	0	0
SE/CO	0	0	0	0
S	0	0	0	0
UTE	0	22	0	22
TOTAL	**0**	**95**	**23**	**118**

Thanks to the additional availability of hydro resource, there is an increment of hydropower production that causes a reduction of the thermal generation with the relevant costs. This benefit is estimated in 9,807 M$, -23% respect to the optimal scenario with average hydrological conditions.

On the other hand, the higher production by hydropower plants makes more frequent the conditions in which the overgeneration constraint in the system is reached, requiring some curtailment of the new power plants. For this reason, PV and wind power plants decrease their production respectively by nearly 1,700 GWh and by 7,600 GWh respect to the final optimal scenario with average hydrological conditions.

Table 78 - Difference of total production of PV plants between optimal scenario and wet conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NWE	-330	330	-11	0	-74
NEC	0	0	-1	0	-1
PAT	0	0	0	0	-
N	-386	386	0	0	-531
NE	-963	963	42	0	-223
SE/CO	-5	5	1	0	-1
S	0	0	0	0	-
UTE	-1	1	0	0	-8
TOTAL PHOTOV. GENER.	**-1,685**	**1,685**	**31**	**0**	**-109**

Table 79 - Difference of total production of wind plants between optimal scenario and wet conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
NWE	-4	5	0	0	-30
NEC	-2	1	-21	0	-3
PAT	-396	396	5	0	-153
N	-298	297	0	0	-887
NE	-5,957	5,957	39	0	-409
SE/CO	0	0	0	0	0
S	-950	950	0	0	-160
UTE	-9	9	-9	0	-14
TOTAL WIND GENER.	**-7,616**	**7,615**	**14**	**0**	**-260**

Table 80 summarizes the main figures relevant to the operation of the power system during wet years with respect to the scenario with average hydrological condition. The availability of more hydro resource in wet conditions provides a benefit for the whole power system equal to 2,880 M$.

Table 80 - Total benefit of the sensitivity case wet hydrological conditions

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-47,864	2,881
RES CURTAILMENT	9,546	-
TOTAL EENS	-1.2	2
TOTAL BENEFIT	**-**	**2,883**

Figure 22 shows that in the wet conditions, Brazil increase the energy exported towards the neighboring countries, and the interconnection limits are reached for nearly 3,500 h/year.

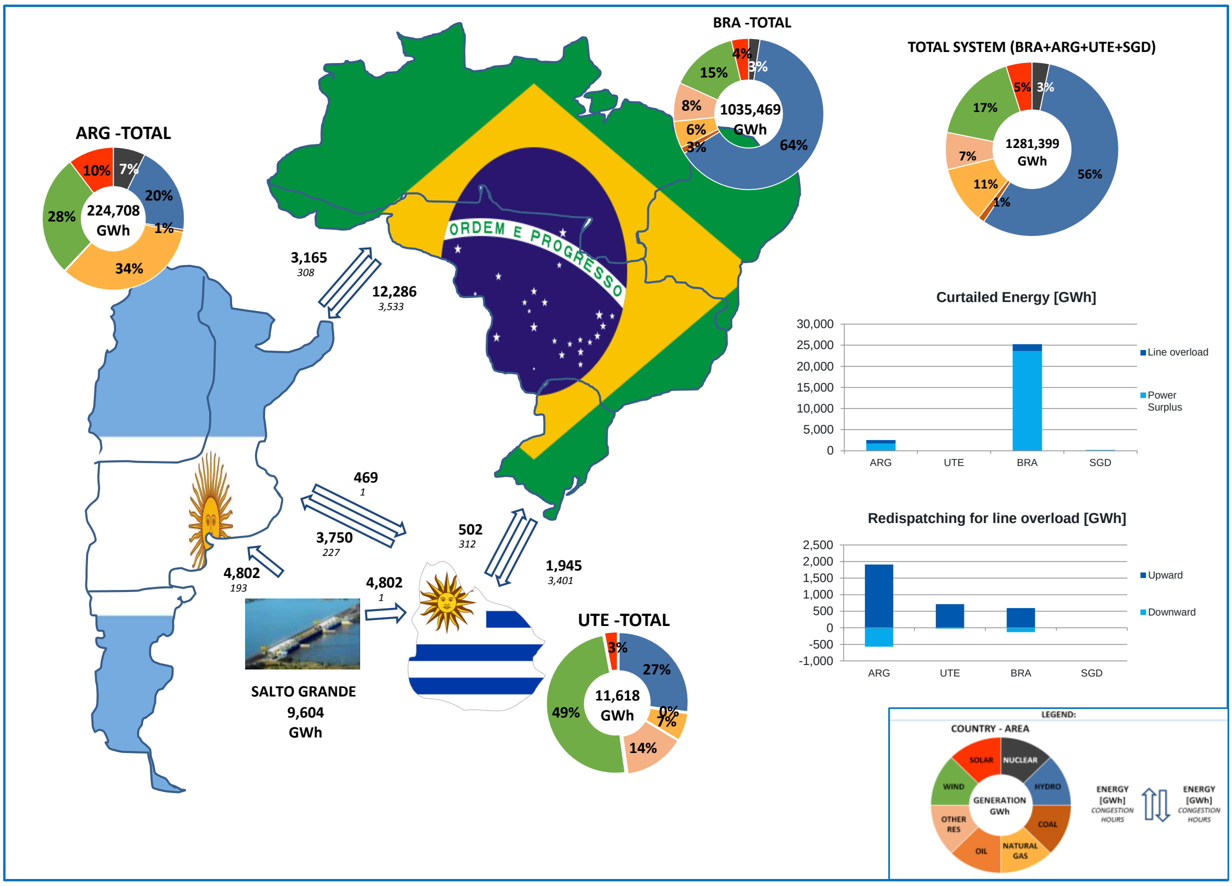

Figure 22 - Total production and energy exchanges – ARG, BRA and UY interconnected with wet hydrological conditions

4 VARIANTS

4.1 First Variant: accelerated decarbonization and strong economic development

In the first Variant a higher demand growth together with an important change in the generation fleet, due to a transition to a carbon-free condition, has been examined. The main aspects that characterize this scenario with respect to the final optimal configuration described in paragraph 3.3.4.6 are described in the following.

Electric demand

In this Variant a strong increase of the demand is analyzed. The main drivers which can contribute to a demand higher than the one in the final optimal configuration are:

- Stronger economic growth of the countries
- Increase of population
- Higher electricity penetration, with particular reference to transport sector and residential use

The annual energy consumption is deemed to become 8% higher than the final optimal scenario in each considered country (Argentina, Brazil and Uruguay). The increase of the load is assumed to be mainly due to a stronger economic growth and partially to the impact of the e-mobility, concentrated in the biggest cities.

According to the values defined in [1], the additional demand due to e-mobility is estimated in 0.75 TWh in Argentina (0.32% of the total load and about 4% of the total increase), about 0.35 TWh in Brazil (0.04% of the total load and 0.5% of the increase) and nearly 0.2 TWh in Uruguay (1.35% of the total load and 15% of the increase). This demand due to e-mobility is considered to be concentrated in the urban areas of Grand Buenos Aires, Sao Paulo, Rio de Janeiro and Montevideo, during the night hours (between 12pm and 07am). The rest of the demand increase (the part caused by a general higher economic growth of the countries) is applied in a flat way in all the regions.

The energy increase is sum up in the following table.

Table 81 - First Variant - Energy Increase

COUNTRY	Energy increase due to e-mobility [GWh]	Energy increase due to population and economic growth [GWh]
Argentina	750	17,625
Brazil	336	76,646
Uruguay	198	937

Generation

The generation fleet assumed in this first Variant is basically the same as the one considered in the final optimal interconnected scenario (paragraph 3.3.4.6), with the transition towards a "carbon-free" generation in Argentina, Brazil and Uruguay, considered to minimize GHG emission. The coal power plants have been removed and tentatively replaced by equivalent VRES power plants or with Natural Gas power plants in case the increase of VRES plants is not sufficient to substitute all of them keeping a suitable level of generation adequacy.

The amount of coal plants to be replaced is 240 MW in Argentina and about 3,460 MW in Brazil.

Electric storage systems

Also the need of storage systems has been evaluated, to increase the flexibility of the overall system, reducing the constraints on the minimum production and increasing also the ability to cope with the peak load. With reference to the hydro power plants, the higher flexibility has been obtained considering an increased installed power in some specific plants as indicated in the SRG/ANEEL Technical Note No. 026/2011 (Table 46 of paragraph 3.3.2.4) and considering that also run-of-river plants can use their storage capacity, if any, to contribute to production modulation. Moreover, as done in the previous analysis, additional batteries are introduced related to the installation of new VRES power plants.

4.1.1 Reference scenario for Variant 1

The ***Reference scenario for Variant 1*** is defined starting from the scenario with the optimal economic amount of additional VRES with the interconnected countries (paragraph 3.3.4.6).
The ***total amount of VRES*** installed power is indeed:

Table 82 - Total VRES installed power in the reference scenario for Variant 1 [MW]

COUNTRY	AREA	PV installed power [MW]	Wind installed power [MW]
ARGENTINA	NEC	1,100	9,400
	NWE	9,000	300
	PAT	0	5,200
	Total	***10,100***	***14,900***
URUGUAY	UTE	230	2,050
	Total	***230***	***2,050***
BRAZIL	N	1,460	670
	NE	8,470	28,990
	SE/CO	10,590	30
	S	0	11,910
	Total	***20,520***	***41,600***

The ***demand is increased of 8%*** taking into account also the ***high electric vehicles penetration*** (increased load during the night in Buenos Aires, Sao Paulo, Rio de Janeiro and Montevideo areas). ***Coal plants*** present in the Argentinian and Brazilian power systems have been ***switched off,*** in order to have a "coal-free" system.
The simulation of this scenario, which becomes the reference for the comparison of results of other simulations, brings to the following results:

- ***EENS*** is around 2.3 TWh, it is about 1.7×10^{-3} of the total load. In the considered conditions, the power system doesn't have an acceptable level of adequacy, due to the increased load and the absence of more than 3,500 MW coal plants.
- ***Overall generation costs*** are close to 22,370 M$; there is an increase of the costs of about 43% respect to the final optimal scenario. This increase is due to both increased load and higher cost of generation used respect to the coal.
- Expected ***generation by PV*** power plants is close to 65 TWh (higher than the PV production in the final optimal scenario). The reduction of PV curtailments respect to the final optimal scenario is about 1,200 GWh, thanks to the higher load.
- Expected ***generation by wind*** power plants is close to 230 TWh. The reduction of wind curtailments respect to the final optimal scenario is about 3,900 GWh, thanks to the higher load.

These results suggest that in this scenario there is space for additional VRES installations.

The following Table 83 shows the EENS, expressed as MWh/year, split by area and reason. As expected, the higher load and the lower availability of generation cause a dramatic increase of the EENS compared to the final optimal scenario, and the system doesn't have an acceptable level of adequacy.

EENS due to lack of power or lack of interconnection increases because with a higher load and without the coal power plants there are more conditions in which the generation available in the system or in a specific area is not sufficient to cover the power peak. The EENS due to line overloaded increases since the system is generally more overloaded due to the growth of the demand.

This scenario cannot be deemed a description of a real behavior of a power system, but is to be taken as reference for the assessment of the benefits deriving by the introduction of additional VRES.

