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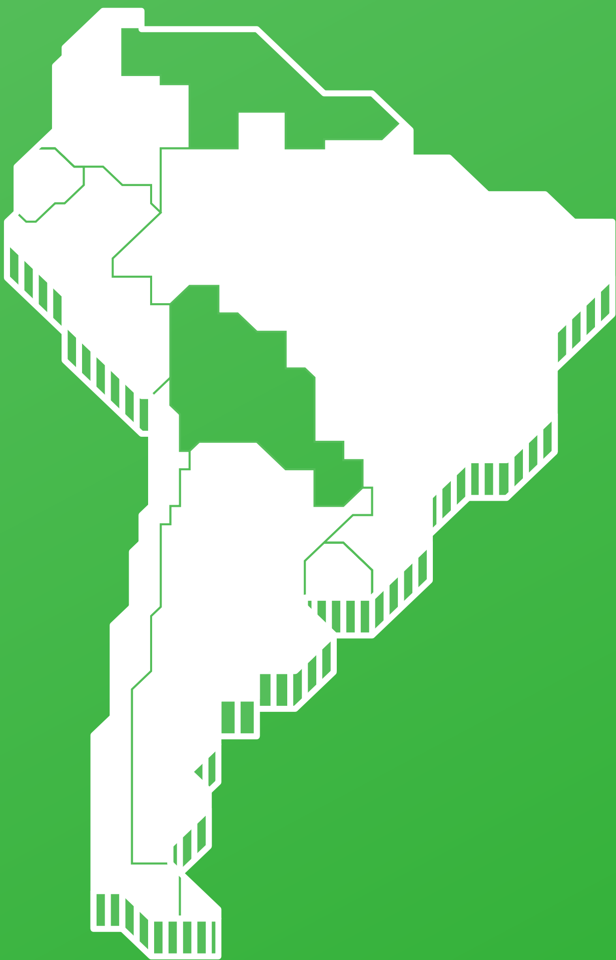

Variable Renewable Energy Sources (VRES) deployment in South America and role of interconnection lines for their optimal exploitation

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-	10/02/2020		Sensitivities and Variants added
-	06/03/2020		Minor revisions
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LIST OF ACRONYMS

BESS	Battery Energy Storage System
CCGT	Combined Cycle Gas Turbine
EENS	Expected Energy Not Supplied
EOH	Equivalent Operating Hours
EPE	Empresa de Pesquisa Energética
GHG	Greenhouse gas
GT	Gas Turbine
HVDC	High Voltage Direct Current
LATAM	Latin America
LCOE	Levelized Cost of Energy
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PV	PhotoVoltaic
RES	Renewable Energy Source
RoR	Run-of-River
VRES	Variable Renewable Energy Source

1 FOREWORD

1.1 General objective of the study

Latin America is endowed with outstanding renewable energy resources (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 if compared 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 for the externality costs associated to the power generation (see costs associated to the various GHG emissions and particulates).
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)[2].

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

[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

[2] 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.

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

The study has been first focused on three different clusters with limited groups of countries (respectively Argentina-Chile, Argentina-Brazil-Uruguay and Colombia-Ecuador-Peru) defined on the basis of geographical criteria and of the current configuration of the power systems; in this way it was possible to perform a deeper analysis of the operation of the national systems in order to optimize the VRES development with a more local approach.
Following the results of these three clusters, the above-mentioned countries – Argentina, Brazil, Chile, Colombia, Ecuador, Peru and Uruguay – have been analysed together, in a so-called "continental analysis".

1.2 Contents of the report

After summarizing the assumptions and the main results of the analyses aimed at assessing the optimal economic penetration of VRES generation (wind and PV) performed for the three different clusters of countries (Argentina-Chile, Argentina-Brazil-Uruguay, Colombia-Ecuador-Peru), this report investigates the operation of all the above-mentioned countries connected together in order to estimate the optimal installed capacity of VRES in 2030.
The starting point for this comprehensive evaluation is represented by the optimal values of VRES installed power defined for each single cluster at the end of each relevant analysis. The evaluation of the optimal penetration of VRES generation has been carried out assessing and comparing the economic benefits, which result for the system from the introduction of new VRES capacity (PV and wind) with the investment costs needed for such new power plants. Optimal values correspond to the limit for which the required costs are equal to the expected benefits.
This report presents the main outcomes of the operation of the whole power system with the defined optimal installed capacity of VRES, highlighting the role that interconnections have in ensuring the optimal exploitation of the PV and wind plants and the security of the system. Additional factors which might foster even more the convenience of further VRES plants are also evaluated.

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

2.1 Introduction

The objective of the analyses performed during the study and reported in [1][2][3] 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 technical 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[3]), 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, affecting their profitability.
Optimal amount of VRES installed power has been defined for each cluster of countries, thanks to the quantitative results of the simulations. The PV and wind plants have been introduced in the areas with highest potential but also with a good transmission capacity, able to evacuate the production.
In a first step, the optimal amount and mix of technologies has been calculated for each country as isolated, looking for the best configuration providing highest benefit to each system independently from the others. Then, some additional plants have been introduced in the most favourable areas which benefit from the presence of the interconnections. A more detailed description of the methodology applied in the study can be found in [1][2][3].

In chapter 2.2, the main assumptions at the basis of the analysis are recalled in a schematic way, highlighting possible variations with respect to the ones of the previous studies with the objective of harmonizing the hypotheses.

[3] 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 solve line overloads that cannot be resolved only with a different dispatching of generators)

In the following chapters the continental analysis is presented with two cases. In the first, the simulation is performed without considering the possibility to exchange power between the countries. Each country is isolated from the others and must supply its demand facing variability of PV and wind power plants by its own. In the second case, interconnections between the countries are introduced and the relevant maximum exchange allowed. Considerations on the resulting operation are presented, focusing on the advantage deriving from the possibility to transfer energy from one country to the other.

2.2 Main assumptions

In order to calculate the optimal economic amount to VRES plants in 2030 several assumptions on technical and economic aspects have been put forward. In the following paragraph a summary of the most significant ones is presented. More details are available in the reports relevant to the analysis of each cluster of country ([4]-[6]).

2.2.1 Demand

Table 1 lists the total demand and the power peak of each considered country. During the simulation of the expected operation of the power systems, losses on the transmission system are added depending on the loading of the equipment.