Table 83 - Expected Energy Not Supplied - Reference scenario for Variant 1

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	2,865	623	145	3,633
NEC	58	2,292	0	2,350
PAT	0	0	0	0
N	3,386	360	296,165	299,911
NE	31,019	24,868	434,728	490,615
SE/CO	121,293	104	1,337,820	1,459,217
S	2	3	0	5
UTE	65	238	0	303
TOTAL	**158,688**	**28,488**	**2,068,858**	**2,256,034**

Table 84 shows the total energy produced in each area and the related costs. In this reference scenario of the first variant overall generation costs are around 22,371 M$/year in the whole system (Argentina, Brazil and Uruguay), with a growth of 43% with respect to the final optimal scenario. This is due to the higher load and to the replacement of the coal plants with the more expensive.

Table 84 - Total production and fuel costs – Reference scenario for Variant 1

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NWE	54,156	1,884	39	-475	835	48
NEC	187,805	6,993	0	-1,883	1,346	9
PAT	30,925	116	276	-380	5	-5
N	141,555	1,072	269	-14	74	28
NE	233,195	2,131	1,769	-566	221	17
SE/CO	481,866	7,210	0	-79	826	104
S	234,991	2,448	0	-974	421	116
UTE	12,886	189	0	-43	686	12
SALTO GRANDE	8,547	0	1	0	0	0
TOTAL	1,385,926	22,042	2,354	-4,414	4,414	329

The following table shows PV generation and curtailments for each area of the system. Total production is nearly 65,000 GWh/year. The curtailed energy, which in the scenario with standard load was about 1,750 GWh, drops down to 500 GWh. This is due to the fact that with a higher load more generators are in service and also less constrained to the minimum when the PV production is high, providing more flexibility to the overall system.

Table 85 - Total production of PV plants – Reference scenario for Variant 1

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	21,946	38	-13	0	2,431
NEC	2,083	0	-4	0	1,891
PAT	0	0	0	0	-
N	3,046	69	0	0	2,045
NE	17,758	292	-86	0	2,051
SE/CO	19,820	0	-1	0	1,872
S	0	0	0	0	-
UTE	345	0	0	0	1,505
TOTAL PHOTOV. GENER.	**64,998**	**399**	**-104**	**0**	**2,091**

The wind production is reported in Table 86. The annual wind production reaches nearly 230,000 GWh/year and still there are conditions with risk of curtailments up to about 2,400 GWh/year (almost one third with respect to the optimal economic scenario).

Table 86 - Total production of Wind plants – Reference scenario for Variant 1

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	775	1	0	0	2,563
NEC	38,960	0	-323	0	4,107
PAT	23,479	276	-270	0	4,442
N	2,554	33	0	0	3,758
NE	115,632	1,478	-78	0	3,935
SE/CO	102	0	0	0	3,636
S	43,189	0	-1	0	3,626
UTE	5,761	0	-14	0	2,796
TOTAL WIND GENER.	**230,452**	**1,788**	**-686**	**0**	**3,895**

The following Figure 26 provides a visual summary of the operation of the Argentinian, Brazil and Uruguay in the reference scenario for Variant 1, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

Brazil import a great amount of energy from the other countries, as it has a strong lack of power. International exchanges are saturated for nearly 6,000h /year.

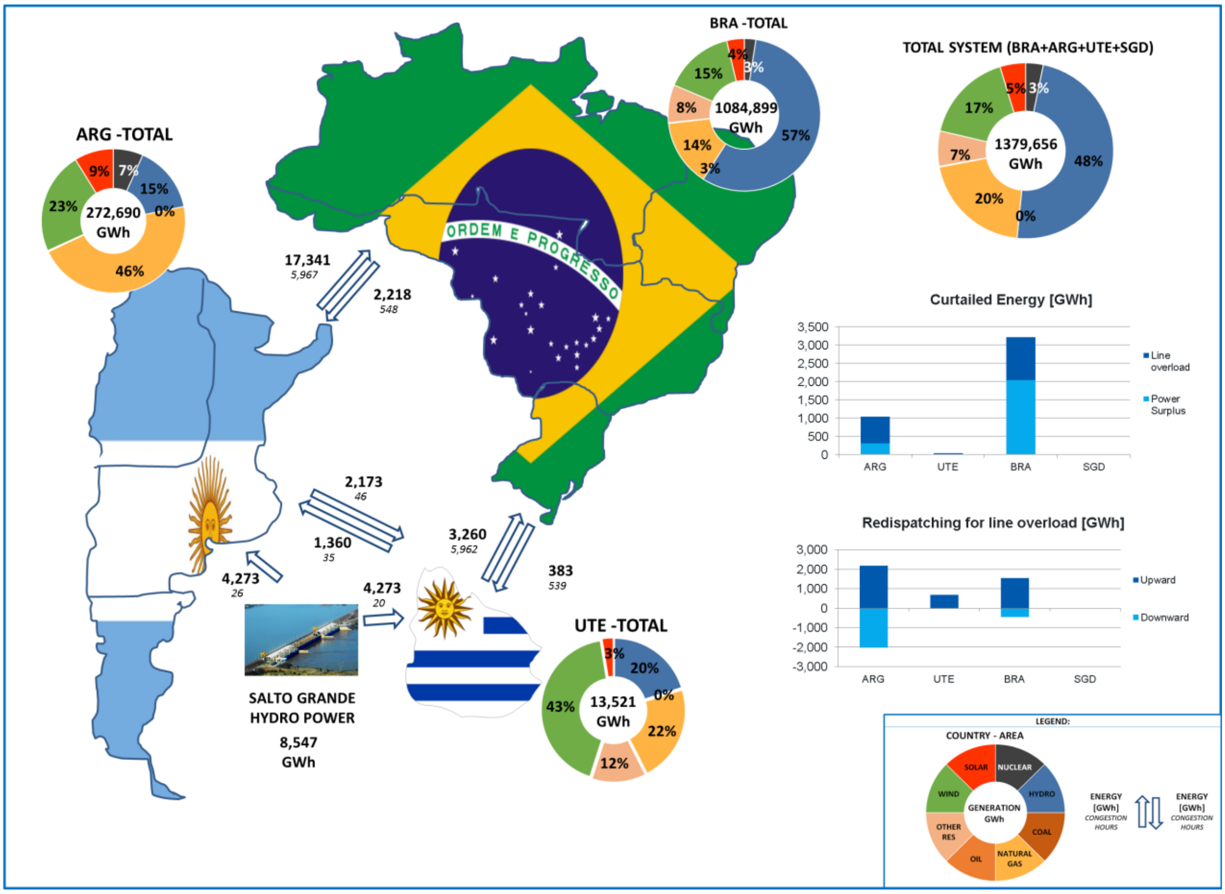

Figure 23 - Total production and energy exchanges – Reference scenario for Variant 1

4.1.2 *Scenario V1a: additional VRES*

A new optimal configuration with ***additional VRES power plants*** has been evaluated: 17,500 MW of PV power plants and 22,000 MW of wind power plants are added because the higher load in Variant 1 requires more generation and makes profitable the introduction of these new VRES. Moreover 6,140 MW of storage system has been considered.
The amount of additional VRES has been calculated and divided between the countries and areas considering the load increase, the lack of generation due to the switch-off of the coal plants and system constraints highlighted in previous analyses.
The Table 87 sums up the additional VRES installed in this scenario. The highest share of new plants is in Brazil, which suffers the highest EENS.

Table 87 - Additional VRES installed power in Variant 1a [MW]

COUNTRY	AREA	Additional PV power plant [MW]	Additional wind power plant [MW]
ARGENTINA	NEC	300	1,200
	NWE	1,200	0
	PAT	0	300
	Total	***1,500***	***1,500***
URUGUAY	UTE	0	500
	Total	***0***	***500***
BRAZIL	N	3,000	1,000
	NE	5,000	9,000
	SE/CO	8,000	0
	S	0	10,000
	Total	***16,000***	***20,000***

The simulation of this scenario, leads to the following results:
- ***EENS*** is around 247.8 GWh; it is about 1.9×10^{-4} of the total load.
- ***Overall generation costs*** are close to 13,703 M$; the thermal costs decrease by 8,668 M$ thanks to the higher VRES generation.
- Expected ***generation by PV*** power plants is close to 98 TWh, about 33 TWh more than the one in the reference scenario. The production curtailments are about 5,400 GWh.
- Expected ***generation by wind*** power plants is close to 300 TWh, nearly 70 TWh more than the one in the reference scenario. The production curtailments are about 18,000 GWh.

Almost all the load increase can be supplied by the additional VRES introduces, but they are not able to ensure a good adequacy to the system. Above the considered amount of new plants, the risk of curtailments becomes too high and the VRES not profitable anymore.

Table 88 shows the EENS, expressed as MWh/year, split by area and reason. The results shows that with respect to the reference scenario the considered additional VRES generation reduces the values of EENS in all three considered countries, in particular in the Argentinian and Uruguayan power systems.

However, the Brazilian system still presents high value of EENS and it doesn't have a good level of adequacy.

Table 88 - Expected Energy Not Supplied - scenario V1a

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	93	48	104	245
NEC	0	94	0	94
PAT	0	0	0	0
N	0	29	25,081	25,110
NE	509	2,791	57,311	60,611
SE/CO	2,704	9	158,985	161,698
S	0	2	0	2
UTE	0	1	0	1
TOTAL	**3,306**	**2,974**	**241,481**	**247,761**

Table 89 shows the total energy produced in each area and the related costs. Respect to the reference scenario there is a reduction of 8,668 M$ thanks to the higher VRES generation which replaces expensive thermal generation.

Table 89 - Total production and fuel costs – scenario V1a

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NWE	50,777	1,491	542	-266	690	44
NEC	170,276	5,646	1	-1,927	2,293	89
PAT	31,320	74	809	-442	6	-3
N	143,439	842	2,805	-47	30	3
NE	251,923	1,207	17,501	-747	89	-3
SE/CO	457,243	3,560	0	-149	748	43
S	261,541	587	1,096	-961	50	11
UTE	12,886	189	0	-43	686	12
SALTO GRANDE	8,488	0	58	0	0	0
TOTAL	**1,388,086**	**13,515**	**22,818**	**-4,639**	**4,639**	**188**

In the Table 90 and Table 91 the PV and wind production are reported. Compared to the reference scenario for this Variant, there is a significant increase, about +50% and +30% respectively. Also the curtailments increase considerably, up to about three times, but still the VRES remain profitable because they replace more expensive generation with respect to the previous case.

Table 90 - Total production of PV plants – scenario V1a

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	24,377	536	-41	0	2,332
NEC	2,649	0	-8	0	1,887
PAT	0	0	0	0	-
N	8,328	1,206	0	0	1,598
NE	25,306	3,369	-233	0	1,611
SE/CO	36,930	0	-4	0	1,987
S	0	0	0	0	-
UTE	344	0	0	0	1,501
TOTAL PHOTOV. GENER.	97,934	5,111	-286	0	1,914

Table 91 - Total production of Wind plants – scenario V1a

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	769	7	-3	0	2,513
NEC	43,970	1	-746	0	4,075
PAT	24,326	809	-368	0	4,484
N	6,005	437	0	0	3,332
NE	139,333	14,132	-287	0	3,288
SE/CO	102	0	0	0	3,636
S	78,356	1,096	-1	0	3,526
UTE	7,308	5	-69	0	3,519
TOTAL WIND GENER.	300,169	16,487	-1,474	0	3,540

Considering the costs and benefits, this scenario present an overall benefit for the whole power system equal to 9.733 M$, of which a big part is due to the reduction of the EENS, which was too high in the starting condition.

Table 92 - Total benefit of the scenario V1a respect to the reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	39,500	-5,290
STORAGE	6,140	-348
ADDITIONAL DISPATCHABLE	-	-
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-98,124	11,355
RES CURTAILMENT	20,429	-
TOTAL EENS	-2,008	4,017
TOTAL BENEFIT	-	9,733

The following Figure 24 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system in the scenario V1a. Compared to the reference scenario of this Variant 1, it is possible to note how Brazil now exports about 2 TWh towards Argentina, covering its demand need. But even in this condition, as explained above, Brazil suffers high EENS which cannot be solved only with VRES.

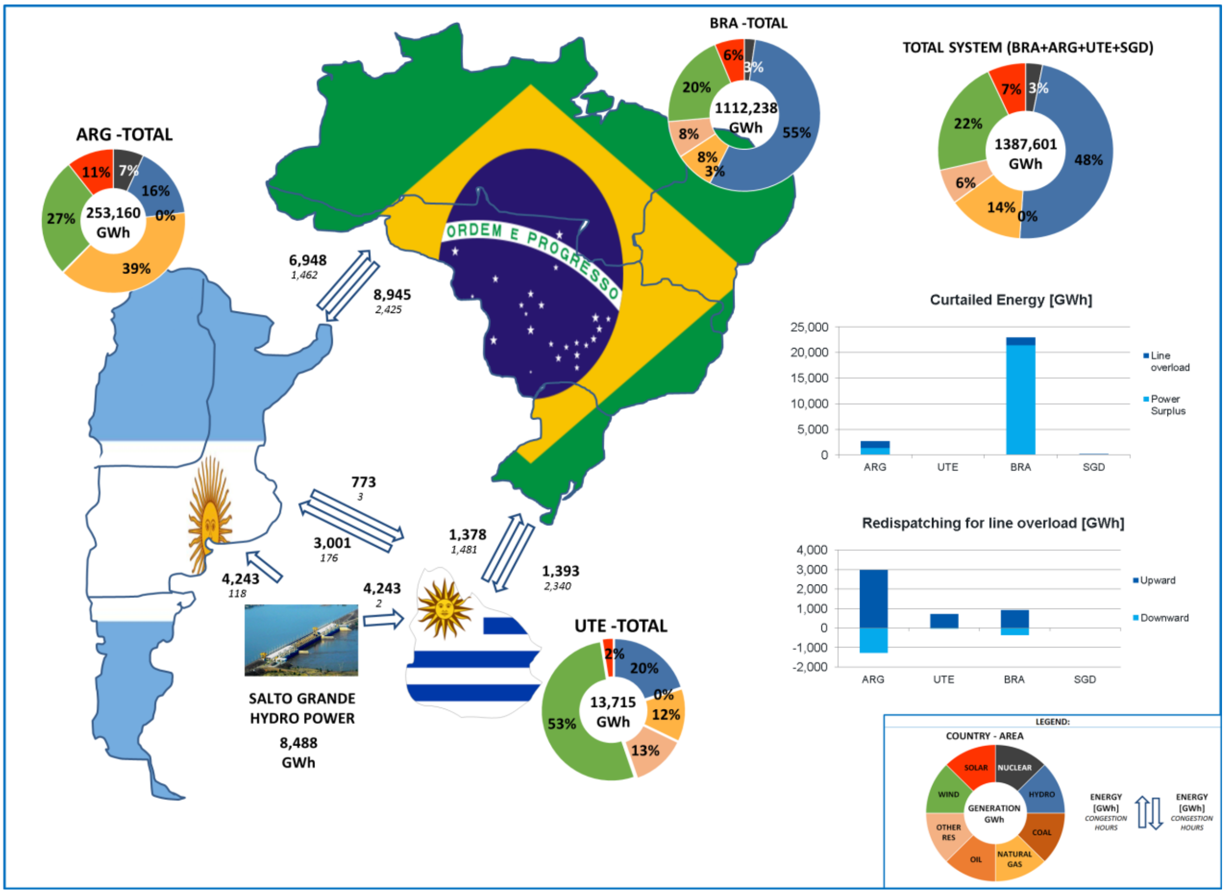

Figure 24 - Total production and energy exchanges – scenario V1a

4.1.3 Scenario V1b: V1a with additional 2,700 MW of OCGT

Starting from the scenario V1a, the possibility to install additional VRES in order to cover the load in the Brazil power system to reduce the value of EENS has been checked.
The results show an increasing of the VRES curtailments without a substantial reduction of EENS.
Therefore, in order to reach a configuration with proper security of supply where the EENS remained high in scenario V1a, in the scenario V1b the installation of flexible thermal generation in the Brazilian power system has been studied: 2,700 MW of OCGT power plant has been considered, as reported in
Table 93.

Table 93 - Additional OCGT power plant considered in the scenario V1b [MW]

COUNTRY	AREA	Additional OCGT power plant [MW]
BRAZIL	N	600
	NE	900
	SE/CO	1,200
	S	0
	Total	***2,700***

The simulation of this scenario leads to the following results:

- ***EENS*** is around 60.5 GWh (it is about 4.7×10^{-5} of the total load), -187 GWh with respect to the scenario V1a;
- ***Overall generation costs*** are close to 13,500 M$.
- Expected ***generation by PV and wind*** power plants is the same one of the scenario V1a. Also the RES curtailments remains equal to the one of the previous case.

Table 94 shows the EENS, expressed as MWh/year, split by area and reason. The results shows that the installation of the 2,700 MW of OCGT reduces the EENS in the Brazilian power system. The main reduction is highlighted in SE/CO area where 1,200 MW of new OCGT have been installed. With the installation of flexible thermal generation the total EENS in Brazil is reduced from 2.25×10^{-4} (V1a scenario) to 5×10^{-5} of the load.

Table 94 - Expected Energy Not Supplied - scenario V1b

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
NWE	24	48	104	176
NEC	0	95	0	95
PAT	0	0	0	0
N	0	24	3,797	3,821
NE	71	2,053	13,993	16,117
SE/CO	409	6	39,903	40,318
S	0	1	0	1
UTE	0	1	0	1
TOTAL	**504**	**2,228**	**57,797**	**60,529**

Comparing this scenario with the reference scenario (Table 95), there is a total benefit for the whole power system higher than 10,500 M$ thanks to the reduction of thermal generation costs and of EENS cost.

Table 95 - Total benefit of the scenario V1b respect to the reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	**MUSD/year**
ADDITIONAL VRES	39,500	-5,290
STORAGE	6,140	-348
ADDITIONAL DISPATCHABLE	2,700	-138
	GWh/year	**MUSD/year**
TOTAL THERMAL GENERATION	-97,848	11,901
RES CURTAILMENT	20,472	-
TOTAL EENS	-2,195	4,391
TOTAL BENEFIT	**-**	**10,516**

Figure 25 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system in the scenario V1b. Exchanges do not differ significantly from the ones resulting in V1a, because the added OCGTs have an important impact on the limitation of EENS, but not on the energy balances of the countries.

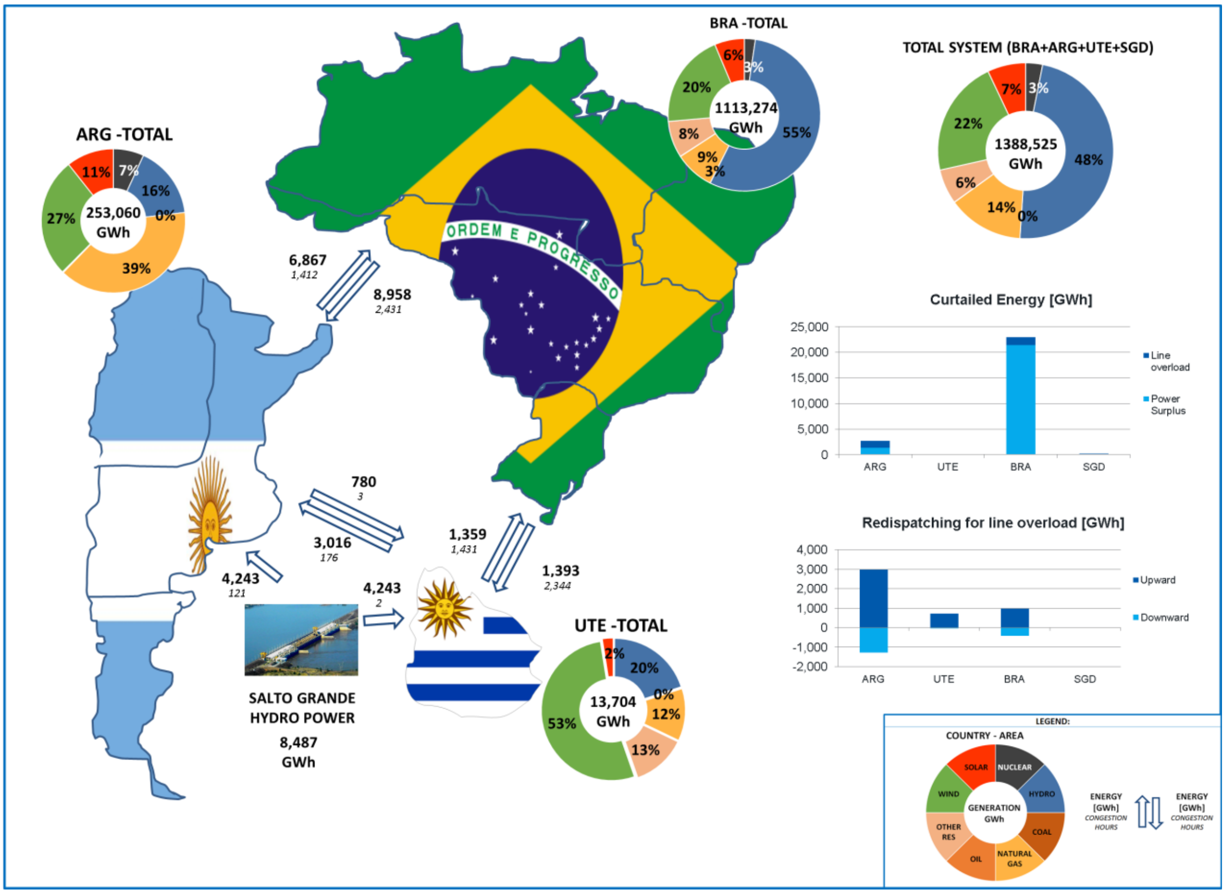

Figure 25 - Total production and energy exchanges – scenario V1b

4.2 Second Variant: enhanced energy efficiency

In the second Variant a lower demand scenario has been considered. The rationale behind a lower demand scenario is related, on the one hand, to the possibility that the economic growth in the countries will not be in line with the forecasts, and on the other hand to the increase of the energy efficiency with respect to what already accounted for in the Reference Scenario, which can reduce the amount of electrical energy needed for specific uses (light, electric motors, industrial processes…).

The key parameters that are modified with respect to the Reference Scenario are described below.