Table 1 - Total demand and power peak in the countries at 2030

COUNTRY	Demand [TWh]	Power peak [MW]
ARGENTINA	229.9	42,850
BRAZIL	874.8	138,600
CHILE	108.6	15,750
COLOMBIA	100.8	13,810
ECUADOR	49.4	7,640
PERU	85	11,330
URUGUAY	14.7	2,590

2.2.2 Generation fleet (installed capacity)

Table 2 provides a summary of the installed capacity in the different countries, depending on the technologies, assumed as starting point for the optimization of the VRES capacity. These values have been derived from the plans set up by each country and reported in [4][5][6].

Table 2 - Installed capacity per technology at 2030 in the initial condition [MW]

COUNTRY	HYDRO	THERMAL	NUCLEAR	PV	WIND	OTHER
ARGENTINA	13,700	27,600	2,500	5,000	4,950	100
BRAZIL	113,000	41,600	3,400	9,600	28,500	18,200
CHILE	7,000	13,100	0	4,100	3,900	600
COLOMBIA	14,500	5,900	0	1,100	1,200	300
ECUADOR	6,700	3,800	0	100	100	200
PERU	5,800	9,700	0	300	400	0
URUGUAY	1,500	1,200	0	230	1,550	300
TOTAL	162,200	90,700	5,900	20,430	40,600	19,700

Thermal power plants are characterized by CO_2 emission factors, based on available data or on typical values per technology, which allow to estimate the amount of CO_2 (in Mt) produced.

It is assumed also that a share of VRES power plants is associated to battery energy storage systems (BESS), the role of which is basically load shifting which also constitutes a support for a better "dispatchability" of PV and wind production within a limited time frame and power. In order to ensure that a proper amount of energy is available to be shifted from periods with high VRES production to periods with risk of EENS, a maximum storage capacity equal to 5 hours is supposed in the definition of the optimal solution. Each new VRES plant is associated with storage system with nominal power between 10% and 20% of the plant power, which ensures a smoother production variability, also reducing the errors with respect to the production forecasts. The utilization of BESS for energy shifting is coordinated at national level, in order to optimize their usage depending on the system needs.

2.2.3 Interconnections

Figure 1 provides a graphical representation of the considered NTCs between the countries.

It is worth recalling that Chile, Argentina and Uruguay are operated at 50 Hz, while Brazil, Peru, Ecuador and Colombia operate at 60 Hz. The interconnections between countries with different nominal frequency are realized by means of proper back-to-back or HVDC links, which allow the control of the transmitted power, increasing the possibility to exploit the interconnections up to their maximum capability.

Many interconnection lines are already in operation, even if not always fully utilized due to technical issues and lack of regulations aimed at creating a coordinated electricity market among different countries.

The Salto Grande dam is modelled injecting half of its power in the Argentinean system and half in the Uruguayan, which are then interconnected at the 500 kV level.

The most important reinforcements considered in the studies with respect to the interconnections already in operation are the following:

- between Argentina and Chile, a new 500 kV line increasing the total NTC up to 1,200 MW;
- between Argentina and Brazil, a new 500 kV line increasing the NTC up to 2,300 MW;
- between Chile and Peru, new interconnections at 220 kV and 500k kV levels allowing an NTC equal to 1,000 MW.

Figure 1 - Graphical representation of NTCs between countries at 2030

2.2.4 Main financial and costs assumptions

Table 3 summarises the main parameters which affect the cost of the energy produced by PV and wind power plants, and in particular the economic and financial parameters (discount rate, CAPEX, OPEX) and the average resulting equivalent hours from the previous analysis, which quantify the available resources.

Table 3 - Main assumptions on costs of PV and wind power plants at 2030

COUNTRY	ARG	BRA	CHI	COL	ECU	PER	URU
Discount rate	10%	8%	7.5%	8%	10%	8%	8%
CAPEX PV [kUSD/MW]	860	740	670	670	860	600	860
O&M cost PV [kUSD/MW]	11.5	11.5	11.5	9.4	9.4	9.4	11.5
Lifetime PV [years]	30						
CAPEX wind [kUSD/MW]	1,180	1,180	1,145	1,145	1,180	1,140	1,180
O&M cost wind [kUSD/MW]	48	48	52	23.8	23.8	23.8	48
Lifetime wind [years]	20						
Resulting eq. hours PV	2,360	1,930	2,420	1,650	1,500	2,240	1,510
Resulting eq. hours wind	4,160	3,790	2,420	4,370	2,190	4,110	2,800

For BESS, a cost equal to $ 0.55 million for a 1 MW turnkey system with a storage capacity of 5 MWh have been assumed. Efficiency (i.e. ratio between the energy discharged in the system and the energy absorbed) is considered equal to 90%.

2.2.5 Fuel costs

In conclusion, Table 4 reports the costs of the primary energy resources in the different countries.

Table 4 - Costs of primary energy resources at 2030

COUNTRY	ARG	BRA	CHI	COL	ECU	PER	URU
Crude oil [USD/barrel]	98.9	85	100	128.5	128.5	128.5	98.9
Natural Gas USD/MBTU]	9	10	10	8.2	7.8	4.35 - 6.8	10
Coal [USD/MBTU]	3.1	3.1	3.3	1.8	3	3	-

The cost of natural gas in Argentina is obtained considering an average between the cost of indigenous resources and the cost of gas imported from Bolivia. Similarly, for Uruguay natural gas is assumed coming mainly from Argentina through the existing pipeline and partially supplied by LNG plant (currently under evaluation to improve security of supply) and the resulting cost is higher.
Finally, in Peru natural gas costs 4.35 USD/MBTU if subsidies are considered and 6.8 USD/MBTU if they are not. Subsidies are assumed only for the coverage of the internal demand and not for export towards other countries.

2.3 Results of Base Case

This chapter illustrates the results of the assessment of the optimal amount of PV and wind power plants in the countries, performed through an iterative process based on the evaluation of main indices of the system with increasing penetration of VRES in the areas with best resources.
More details on the applied methodology and on the main outcomes of the analyses executed on isolated countries or smaller groups of countries (clusters) can be found in [1][2][3].
All the results are obtained by probabilistic 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 non-programmable 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[4]) and for each country. 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 risk of curtailments due to overgeneration in the system and overloads on considered HV transmission grid;
- total generation cost or its variations;
- where significant, CO_2 emissions;
- 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 has been 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[5] of the investments. This method allows the comparison of the benefits obtained from different scenario and the selection of the most convenient one.