Demand

In this Variant 2 a scenario with lower demand is analyzed. The main drivers which can contribute to a demand lower than the one considered in the previous analyses is a possible lower economic growth of the country and improvement of energy efficiency. According to what defined in [1], the load is reduced 15% in Argentina, 10% in Brazil and 8% in Uruguay. The demand reduction, caused by a general impact of energy efficiency is distributed proportionally in all the regions.

The changes of the demand considered in this Variant 2 are summarized in the following table.

Table 96 - Second Variant - Energy reduction

COUNTRY	Energy reduction [GWh]
Argentina	-34,454
Brazil	-96,228
Uruguay	-1,135

It is worth noting that the reduction of the demand in Brazil is equal to about 100 TWh, which represents a very big amount of energy, equivalent to the theoretical generation of about 11 GW for all the 8760 hours in a year. Even if very big in absolute value, this reduction it is possible thanks to investments in energy efficiency (EPE proposes more than 4% electricity savings in 2026 which can be extrapolated to more than 5% at 2030) and a lower economic growth (a reduction of 5% load from today to 2030 correspond to a reduction of the of the growth by about 0.4% year-to-year).

<u>Generation</u>

The generation fleet assumed in the Variant 2 is the same as the one considered in the reference scenario of the each single country (respectively described in chapters 3.3.1.1, 3.3.2.1 and 3.3.3.1). In particular, the amount of VRES installed power included in the starting conditions is listed in Table 97.

Table 97 - Second Variant - Installed PV and Wind power in the starting condition [MW]

COUNTRY	PV	Wind
Argentina	5,000	5,000
Brazil	9,650	28,500
Uruguay	230	1,550
Total	**14,880**	**35,050**

4.2.1 Reference scenario for Variant 2

Reference scenario for Variant 2 is defined by the interconnected scenario with lower demand and with a generation fleet equal to the one considered in the reference scenario of the each single country.

The ***demand is reduced*** by 15% in Argentina, 10% in Brazil and 8% in Uruguay, simulating a possible lower economic growth and the impact of energy efficiency on the power system.

The simulation of this scenario, which becomes the reference for the comparison of results of other simulations, brings to the following results:

- ***Optimal adequacy of the whole power system***, with value of EENS null in all the considered countries. This is due to the fact that the considered generation fleet, sized on the higher load, is adequate to cover the lower load demand.
- ***Overall generation costs*** are close to 11,160 M$, which include the costs due to redispatching to solve overloads equal to 3 M$.
- Expected ***generation by PV*** power plants is 30.4 TWh. The PV curtailments are equal to 215 GWh/year.
- Expected ***generation by wind*** power plants is 132.5 TWh. The wind curtailments are equal to 4,850 GWh/year.
- An already significant curtailment of hydroelectric production (more than 5 TWh) is present in Brazil, due to the high amount of hydro installed power and huge availability of hydro resource.

In Reference scenario for Variant 2, EENS is null in every areas of the considered network, due to the lower value of load demand with respect to the considered generation fleet. In this scenario, there is always generation available to cover the load and to solve transmission congestions.

Table 98 shows the total energy produced in each area and the related costs. Generation costs are around 11,168 M$/year in the whole system (Argentina, Brazil and Uruguay). Some overgeneration conditions are already present in N and NE areas, due to the strong presence of hydropower and VRES plants and the low demand.

Table 98 - Total production and fuel costs – Reference scenario for Variant 2

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NWE	37,977	1,362	2	-24	62	3
NEC	133,198	5,447	0	-69	59	0
PAT	18,688	102	1	-7	1	0
N	126,380	832	5,817	-7	1	0
NE	182,336	921	4,855	-44	17	0
SE/CO	417,659	1,956	0	-18	24	1
S	206,858	451	6	-4	1	0
UTE	10,016	94	0	-43	50	-1
SALTO GRANDE	8,549	0	0	0	0	0
TOTAL	**1,141,661**	**11,165**	**10,681**	**-216**	**215**	**3**

The following table shows PV generation and curtailments for each area of the system. Total production is greater than 30 TWh/year. The curtailed energy is equal to 215 GWh/year, concentrated in N and NE area as described above.

Table 99 - Total production of PV plants – Reference scenario for Variant 2

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	12,197	2	-5	0	2,439
NEC	44	0	0	0	2,458
PAT	0	0	0	0	-
N	170	34	0	0	1,427
NE	3,563	170	-4	0	1,936
SE/CO	14,114	0	0	0	1,810
S	0	0	0	0	-
UTE	345	0	0	0	1,505
TOTAL PHOTOV. GENER.	**30,433**	**206**	**-9**	**0**	**2,030**

The wind production is reported in Table 100. The annual wind production reaches more than 130 TWh/year and the amount of curtailed energy is about 4,840 GWh/year.

Table 100 - Total production of Wind plants – Reference scenario for Variant 2

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	776	0	0	0	2,570
NEC	9,099	0	0	0	3,702
PAT	10,034	1	0	0	4,600
N	785	141	0	0	2,680
NE	91,356	4,686	-4	0	3,645
SE/CO	102	0	0	0	3,636
S	16,060	5	0	0	3,624
UTE	4,360	0	-10	0	2,797
TOTAL WIND GENER.	**132,572**	**4,833**	**-14**	**0**	**3,652**

The following Figure 26 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system in the reference scenario for Variant 2. Brazil has abundance of generation, due to hydro resource (hydropower plants produce more htan 600 TWh) and already included VRES, so there a significant export towards the other countries and risk of generation curtailments higher than 10 TWh to avoid overproduction situations.

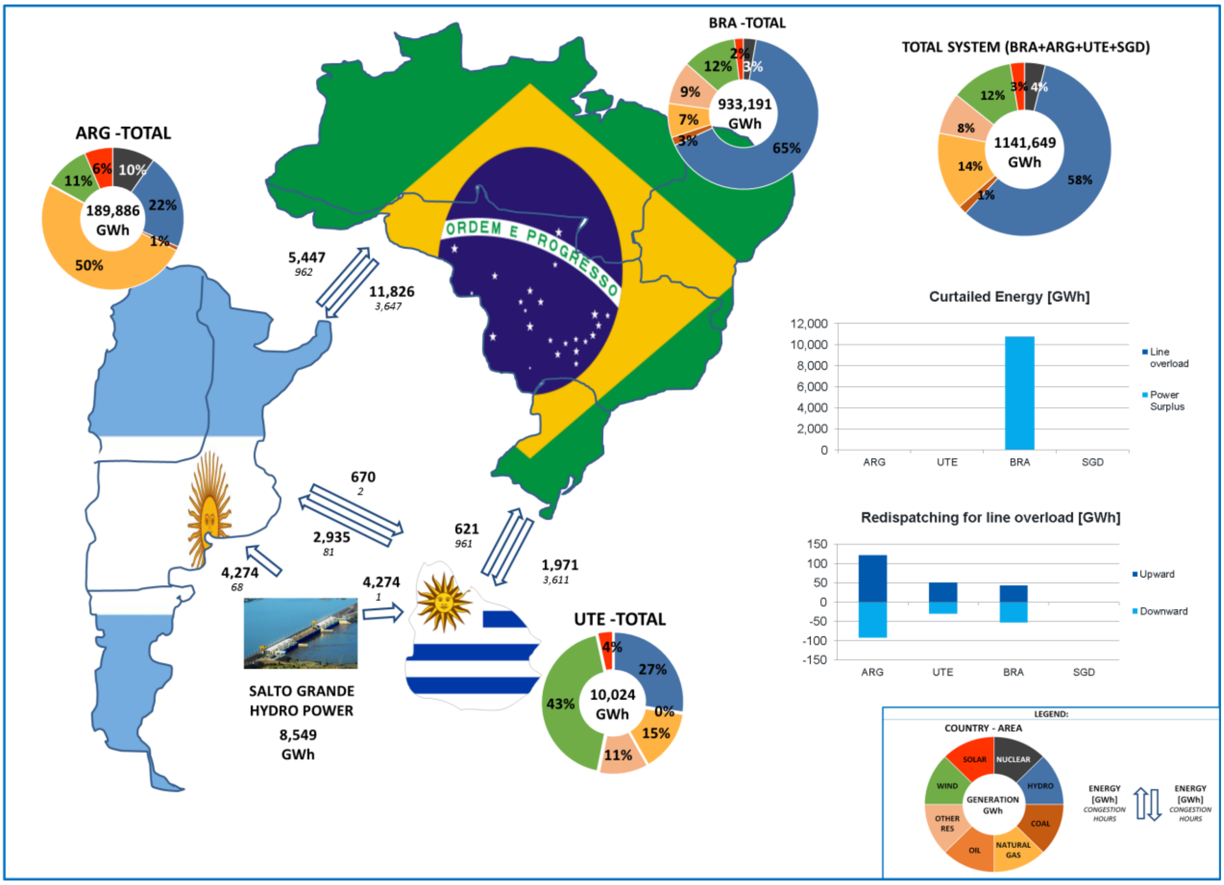

Figure 26 - Total production and energy exchanges – Reference scenario for Variant 2

4.2.2 Scenario V2a: additional VRES

The optimal amount of ***additional VRES power plants*** has been calculated: only 1,000 MW of PV power plants and 3,500 MW of wind power plants are added together with 620 MW of storage system in Argentina and Uruguay. Due to the high hydro resource availability and low demand, there is no convenience to install further VRES in Brazil, in addition to the 38 GW already present. The Table 101 sums up the additional VRES installed in this scenario.

Table 101 - Additional VRES installed power in Variant 2a [MW]

COUNTRY	AREA	Additional PV power plant [MW]	Additional wind power plant [MW]
ARGENTINA	NEC	0	1,500
	NWE	1,000	0
	PAT	0	1,500
	Total	***1,000***	***3,000***
URUGUAY	UTE	0	500
	Total	***0***	***500***
BRAZIL	N	0	0
	NE	0	0
	SE/CO	0	0
	S	0	0
	Total	***0***	***0***

The simulation of this scenario, leads to the following results:

- ***Optimal adequacy of the whole power system***, the EENS remains null as in the reference scenario.
- ***Overall generation costs*** are close to 10,350 M$; the thermal costs decrease by 812 M$ with respect to the reference scenario thanks to the added VRES generation.
- Expected ***generation by PV*** power plants is close to 32,800 GWh. The production curtailments are about 263 GWh (+48 GWh respect to the reference case).
- Expected ***generation by wind*** power plants is close to 146,900 GWh. The production curtailments are about 5,108 GWh (+268 GWh respect to the reference case).

At the end of the optimization process aimed at defining the amount of VRES which is convenient to add in the system in the reduced load Variant, it turns out that this quantity is limited to 1,000 MW PV and 3,500 MW wind distributed in Argentina and in minor part in Uruguay. The introduction of this additional VRES generation does not affect the security of supply in the system, and EENS remain null everywhere. Table 102 shows the total energy produced in each area and the related costs. Respect to the reference scenario there is a reduction of 812 M$ thanks to the additional VRES generation.

Table 102 - Total production and fuel costs – scenario V2a

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
NWE	38,218	1,226	35	-37	84	4
NEC	130,004	4,963	0	-68	129	3
PAT	25,359	92	63	-18	3	0
N	125,776	810	5,910	-14	1	0
NE	181,645	892	5,031	-50	13	0
SE/CO	415,689	1,856	0	-36	16	0
S	206,711	442	6	-12	1	0
UTE	10,846	61	0	-74	63	0
SALTO GRANDE	8543	0	7	-1	0	0
TOTAL	**1,142,791**	**10,341**	**11,052**	**-310**	**310**	**7**

In the Table 103 and Table 104 the PV and wind productions are reported, which increase in the areas where additional plants have been introduced. Also the curtailments due to overgeneration conditions increase slightly.