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[4] Load shedding is assigned to "Lack of Power" in case in the system there are no enough generation resources to cover the total demand; to "Lack of Interconnection" in case one area has no enough resources and generators from other areas cannot support due to active constrains on the interconnection lines; to "Line overload" when load shedding is necessary to resolve line or transformer overloads that cannot be resolved with redispatching of generators.

[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.

2.3.1 Interconnected countries

At the end of the analysis of the Base Case, 49.5 GW PV and 71.2 GW wind represent the optimal VRES capacity in the system, increasing the quantities foreseen in the considered generation expansion plans by 150% and by 75% respectively. The simulation of the expected system operation with the optimal generation fleet provides the following results:

- Very good generation adequacy, with the EENS equal to 4.2 TWh ($3 \cdot 10^{-6}$ of the total demand)
- Total PV production equal to 106 TWh and wind production equal to 265.5 TWh, respectively more than 7% and 18% of the total demand in the system. Curtailments due to overgeneration conditions or transmission constraints are limited to about 3% of their total potential production
- Lower generation by thermal power plants (-167 TWh) with respect to the case with the VRES quantities assumed as starting condition, and lower CO_2 emissions (-84 Mt)
- Estimation of total benefits for the system in terms of lower fuel costs and considering the annuity of the investments needed for the additional VRES plants equal to about USD 3.6 billion at the target year

At the end of the optimization process carried out with iterative approach based on the simulations of the system operation, the optimal values of PV and wind capacity has been defined, reported in Table 5. BESS are also associated to the new VRES plants to ensure a smoother and more flexible dispatching, reducing errors between forecasts and effective production in real time operation and enabling shifting the energy in periods with higher demand.

Table 5 – Optimal VRES capacity in Base Case at 2030 [MW]

COUNTRY	PV	Wind	Storage
ARGENTINA	10,600	15,870	2,500
BRAZIL	20,500	41,600	3,700
CHILE	11,300	5,270	2,000
COLOMBIA	2,400	2,700	220
ECUADOR	1,750	2,050	260
PERU	2,750	1,700	320
URUGUAY	230	2,050	20
TOTAL	49,530	71,240	9,020

Comparing the quantities reported in Table 5 with those from Table 2, it is possible to note that VRES capacity reaches nearly the double of the values planned by each country (120.8 GW against 61 GW), with the PV increasing almost by 150% and the wind about 75%. The main drivers for the expansion of the VRES penetration in the countries are the availability of the natural resource, the cost of the PV and wind plants and the cost of the thermal generation which is replaced by the VRES plants.

In the final configuration, the system has a very good adequacy, with the EENS equal to 4.2 GWh ($3 \cdot 10^{-6}$ of the total demand), concentrated mainly in Brazil (due to lack of generation/interconnection) and in Peru (due to line overloads[6]). Table 6 shows the detailed values per country and cause.

Table 6 - Expected Energy Not Supplied at 2030 – Optimal system configuration, interconnected countries

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
ARGENTINA	0	72	21	93
BRAZIL	0	367	2,053	2,420
CHILE	0	122	0	122
COLOMBIA	0	0	0	0
ECUADOR	0	0	0	0
PERU	0	1,556	0	1,556
URUGUAY	0	0	0	0
TOTAL	0	2,117	2,074	4,191

Table 7 provides the expected production of PV plants in the countries and the possible limitations, which might incur due to overgeneration conditions or due to redispatching necessary to solve network congestions.
The sum of PV production in all the countries reaches almost 106 TWh (about 6.5% of the overall electricity generation in the analysed system[7]), and risk of curtailments sums up to more than 3.1 TWh (3% of the total PV potential production). Chile and Peru suffer the highest share of curtailments due to network constraints as the areas with best PV production are located at the extreme of the power systems (respectively in the northern part or in the south-east) and the generation must be transferred to the main load centres through long transmission lines which might represent a bottleneck.

[6] It is worth recalling that the transmission network in Peru included in the Base Case mainly the network reinforcements planned only up to 2024, while the load has been increased to the levels expected at 2030. For this reason, EENS higher than in other countries can be accepted.

[7] Corresponding also to 7% of the total demand of the system

Table 7 - Total production of PV plants at 2030 – Optimal system configuration, interconnected countries

PV PLANTS AREA	TOTAL NET PRODUCTION [GWh/y]	RISK OF CURTAILMENT [GWh/year]		Installed capacity [MW]	Equivalent hours [MW]
		System constraints	Network constraints		
ARGENTINA	25,081	297	49	10,600	2,366
BRAZIL	39,586	1,348	74	20,500	1,931
CHILE	28,047	409	531	11,300	2,482
COLOMBIA	3,956	199	0	2,400	1,648
ECUADOR	2,622	142	7	1,750	1,498
PERU	6,271	0	75	2,750	2,280
URUGUAY	345	0	0	230	1,500
TOTAL	105,908	2,395	736	49,530	2,138

Similarly, Table 8 reports the expected production and risk of curtailments of wind power plants in the different countries. The total wind generation is higher than 265 TWh (more than 16% of overall production in the system[8]), and the risk of curtailment is about 7.6 TWh (less than 3% of the wind potential), mainly due to overgeneration conditions in the North-East part of Brazil where most of the plants are located. Argentina suffers curtailments due to the network constraints as the wind farms are located mainly along the coast and can lead to some transmission overloading when favourable wind conditions are present.

Table 8 - Total production of Wind plants at 2030 – Optimal system configuration, interconnected countries

WIND PLANTS AREA	TOTAL NET PRODUCTION [GWh/y]	RISK OF CURTAILMENT [GWh/year]		Installed capacity [MW]	Equivalent hours [MW]
		System constraints	Network constraints		
ARGENTINA	66,001	678	1,011	15,870	4,159
BRAZIL	157,740	5,218	78	41,600	3,792
CHILE	12,890	82	4	5,270	2,446
COLOMBIA	11,803	388	8	2,700	4,371
ECUADOR	4,487	113	1	2,050	2,189
PERU	6,993	0	4	1,700	4,114
URUGUAY	5,748	2	12	2,050	2,804
TOTAL	265,662	6,481	1,118	71,240	3,729

Considering also possible curtailments of hydropower plants due to overgeneration, Brazil suffers the highest risk of RES production limitation (8.8 TWh), followed by Argentina (2 TWh) and Chile (1.1 TWh). The other countries have a total curtailment lower than 1 TWh together. A better coordination of VRES operation with hydroelectric and thermal plants, together with more precise short-term VRES forecasts

[8] Corresponding to 18% of the total demand without network losses

and planning of the thermal fleet might reduce these amounts during real operation of the system, with corresponding benefits.