Table 103 - Total production of PV plants – scenario V2a

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	14,605	34	-14	0	2,427
NEC	44	0	0	0	2,458
PAT	0	0	0	0	-
N	169	35	0	0	1,406
NE	3,556	177	-3	0	1,928
SE/CO	14,114	0	0	0	1,810
S	0	0	0	0	-
UTE	345	0	0	0	1,505
TOTAL PHOTOV. GENER.	**32,833**	**246**	**-17**	**0**	**2,050**

Table 104 - Total production of Wind plants – scenario V2a

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
NWE	775	1	0	0	2,563
NEC	15,362	0	0	0	3,881
PAT	16,873	63	-3	0	4,566
N	783	144	0	0	2,659
NE	91,188	4,853	-3	0	3,631
SE/CO	102	0	0	0	3,636
S	16,060	5	0	0	3,624
UTE	5,761	0	-36	0	2,785
TOTAL WIND GENER.	146,904	5,066	-42	0	3,686

Considering the costs and benefits, this scenario presents an overall advantage for the whole power system equal to 39 M$.

Table 105 - Total benefit of the scenario V2a respect to the reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	4,500	-740
STORAGE	620	-40
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-15,399	819
RES CURTAILMENT	313	-
TOTAL EENS	0	0
TOTAL BENEFIT	-	39

The amount of additional VRES plants in this Variant 2 is limited with respect to the optimal quantity resulting in the Base Case because the demand has been lowered in the whole system by more than 130 TWh while the generation fleet has been kept the same, with the same hydro resource. This results in a higher availability of generation, and in particular cheap one by hydroelectric power plants, which reduces the need of further plants and limits the convenience to have more VRES.

However it is important to highlight that in the optimal configuration of Variant 2, almost 55 GW of PV and wind plants are present in the system, which represent a value much higher than today situation.

Moreover, it is possible that especially in Brazil some non-VRES power plants (thermal, hydro, biomass…) considered in the generation fleet foreseen at 2030 will not be developed because not profitable in a scenario of lower demand growth (as they would be operated a lower number of hours) or because might incur difficulties during authorization process. In this case, VRES plants can become again a preferable solution to replace traditional generation, or to reduce environmental issues which for instance might affect big hydroelectric power plants. Flexibility and modularity of the VRES plants also

constitute positive characteristics in this context because allow the development and construction of generation facilities of different sizes which can better fit the needs of different areas. And finally, it is worth mentioning that also the shorter time required for the realization of VRES plants with respect to other technologies might become an advantage for PV and wind, because it allows to define more flexible generation development plans which can be adjusted depending on the demand growth in the areas and the development of the transmission grid. Moreover, it is worth mentioning that the development of the generation fleet, even in a scenario with lower increase of the load, should remain balanced with a mix of technologies and sources that will allow the operational conditions to meet the energy load, modulation for intermittence and peak of demand.
In a context with high uncertainties relevant to the evolution of the demand in the next years, the flexibility and the shorter installation time of VRES plant, together with competitive LCOE, can be key factors which might foster the VRES penetration even in low demand growth scenario.

Figure 27 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system in the scenario V2a. Argentina and Uruguay increase their internal production, and consequently there is a lower energy flow from Brazil to the other countries.

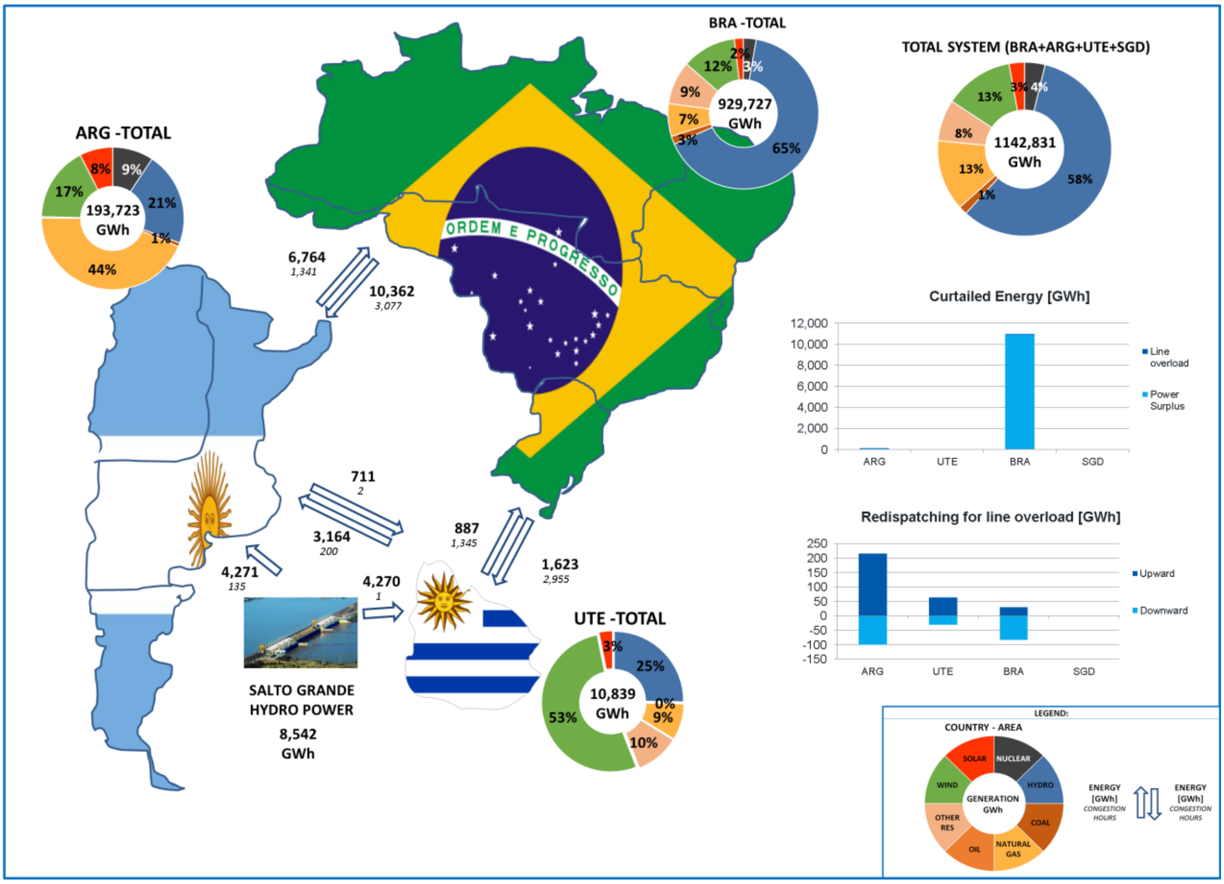

Figure 27 - Total production and energy exchanges – Scenario V2a

4.2.3 Scenario V2b: additional VRES in Argentinian system

From the results of the scenario V2a (Figure 27), it is possible to note that the Argentinian system import more than 6 TWh, in particular from Brazil which has a high hydro production availability, and from Uruguay, which also has a positive energy balance.

Argentina might then be interested to increase its internal production installing additional VRES power plants to reach higher independency from the other countries.

To this aim, a scenario with ***additional VRES power plants installed*** in the Argentina has been simulated to assess the economic impact of this decision.

Table 101 sums up the additional VRES, respect to the reference scenario, considered in V2b scenario with respect to the Reference case for this Variant.

Table 106 - Additional VRES installed power in Variant 2b [MW]

COUNTRY	AREA	Additional PV power plant [MW]	Additional wind power plant [MW]
ARGENTINA	NEC	800	5,100
	NWE	2,900	0
	PAT	0	2,200
	Total	***3,700***	***7,300***
URUGUAY	UTE	0	500
	Total	***0***	***500***
BRAZIL	N	0	0
	NE	0	0
	SE/CO	0	0
	S	0	0
	Total	***0***	***0***

The simulation of this scenario, leads to the following results:

- ***Optimal adequacy of the whole power system***, the EENS remains null as in the reference scenario.
- ***Overall generation costs*** are close to 9,500 M$; the thermal costs decrease by 1,677 M$ respect to the reference scenario thanks to the added VRES generation.
- Expected ***generation by PV*** power plants is close to 38,500 GWh. The production curtailments are about 765 GWh.
- Expected ***generation by wind*** power plants is close to 164 TWh. The production curtailments are about 6 TWh.
- The net power exchanges between Argentina and the other countries are balanced: the Argentina import about 1.2 TWh from Uruguay and export about 1.1 TWh to Brazil.

The scenario V2b represents a situation where the Argentinian power system, installing 11,000 MW of VRES power plants, reaches the energy independency respect to the scenario V2a. Indeed, considering the power balance of the scenario V2a the Argentina imports about 3.6 TWh from Brazil and about 2.5 TWh from Uruguay. In the scenario V2b the Argentinian power system reaches an almost net balance

exchange with the neighboring countries, as it imports 1.2 TWh from Uruguay but exports a similar energy amount towards Brazil.
From the economic point of view, as reported in Table 107, this scenario presents an overall cost of 126 M$ for the whole system. This demonstrates that if the power systems are operated in a coordinated way exploiting the interconnection capacity, there might be savings in terms of avoided investments in new generation which also cause the risk of generation curtailments to increase

Table 107 - Total benefit of the scenario V2b respect to the reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	11,500	-1,830
STORAGE	1,676	-108
ADDITIONAL DISPATCHABLE	-	-
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-37,034	1,812
RES CURTAILMENT	1,952	-
TOTAL EENS	0	0
TOTAL BENEFIT	**-**	**-126**

The Figure 28 provides a visual summary of the operation of the Argentinian, Brazilian and Uruguayan power system in the scenario V2b. It is possible noting that the additional 2 TWh curtailed energy are not limited only to the Argentinean System, but have an impact also on the Brazilian one, because when there is overgeneration in the whole system, generators in all the areas have to be reduced. In an interconnected system, the development of the generation in one country can have an impact on the others, as the possibility to exchange energy might be affected by the presence of the new plants, even if the transmission system is not modified.