The total production of VRES is then about 371.5 TWh. The PV and wind plants added during the optimization process contribute for almost half of this value, lowering the thermal generation by 167 TWh.
The overall benefit for the system, considering the fuel savings and the annuity of the investments needed for the additional VRES plants and related storage, are about USD 3.6 billion in the target year (2030). Moreover, the generation by VRES reduces the CO_2 emission by more than 84 Mt per year, which represents an additional positive externality to be considered, together with the reduction of other pollutants. Furthermore, there are other additional benefits deriving from the possibility to avoid some investments in other technologies thanks to the VRES plants. This evaluation should be done on a country basis, following its own planning procedures and criteria for investments.

Figure 2 provides a graphical representation of the energy flows between the countries and of the utilization of the generation fleet in each of them.
Thanks to the interconnections which increase the evacuation capacity, the countries with the highest availability of cheap energy become exporters: in particular Chile (+ 2.1 TWh), Colombia (+1.9 TWh) and Uruguay (+1.3 TWh) can export the highest amount of energy. For other countries is convenient to import electricity from neighbouring systems: Brazil (-3.4 TWh), Argentina (-1.1 TWh) and Ecuador (-0.7 TWh) become importers.

It is worth noting that there are no critical constraints caused by the interconnections between countries. In general, the energy is exchanged reaching the NTC limits in a limited number of hours during the year: the highest values are relevant to the flows from Colombia to Ecuador (540 hours) and from the North of Chile to Argentina (about 400 hours), which are also the borders with the weakest interconnections. The limited time in which the interconnections constitute a constraint for the most economic energy exchange between countries means that the foreseen development is generally adequate for an optimal operation of the system even in presence of high VRES installed capacity.

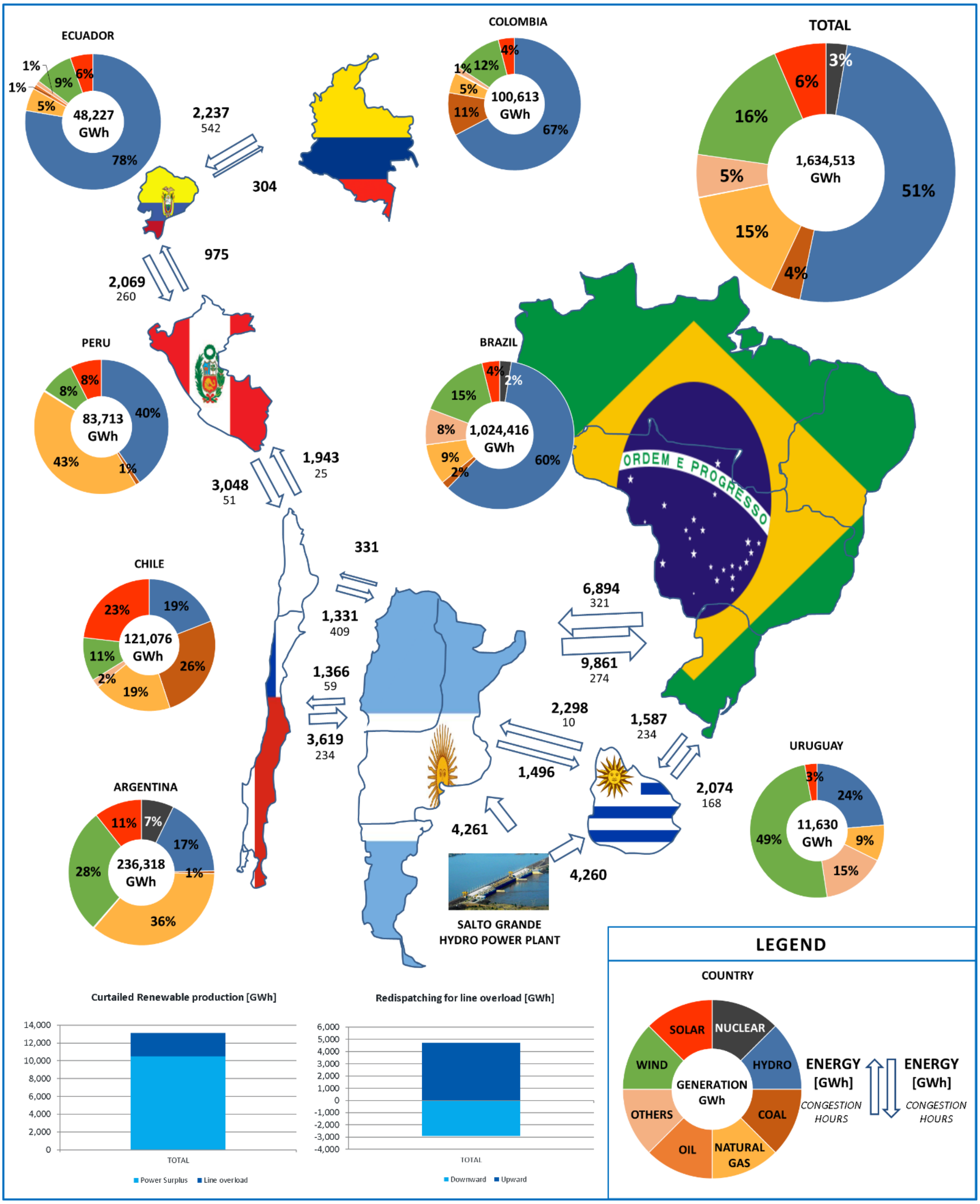

Figure 2 - Total production and energy exchanges at 2030 – Continental case with interconnected countries

2.3.2 *Isolated countries*

The scenario in which countries are not allowed to exchange energy has been simulated to estimate the net contribution of the interconnections to the optimal operation of the system. In this condition

- Total EENS in the system raises to 21.1 GWh ($1.4 \cdot 10^{-5}$ of the total demand), mainly in regions with high penetration of VRES plants and limited other resources to compensate their variability
- Risk of curtailments for PV and wind plants increase by 3.2 TWh and 4 TWh, reaching respectively about 6% and 4% of the total potential production
- Thermal plants increase their generation by 4.5 TWh, and more expensive plants must be used due to the impossibility to share the most economic ones. The fuel costs result USD 680 million higher than in the interconnected case

In the previous chapter the optimal VRES capacity in the countries has been assessed together with the expected benefits deriving from the presence of the additional plants. In order to estimate the net contribution of the interconnections, the operation of the system is now simulated without the possibility to exchange energy between neighbouring countries. The comparison between the results will allow to highlight the benefits deriving from the joint operation of the system.
The generation fleet is kept the same as the one in the optimal configuration.

Table 9 shows the values of EENS in the different areas and countries, which is globally more than four times higher than when the mutual support between countries is possible. The EENS is mainly present in countries that are energy importers (Brazil and Argentina) and due to situations in which the high variability of VRES and the errors in the production forecasts cause a reduction of the available generation in the country which cannot be completely covered with the programmed reserve. Some additional EENS due to transmission constraints[9] appears also in other countries as the power generated by VRES plants flows in a different way.
Notwithstanding the EENS increase, in general the system maintains a good adequacy (the EENS is about $1.4 \cdot 10^{-5}$ of the total demand). The criticalities in Argentina might be reduced during real-time operation with more precise PV production forecasts and increasing the reserve made available by dispatchable technologies.

[9] For Peru, note [6] at page 13 still applies.

Table 9 - Expected Energy Not Supplied at 2030 – Optimal system configuration, isolated countries

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
ARGENTINA	0	351	14,774	15,125
BRAZIL	0	456	3,124	3,580
CHILE	0	606	8	614
COLOMBIA	0	0	0	0
ECUADOR	0	1	0	1
PERU	0	1,728	0	1,728
URUGUAY	0	0	53	53
TOTAL	0	3,142	17,959	21,101

With regard to VRES generation, the lower capacity to evacuate the power in the different areas increases the risk of curtailments.

Table 10 shows the expected production for PV plants. Compared to the interconnected case, the production is reduced by about 3.2 TWh mainly concentrated in Chile, North-West Argentina and Ecuador. In Chile, there is a significant increase of curtailments due to transmission constraints as the PV generation can only flow southwards from the northern part of the country where there is the best availability of resource. In this condition, the transmission system suffers some possible overloads which diminish if the power can be evacuated also towards Peru or Argentina.

The overall curtailments are equal to about 6%, and this percentage becomes greater if calculated only on the newly added plants. However, the average number of equivalent full load hours is higher than 2,000, confirming the very good resource availability in this region.

Table 10 - Total production of PV plants at 2030 – Optimal system configuration, isolated countries

PV PLANTS	TOTAL NET PRODUCTION [GWh/y]	RISK OF CURTAILMENT [GWh/year]		Installed capacity [MW]	Equivalent hours [MW]
AREA		System constraints	Network constraints		
ARGENTINA	24,551	838	37	10,600	2,323
BRAZIL	39,209	1,745	54	20,500	1,914
CHILE	26,581	1,290	1,116	11,300	2,352
COLOMBIA	3,742	413	0	2,400	1,559
ECUADOR	1,917	853	1	1,750	1,094
PERU	6,334	0	12	2,750	2,303
URUGUAY	334	4	7	230	1,457
TOTAL	102,668	5,143	1,227	49,530	2,072

Regarding wind generation (Table 11), total production is higher than 261.5 TWh/year and risk of curtailments due to overgeneration or constraints in the transmission system increases up to 11.5 TWh, corresponding to a bit more than 4% of the total potential production. The increase is caused by the more frequent overgeneration conditions in all the analysed countries except Peru, while no significant variations due to network constraints can be detected.

Table 11 - Total production of Wind plants at 2030 – Optimal system configuration, isolated countries

WIND PLANTS	TOTAL NET PRODUCTION [GWh/y]	RISK OF CURTAILMENT [GWh/year]		Installed capacity [MW]	Equivalent hours [MW]
AREA		System constraints	Network constraints		
ARGENTINA	65,590	1,133	968	15,870	4,148
BRAZIL	155,827	7,144	65	41,600	3,748
CHILE	12,726	249	1	5,270	2,390
COLOMBIA	11,370	827	3	2,700	4,211
ECUADOR	3,696	905	0	2,050	1,802
PERU	6,996	0	1	1,700	4,115
URUGUAY	5,542	156	65	2,050	2,696
TOTAL	261,747	10,414	1,103	71,240	3,671

The impossibility to exchange energy between the countries reduces the power flows over long distances decreasing the overall losses in the system. However, the net balance between the lower generation by renewable plants and the lower losses requires that thermal power plants produce about 4.5 TWh more than the energy needed in the interconnected case.

Moreover, without interconnections, energy markets of the different countries are not coupled and sharing the most economic thermal generators is not possible. In this condition, not only more thermal power plants must be activated to compensate the missing renewable production, but it is also necessary to use more expensive facilities, as the cheapest ones might be not fully available due to transmission limits.

In total, the additional costs for fossil fuels when the countries are operating as isolated sum up to about USD 680 million, and the CO_2 emissions also raise by about 2 Mt per year.

These values can be considered as the savings introduced in the system by the optimal exploitation of the interconnections between the countries. The actual share of benefits achievable in the real operation depends on the actual level of flexibility and coupling of the markets in the different countries. The more it is possible to share the cheapest resources available in the countries also from a regulatory point of view, the more benefits will be ensured for the whole system.

The following Figure 3 provides a visual summary of the operation of the system when the countries are not allowed to exchange energy.

The countries with the highest amount of curtailed VRES and hydro generation due to overgeneration or transmission line overloads are Brazil (13.3 TWh), Argentina (3.1 TWh) and Chile (2.9 TWh). Colombia and Ecuador also suffer some curtailments, totalling 3 TWh together.