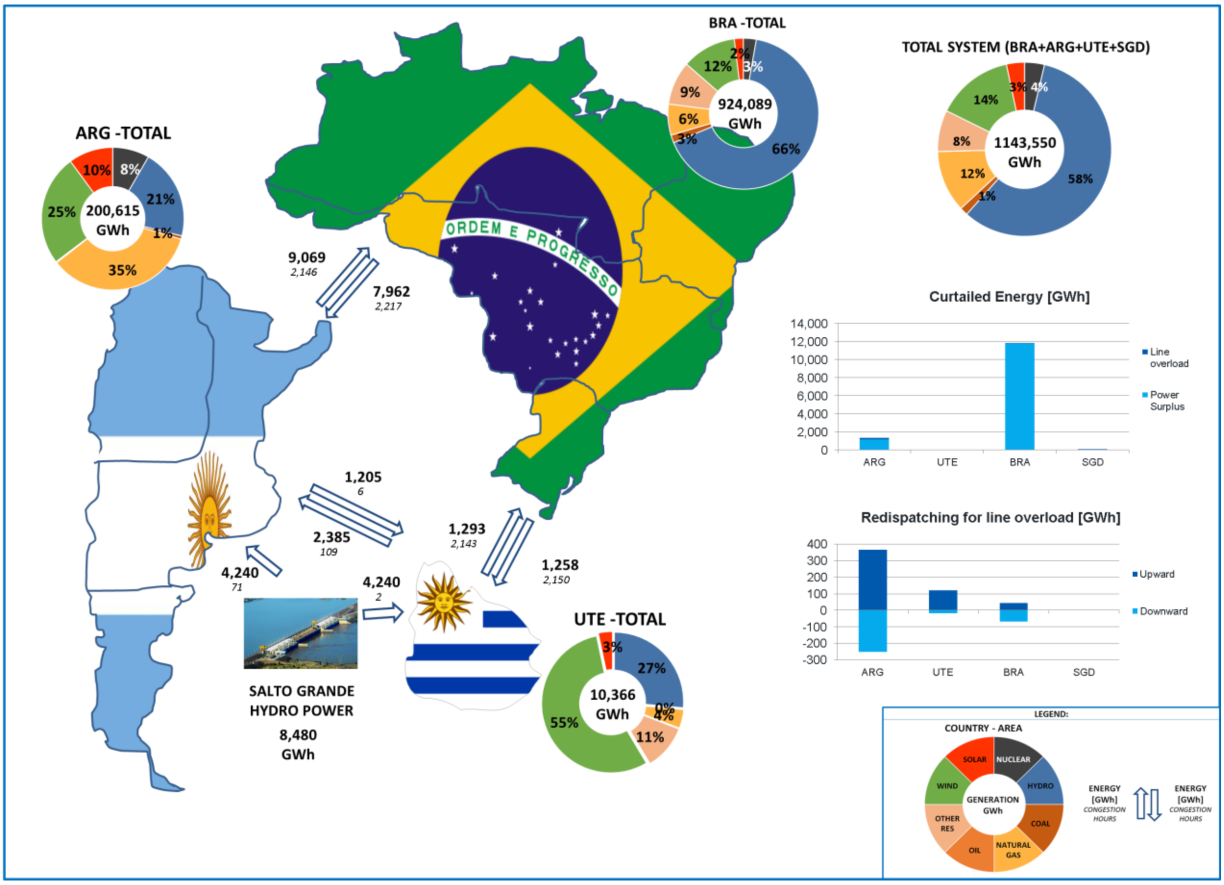

Figure 28 - Total production and energy exchanges – Scenario V2b

4.3 Conclusions on Variants

Two Variants have been examined, characterized by higher or lower load and the differences in the generation fleet, to verify how the optimal amount of VRES plants defined in Chapter 3 can be modified in case significant changes in the systems take place.

It the Variant with higher load, the demand increase can be substantially covered by VRES production, which is also able to replace the production of the coal power plants assumed as shut down. Additional 17,500 MW of PV power plants and 22,000 MW of wind power plants are introduced in the systems, which allow the overall VRES plants to cover almost 30% of the load in the system. However, the security of supply worsens, and EENS reaches about $2x10^{-4}$ of the total load, mainly in Brazil. To reduce this value below an acceptable level, it is necessary to introduce thermal generation which must be available when there would lack of power due to unavailability of other resources. With 2,700 MW OCGT distributed in Brazilian areas, the system shows a proper security of supply, optimizing the investments.

In the Variant with lower load, there is a significant excess of generation already in the reference case, as the generation fleet is kept the same as in the Base Case, and in particular the hydropower resource in Brazil becomes able to cover alone more than two thirds of the Brazilian demand. In this condition, the optimal amount of VRES to be installed is very limited (4,500 MW), and distributed only in Argentina and Uruguay, because there is no economic convenience to install new VRES plants in Brazil and compete with cheap energy as the one produced by hydropower plants. In this optimal scenario, Brazil tends to export the excess of energy, and Argentina imports about 6 TWh. Argentina might reduce the need for

import installing additional 7,000 MW of PV and wind plants, but this would represent a cost for the whole system, as new investments would be required and cheap generation be not exploited.
The optimal amount of PV and wind plants would increase especially in Brazil in case some of the non-VRES power plants (thermal, hydro, biomass…) considered in the generation fleet foreseen at 2030 will not be developed because not profitable in a scenario of lower demand growth (as they would be operated a lower number of hours) or because might incur difficulties during authorization process. In such a context, flexibility, modularity and shorter installation time of VRES plants with respect to other technologies, in addition to the competitive LCOE, might represent positive characteristics which can foster the penetration of PV and wind plants in the generation development plan also in a lower demand scenario.

5 LOAD FLOW ANALYSES IN SELECTED SNAPSHOTS

At the end of the activity during which the operation of the system has been analyzed with a probabilistic approach, simulating thousands of different operating conditions which might actually happen during a year, some Load Flow calculations have been performed[11], to describe some deterministic snapshots representative of particular situations.

The focus is to highlight some possible critical conditions which might require special countermeasures during the real time operation, and identify whether local reinforcements might be needed.

For this reason, four conditions have been selected among the thousands analyzed in the probabilistic simulations by GRARE, characterized by:

- Low or high load
- Different level of renewable (PV and wind) generation.

For each analyzed scenario, a quick description of the power flows between areas and a list of the most overloaded lines is provided.

No overloads are expected in N condition, as the generation of the different power plants has been derived from the optimized active power dispatching performed by GRARE which already considered the network constraints, but it is expected that the same critical lines highlighted by the probabilistic analysis are operating at their limits also in these analyzed snapshots.

5.1 High load and high VRES production

In this paragraph a situation with high load and high renewable production is presented: in particular, in the selected case the load is about 214 GW and the value of renewable production is nearly to 45 GW. Figure 29 shows the power production of each country and the power flows exchange between them, resulting from the Load Flow calculations. In the Table 108 the power exchanges are summarized.

[11] DC LF have been performed, for sake of consistency with the results obtained in the previous analysis.

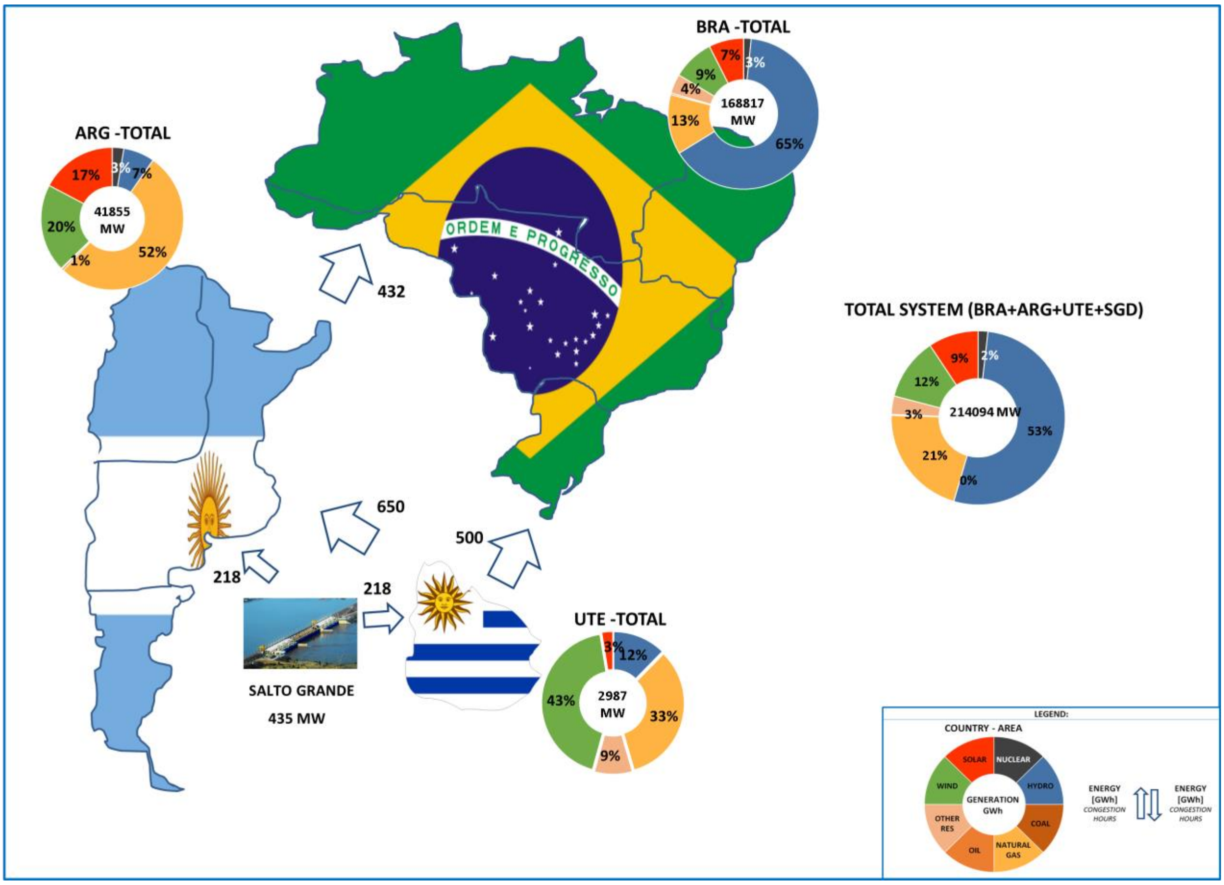

Figure 29 - Static Analysis - Power production and power exchanges with high load and high RES production

Table 108 - Power exchanges between countries

From	To	[MW]
Argentina	Brazil	432
Uruguay	Brazil	500
Uruguay	Argentina	650

As expected, no line is overloaded in sound network condition, as the active power dispatching is obtained by the GRARE optimization which already considered the network constraints.

The most loaded lines are listed in the Table 109: it can be noted that the ones which are at their transmission limit are the lines: Puerto Madryn-Comodoro and Chaco-Monte Quemado in Argentina, Colita-Colina and Xingo-Angel in Brazil. These lines are among the most critical lines already identified during the probabilistic simulations. They are overloaded because they belong to the main corridors which bring the VRES generation form the areas of production towards the main load areas (GBA in Argentina and SE/CO in Brazil). In this condition, Argentina exports parts of its production to Brazil, showing a cheaper generation also due to the high PV and wind contribution.

Table 109 – Most loaded lines

Line	Un [kV]	I [%]
CHACO - MQUEM-CH	500	100
NPMADRYN- PMD.COM2	500	100
COLITACAP500- COLINA-TO500	500	100
XINGO--SE500- ANGEL2-PE500	500	100

5.2 High load and low VRES production

In this paragraph, the result of the Load Flow calculation performed on a situation with high load and low renewable production is presented. The value of load is about 200 GW and the renewable production is close to 32,750 MW. A night case, with no production by PV plants, has been chosen.

Figure 30 shows the power production of each country and the power flows exchange between them, resulting from the Load Flow calculations. In the Table 110 the power exchanges are summarized. It is interesting to note that the direction of some power exchanges has changed with respect to the previous case.