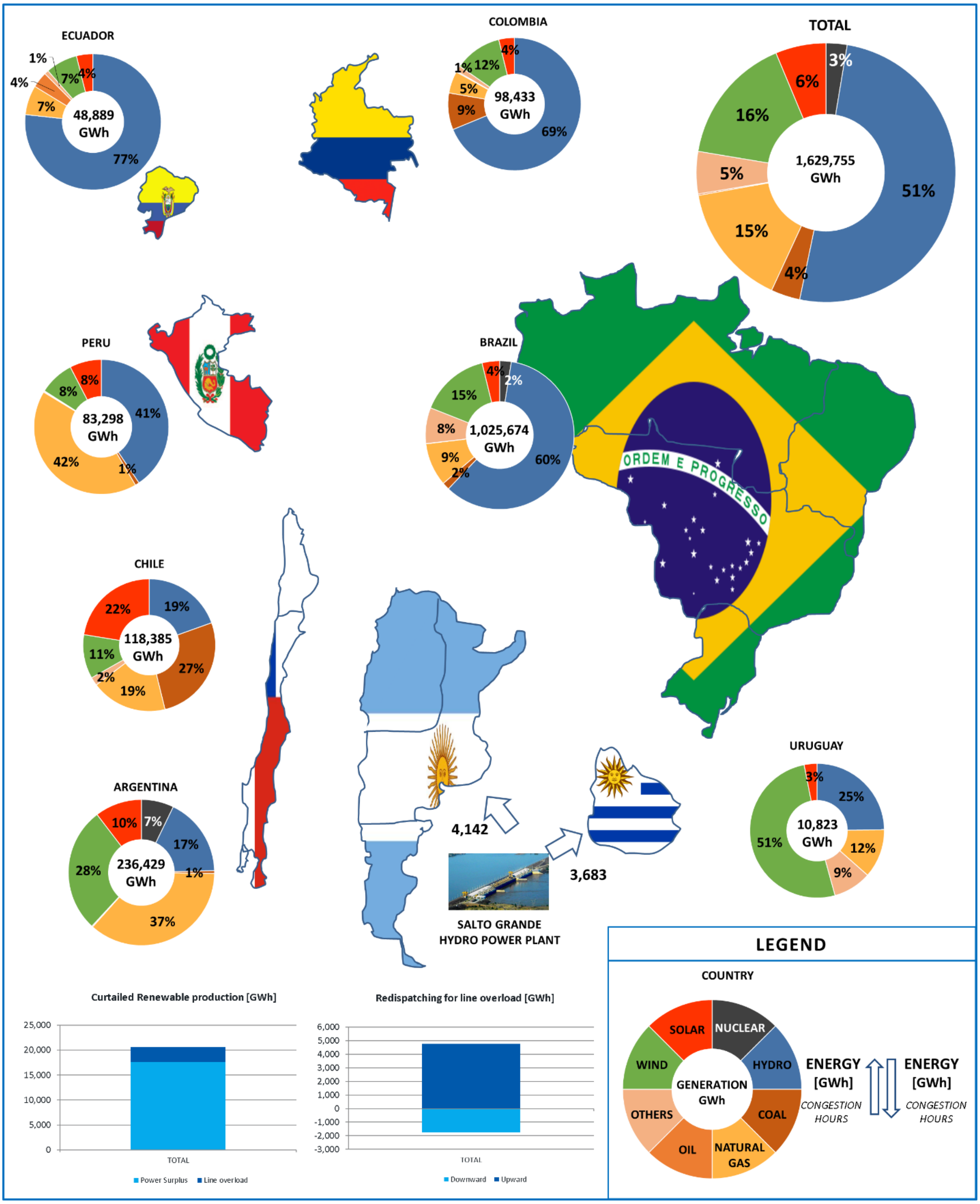

Figure 3 - Total production and energy exchanges at 2030 – Continental case – Isolated systems

2.4 Sensitivities

Some sensitivity analyses have been carried out on the interconnected system resulting from the evaluation performed in chapter 2.3.1. The investigation, aimed at checking how the optimal amount of VRES changes or how the operation of the whole power system is affected if some assumptions are modified, has been focused mainly on:

- variation of costs of VRES technologies, applying further reduction of costs with respect to the ones already assumed at the beginning of each Cluster
- variation of hydrological conditions, checking the adequacy of the generation fleet and the risk of overgeneration in case of dry or wet conditions in the whole system.

In the first case, the scope of the sensitivity is to evaluate how a further reduction of VRES costs can further enhance their development in the system, in the same scenario considered for the Base Case. In the second case, the sensitivity assesses the expected behaviour of the power system (including the optimal amount of VRES plants calculated in the Base Case) if some changes take place with respect to the hydrological conditions assumed in the represented "average scenario". Depending on the variations (higher or lower availability of hydro resource), the VRES plants will suffer higher or lower curtailments, and security of supply also is affected, as well as generation costs. This sensitivity is important because it allows to check whether there are risks for the power system and/or for the VRES plants in some particular conditions which should be addressed in advance defining proper solutions, such as the installation of further generation to ensure an adequate security of supply.

2.4.1 Increased optimal VRES capacity in case of lower investment costs

VRES technologies are experiencing continuous costs decrease thanks to the development of the industry, with significant learning curves and economies of scale enabled by the market growth, and spurred by R&D activities. According to [7] and [8], between 2010 and 2018 installation costs have declined by 74% for PV and by 22% for onshore wind and is expected to continue declining in the next decades.

In order to assess how a further reduction of costs with respect to the expected values assumed in the study (reported in Table 3) can enhance the deployment of VRES plants, a new set of values has been defined and optimal VRES capacity has been calculated for each country. The main assumptions applied for the definition of the new costs are the following:

- PV CAPEX reduced 15% for countries belonging to Cluster 1 and Cluster 2 (Argentina, Brazil, Chile and Uruguay), and 10% for countries of Cluster 3 (Colombia, Ecuador and Peru), which already had lower values than others
- Wind CAPEX reduced by 5% in every country
- PV and Wind OPEX aligned to the values applied in Cluster 3 which already took into account the latest downward trends

Resulting CAPEX and OPEX per technology are reported in Table 12.

Table 12 - Reduced costs for PV and wind power plants at 2030

COUNTRY	ARG	BRA	CHI	COL	ECU	PER	URU
CAPEX PV [kUSD/MW]	731	629	569.5	603	774	540	731
O&M cost PV [kUSD/MW]	9.4	9.4	9.4	9.4	9.4	9.4	9.4
CAPEX wind [kUSD/MW]	1,120	1,120	1,090	1,090	1,120	1,080	1,120
O&M cost wind [kUSD/MW]	23.8	23.8	23.8	23.8	23.8	23.8	23.8

Based on these new assumptions, a higher amount of VRES capacity turns out to be optimal for the system, as the lower costs allow VRES plants to compete against cheaper technologies and also make acceptable a higher risk of curtailments of their production.
The additional capacity installed in the different countries in case of lower VRES costs is reported in Table 13.

Table 13 - Additional optimal VRES capacity under the assumption of lower VRES costs

COUNTRY	PV		Wind	
	Added [MW]	Total [MW]	Added [MW]	Total [MW]
ARGENTINA	3,000	13,600	500	16,370
BRAZIL	6,000	26,500	500	42,100
CHILE	1,000	12,300	-	5,270
COLOMBIA	200	2,600	200	2,900
ECUADOR	-	1,750	-	2,050
PERU	1,500	4,250	500	2,200
URUGUAY	-	230	100	2,150
TOTAL	11,700	61,230	1,800	73,040

Together with the additional 11,700 MW of PV and 1,800 MW of wind plants, in the system are inserted also about 2,500 MW of storage systems, which ensures a better dispatchability of the energy produced by VRES, allowing both reducing the errors with respect to the forecasts and shifting the energy in the periods with higher demand.

Thanks to the new capacity, the VRES production in the different countries increases and reaches the values reported in Table 14.

Table 14 - Additional and total production under the assumption of lower VRES costs

COUNTRY	PV production [GWh]		Wind production [GWh]	
	Additional	Total	Additional	Total
ARGENTINA	5,300	30,400	1,350	67,350
BRAZIL	10,150	49,800	1,750	159,500
CHILE	1,600	29,650	-	12,800
COLOMBIA	300	4,250	650	12,500
ECUADOR	-	2,600	-	4,450
PERU	2,650	8,950	1,900	8,900
URUGUAY	-	350	250	6,000
TOTAL	20,000	126,000	5,900	271,500

With the production of the additional PV and wind plants, VRES are able to supply 27% of the whole system net demand (i.e. without considering losses on the transmission system) and CO_2 emissions are reduced by more than 12 Mt per year.
Moreover, the insertion of these additional plants has a further positive impact on the already good security of supply, with the reduction of EENS in situations with lack of resources (in particular 1.5 GWh in Brazil) and supporting the flexibility for the resolution of network congestions.

Table 15 summarizes the main changes in the systems caused by the operation of the additional 13.5 GW of VRES plants and the relevant costs and benefits. With the assumption of reduced costs, the installation of the new plants and the related storage systems costs about USD 1,200 million per year, but allows saving the production of 24.3 TWh of thermal generation equal to about USD 1,275 million. Considering also the slight improvement of the security of supply, the total benefit can be evaluated in about USD 78 million.

Table 15 - Total benefit for the system due to the additional VRES plants under the assumption of lower costs

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	USD million/year
ADDITIONAL VRES	13,500	-1,063
NEW STORAGE	2,340	-136
	GWh/year	USD million/year
TOTAL THERMAL GENERATION	-24,300	1,274
RES CURTAILMENT	6,480	-
TOTAL EENS	-1	3
TOTAL BENEFIT	**-**	**78**

BENEFIT/MW VRES [kUSD/year]	**6**

It must be underlined how the additional plants suffer a higher risk of curtailments with respect to the situation analysed in chapter 2.3.1: for a total additional generation equal to about 25.9 TWh (as reported in Table 14), the curtailments reaches about 6.5 TWh, corresponding to 20% of the potential production, and this percentage would become even higher if further plants are added. Nevertheless, this level of increased risk is acceptable and represents the optimal value because VRES costs are reduced; on the contrary, higher risks would become too expensive and would reduce the economic benefits for the system.

Figure 4 shows total productions and energy exchanges resulting with the new optimal amount of VRES under the assumptions of reduced VRES costs.
From the comparison with Figure 2 it is possible to notice that, thanks to the additional VRES plants, Brazil reduces the imported energy and Peru increases the export by about 1 TWh, while Argentina and Chile have the convenience to import energy from neighbouring countries.