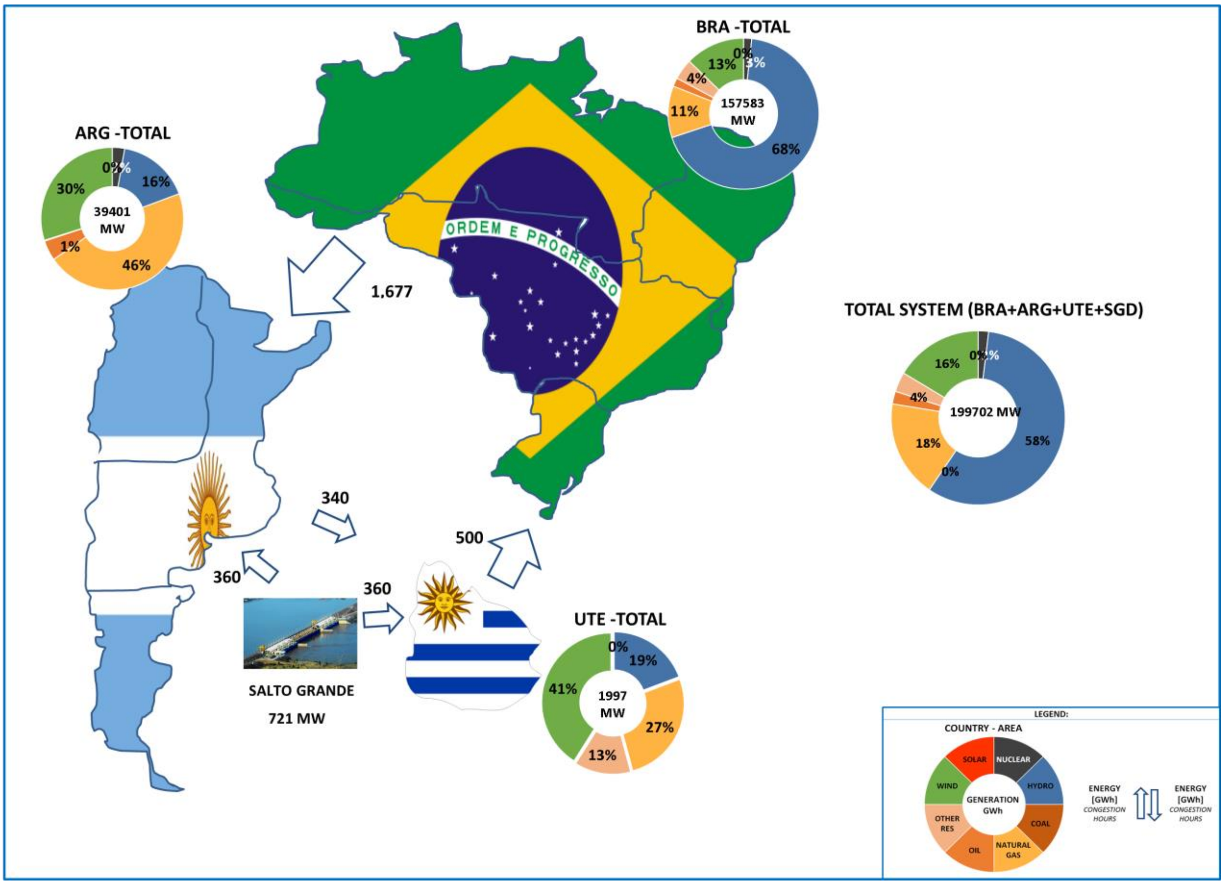

Figure 30 - Static Analysis - Power production and power exchanges with high load and low RES production

Table 110 - Power exchanges between countries

From	To	[MW]
Brazil	Argentina	1.677
Uruguay	Brazil	500
Argentina	Uruguay	340

Also in this case no line is overloaded in sound network condition, as the active power dispatching is obtained by the GRARE optimization which already considered the network constraints. The most loaded lines are in the Argentinian power system: Vivorata-Abasto line at its maximum capacity (which brings the wind production from the coast to GBA), Puerto Madryn-Comodoro line at 99% and Rio Diamante-Los Blancos line at 99%, affected by power flows form PAT to NEC.

Table 111 – Most loaded lines

Line	Un [kV]	I [%]
VIVORATA - ABASTO	500	100
P.MADRYN- COMODORO	500	99
RIO DIAMANTE- LOSBLANCOS	500	99

5.3 Low load and high VRES production

As a third case, the system was analyzed with low load and high renewable production: in particular the selected condition is characterized by a load around 120 GW and the value of renewable production is 40,530 MW.

Figure 31 shows the power production of each country and the power flows exchange between them, resulting from the Load Flow calculations. It is interesting to note that in this case no power exchanges are present between Brazil and Uruguay, and also the exchange between Argentina and Uruguay is very limited.

The analysis in N condition doesn't highlight critical situation, this is due to the low value of the power demand.

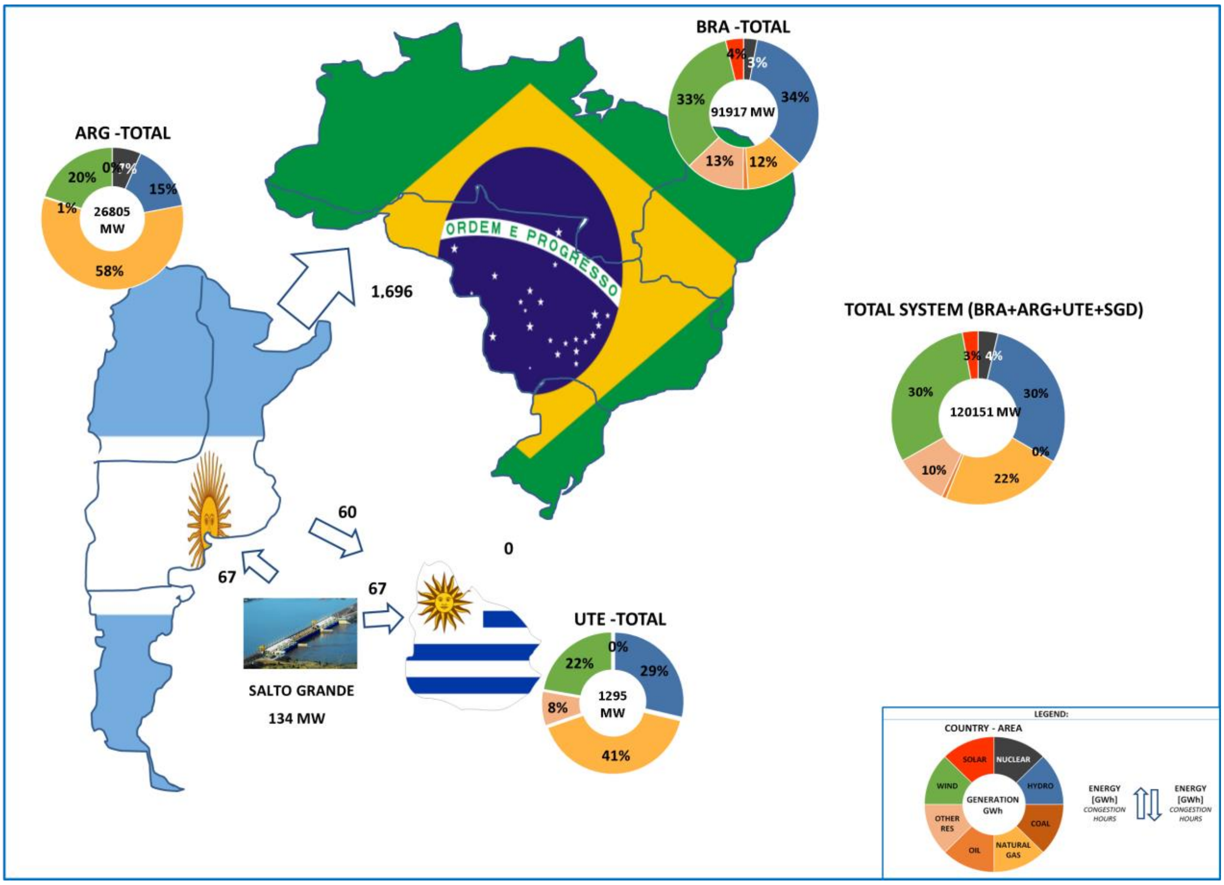

Figure 31 - Static Analysis - Power production and power exchanges with low load and high RES production

Table 112 - Power exchanges between countries

From	To	[MW]
Argentina	Brazil	1696
Brazil	Uruguay	0
Argentina	Uruguay	60

In N condition the only critical line is the 500 kV Colita-Colina loaded at 95%. The other lines are loaded below 90%.

5.4 Low load and low VRES production

The last situation analyzed is characterized by low load and low renewable production: in particular the value of load is a bit higher than 127 GW and the value of renewable production is 30,790 MW.

In this condition, the power exchanges between the different zones are the ones reported in the Table 112 and Figure 32. In this situation the Brazil power system export power to Argentina and Uruguay exploiting the interconnection at the maximum, due to the high production of hydro.

It is interesting noting also that Uruguay has a quite balanced conditions, and only renewable plants (mostly wind) are active to supply the demand.

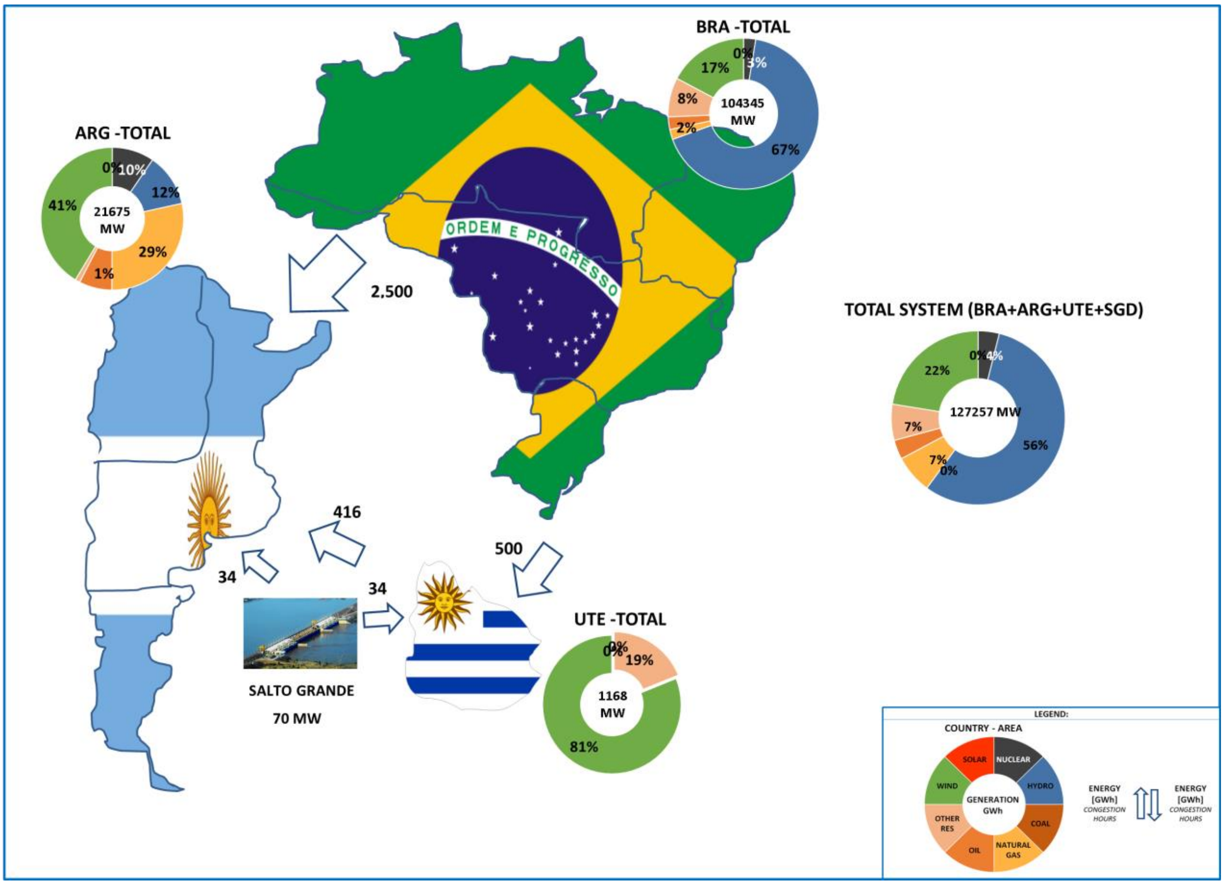

Figure 32 - Static Analysis - Power production and power exchanges in low load and low RES production

Table 113 - Power exchanges between countries

From	To	[MW]
Brazil	Argentina	2500
Brazil	Uruguay	500
Uruguay	Argentina	416

In this snapshot, the only critical loading is the 500 kV line Candio-Melo loaded at 96% in N condition. The other lines are loaded below 90%.

6 CONCLUSIONS

Variable Renewable Energy Sources such as PV and wind have been playing a significant role in the power systems thanks to their technological improvement, which allows increasing the amount of produced energy for a given resource, and the strong cost reductions which makes the produced energy more and more competitive against traditional generation. Moreover, the relatively easy installation of VRES power plants and their scalability increase the advantages of these technologies which can become operative in the power system in a short period.

The analysis carried out in the present study aimed at assessing the optimal amount of VRES plants which can be installed and operated in the year 2030 in Argentina, Brazil and Uruguay considered in a first step as isolated systems and secondly evaluating the advantages which are present when the systems are operated interconnected thanks to the existing and future electrical paths.
In order to increase the penetration of PV and wind plants in the systems, some system operational constraints, such as reserve needs and inertia, have been loosened, assuming that new VRES technologies can actively support the system, sharing the burden usually assigned only to the dispatchable plants. In particular, storage systems have been allocated to new installed VRES plants, aimed at mitigating the variability of their production, which negatively affects the operation of the electric power system, and providing required ancillary services.

Under these assumptions, the optimal solutions in the isolated systems are the following:

- In Argentina, the installation of more than 10,000 MW of PV and nearly 14,000 MW of wind power plants, plus storage systems up to about 2,000 MW represents the optimal economic amount of VRES. These values are respectively 5,000 MW and 9,000 MW higher than the amount foreseen by CAMMESA at 2025. A limited transmission capacities of few 500 kV lines cause VRES production to be curtailed in some conditions to avoid overloads. Improvements of corridors from south to north in PAT and from north to south-west in NWE are then considered, focusing on lines which can increase their transmission capacity with a relatively small investment because it is limited not by the conductors but by some other equipment (such as measuring transformers). The removal of these constraints allows a better exploitation of the VRES plants, reducing curtailments and providing significant benefits in terms of reduced fuel costs to the system.
  The calculated amount of VRES plants is able to cover nearly 35% of the Argentinean load, but to ensure a low EENS in the isolated system it is necessary to introduce also 3,000 MW dispatchable generation which can supply the load when VRES production is not available.
- In Brazil, the optimal solution consists in the installation of 20,500 MW PV and 38,600 MW wind, located in the areas with higher potential, which exceed by respectively 11,000 MW and 10,000 MW the values foreseen by EPE at 2026. An amount of 3,400 MW of storage has been also introduced, even if, due to the particular generation mix in the Brazilian system, strongly dependent on hydropower plants often with huge basins and modulation capacity, the need of electric storage might be reduced by a proper coordination of hydroelectric power plants and VRES production, exploiting the storage capacity of the hydro plants to mitigate the variability of VRES plants.
  This production by PV and wind plants is able to cover about 18% of the load, and VRES become the second source after hydro. There is no need of more dispatchable power plants than the one planned

by EPE at 2026, because the load increase from 2026 to 2030 can be fully covered with the additional VRES plants, keeping a good level of generation adequacy.

- In the Uruguayan isolated system there is no advantage when VRES plants are introduced, due to the small dimension of the country and the presence, in the assumes generation fleet, of an already significant amount of hydropower plants (including the portion of Salto Grande), wind farms (which cover 30% of the load) and a new CCGT just entered in operation. When the system is considered as isolated, the production of these already existing plants is enough to cover the load; as a consequence, the introduction of new VRES is not profitable for the system because often curtailed due to overgeneration conditions, because excess of power cannot be exported to neighboring countries.

Once the optimal solutions for each isolated countries have been defined, the analysis has been focused on the operation of the interconnected system.
The first evaluations have been focused on the definition of the best NTCs between the countries, able to ensure good economic advantages but also not affecting the operational security of the system. It is worth underlining that Argentina and Uruguay are synchronous systems at 50 Hz, while Brazil is operated at 60 Hz and the interconnections with Argentina and Uruguay are constituted by AC/AC converters, able to control the power flow. 1,000 MW are assumed as NTC between Argentina and Uruguay, while from Brazil to Argentina and Uruguay the limits are set at 2,500 MW and 500 MW respectively.
The operation of the interconnected systems brings significant benefits in terms of optimization of the generation (better exploitation of VRES and hydro plants and lower thermal generation costs) and in further improvement of system adequacy, reducing the EENS. In the real operation of the systems, the possibility to exchange energy between the countries must be addressed by a clear regulatory framework, which must set rules, rights and duties of all the involved parties. The more the systems will be operated in a coordinated and flexible way, able to react also to real time events, the more the benefits for the whole system will increase, thanks to the possibility to share the cheapest generation and supply the demand more effectively.
Moreover, thanks to the possibility to exchange energy between the countries and to evacuate excess of power to neighboring countries, Argentina does not require the additional 3,000 MW of dispatchable generation to ensure proper adequacy, because the lack of generation that was present in the isolated system can be compensated with import from the other countries. The removal of the dispatchable generation creates the conditions for the introduction of additional 4,500 MW of wind power plants distributed in the interconnected areas (NEC in Argentina, Sul in Brazil and Uruguay).
Thanks to these new plants, in this final scenario VRES production covers 36% of the demand in Argentina, nearly 20% in Brazil and more than 40% in Uruguay.
The following Table 114 shows the final amount of installed PV and wind power in the different areas, whose production is able to supply the demand increase without requiring any additional thermal generation.

Table 114 - Total VRES installed capacity in final optimal scenario for ARG, BRA and UY interconnected [MW]

COUNTRY	PV installed power [MW]	Wind installed power[MW]	Total VRES [MW]
ARGENTINA	10,100	14,900	25,000
URUGUAY	230	2,050	2,280
BRAZIL	20,520	41,600	62,120
Whole power system	30,850	58,550	89,400

Some sensitivity analyses have been carried out aimed at checking how the power systems with the amount of VRES plants defined in an average scenario operate also in different conditions, with significant variation of the interconnection capacity between some areas or countries or in different hydrological conditions.

When the interconnection capacity between some areas or countries is reduced, because of the absence of a new HVDC between N-NE and SE/CO areas in Brazil or because of the absence of the third interconnection between Argentina and Brazil, the main effect is a negative impact on the generation costs which increase due to the usage of more expensive generation and the higher VRES and hydro curtailments. The reduction of the NTC between Argentina and Brazil increases also the EENS, as predictable when considering that Argentina isolated didn't reach a good adequacy and required additional dispatchable generation.

The operation of the interconnected system in different hydrological conditions (dry and wet year) is aimed at checking that the resulting generation fleet is on one hand enough to ensure a proper security of supply even in case of significant reduction of the hydro resource (dry years), and on the other hand is not curtailed in a way that would affect the profitability of the investments if greater water availability occurs (wet years).

In the dry scenario, Argentina and Uruguay are able to maintain a good adequacy of the system, increasing the production by thermal generation with the relevant higher costs, while Brazil, due to its strong dependency on the hydro resource, suffers a significant EENS increase up to 350 GWh, about $4x10^{-4}$ of its load. This result suggests that a proper development of dispatchable generation must be considered in Brazil to guarantee the resources to face dry periods, and that VRES alone are not enough to avoid negative impact of water shortage. It is worth underlining that in such conditions it is necessary a very close coordination of the whole system in real time operation, based on proper production forecasts by VRES and consequent optimization of the hydro resource.

On the contrary, in the wet conditions there is plenty of hydro resource, which on one hand allows to nearly bring the EENS to zero, but on the other causes more frequent overgeneration conditions, with consequent risk of curtailments of hydro and VRES productions. The expected VRES energy to be reduced increases by nearly 10 TWh, equal to 3% of their production, and this can also be assumed as impact on the profitability of the plants in the wet conditions.

In the second part of the study, two Variants have been examined, characterized by higher or lower load and differences in the generation fleet.

In the first one, the demand increases by 8% and coal plants are shut down. In these conditions, there is economic benefit to introduce additional 17,500 MW PV and 22,000 MW wind plants, which are able to produce the energy needed to supply the load increase and replace coal production. However, the new VRES plants are not able to ensure a good security of supply, and additional OCGTs are considered to bring the EENS to lower level, providing the needed power in the periods when there is unexpected unavailability of VRES production.

The second Variant considers a lower demand as a result of slower economic growth and energy efficiency improvements, keeping the same generation fleet of the Reference scenario, as defined in the available development plans, which already include 55 GW of PV and wind plants. Due to the reduction of the load, the introduction of additional VRES plants becomes nearly not profitable anymore, especially in Brazil where the hydro resource and the already foreseen biomass and VRES plants are able to cover almost all the new reduced load. The result shows that only in Argentina and Uruguay there is convenience to install 1,000 MW PV and 3,500 MW wind power plants. In these conditions, Argentina strongly depends on the import from the other countries (the net balance for Argentina is –6 TWh) and in particular from Brazil, which export the excess of energy due to hydro and VRES plants. To reduce the need for import, Argentina might install additional PV and wind plants, which can represent a positive benefit for Argentina, even if they constitute a cost for the overall system (curtailments also become significant).

In case, especially in Brazil, some non-VRES power plants (thermal, hydro, biomass…) foreseen at 2030 will not be developed because not profitable in a scenario of lower demand growth, VRES plants might represent a good alternative to be considered, thanks to their competitive LCOE and to flexibility, modularity and relative celerity in the execution of the projects with respect to other technologies.

As a summary, the analysis carried out in the present study on the interconnected system constituted by Argentina, Brazil and Uruguay showed a big potential and economic advantages for a development of PV and wind in the regions with highest resources. VRES are able to gain a significant role in the load coverage at 2030, avoiding the need of new thermal generation from 2025-2026. Planned transmission systems in the different countries do not represent a critical bottleneck for the development of VRES. The availability of huge amount of hydro resource, especially in Brazil, on one hand fosters the development of VRES plants, because hydropower plants can compensate their variability reducing the negative impact on the systems, but on the other hand represents the limiting factor, especially in low load conditions, because of the possible overgeneration conditions and because VRES production would compete with generation without fuel costs.

Some limited amount of dispatchable power plants might be needed to ensure a proper security of supply in high load scenario and in case of scarcity of hydro resource.

7 REFERENCES

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