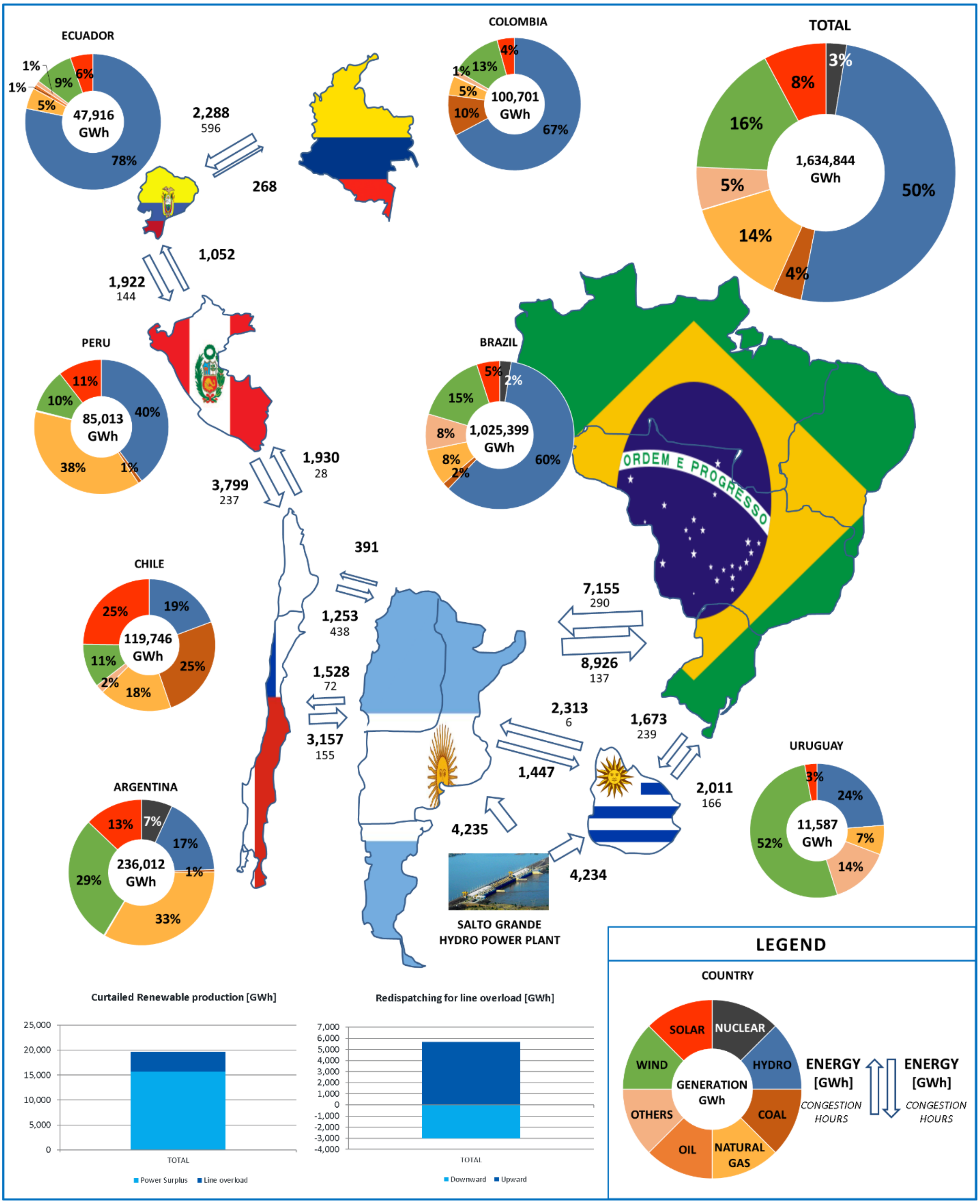

Figure 4 - Total production and energy exchanges at 2030 –

Continental case with interconnected countries under the assumption of lower VRES costs

2.4.2 *Dry hydrological conditions*

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

- The EENS increases considerably up to 420 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 increase up to more than USD 24,500 million, more than 45% higher with respect to the optimal scenario with average hydrological conditions, 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 1.6 TWh and 4.6 TWh.

The Brazilian systems would require adaptations compared to the Base Case to ensure a better adequacy: the installation of some economic and flexible dispatchable plants (such as OCGT) to cover the hours with high demand can represent the easiest solution. Other possible approaches which might improve the performance of the power system, also identified by EPE in PDE2026 [9], are the introduction of pumped-storage plants, the increase of installed capacity in selected hydropower plants, storage systems, demand response mechanism. The addition of further VRES plants does not represent an optimal solution over their lifetime as, despite the contribution they can provide in the dry scenario, they would suffer excessive curtailments in average and wet years, affecting their profitability. Moreover, dispatchable resources are generally better fit to address short term issues.

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. Also demand side response mechanism might contribute to reduce the peak demand and limit the load curtailments. 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 15^{th} percentile of the series. The different behaviour which takes place in the areas has been taken into account in the creation of the scenario: North (N) and North-East (NE) areas show a different reduction of the hydro resource availability with respect to the Sud (S) and South-Est/Central (SE/CO) areas.

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 areas 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 areas.
Finally, based on the available data, in Colombia the dry year has been modelled with a reduction of about 25% of the energy available from hydropower plants, 20% in Ecuador and 15% in Peru.

As expected, the simulation of the scenario with lower availability of hydro resource shows a strong increase of the EENS, up to 420 GWh, equal to about 2.9×10^{-4} of the total load. The EENS increase is recorded mainly in Brazil in the SE/CO, NE and N areas, strongly dependent on hydro and having little advantages from the interconnections with other countries, as they remain very far. Therefore, in dry hydrological conditions the Brazilian power system presents a considerable deterioration of the adequacy since in the simulated scenario it does not have enough generation to cover the reduction of hydropower production. This fact suggests that the generation fleet resulting in the optimal scenario, characterized by the high increase of VRES plants replacing the thermal generation foreseen in the generation expansion plan, is not enough to ensure the load coverage when there is a significant reduction of water availability. To guarantee a better adequacy, additional generation or ways to better exploit the existing one should be considered. Solutions present in the national system development plan [9] to meet peak demand, which were only partially considered in the Base Case optimal scenario as replaced by VRES and flexibility of hydro and storage plants, might represent the right proposal also in this context. Flexible thermal power plants[10], pumped-storage plants, additional installed hydro, additional storage systems or using a demand-response mechanism should be included also in the Base Case final configuration, even if not economically optimal, to ensure that the demand in Brazil can be supplied properly in case of lack of hydro resources. Also the addition of VRES plants would not represent an optimal solution because, even if they can provide some contribution in the dry scenario (which happens few times during their lifetime), they would suffer excessive curtailments during average or wet years, affecting their overall profitability. Moreover, to improve the adequacy of the system in a dry scenario it is preferable the presence of dispatchable resources, which can effectively balance energy needs in the short term, without uncertainties about their availability.
Some other minor EENS is present in the Peruvian system, due to limited capacity[11] of the considered transmission system and not of the generation availability. In order to cope with 2030 load increase and reduced availability of hydro resource, some reinforcements aimed at increasing the flexibility and the adequacy of the transmission system would be necessary.

The produced energy by PV and wind power plants increases due to a reduction of curtailments for overgeneration. PV production reaches 107.5 TWh in total (+1.6 TWh) and wind production more than 270 TWh (+4.6 TWh). The variations take place in the areas with the biggest presence of hydropower plants, which suffer the highest reduction of energy availability, and where there were overgeneration issues in the average hydrological conditions (Base Case).

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[10] 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 possibly with fast ramp rate to compensate variability of VRES production.
[11] See also note [6] at page 13.

In order to supply the load compensating the lower energy by hydroelectric power plants, the thermal generation increases considerably its production (almost +101 TWh) using more expensive plants. As a consequence, the fuel costs reach USD 24.5 billion, about 47% higher with respect to the optimal scenario. Moreover, also the CO_2 emissions increase by more than 50 Mtons (more than 30% growth with respect to the Base Case).

Table 16 summarizes the main economic figures related to 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 (more than USD 8,650 million) due to the higher thermal generation obtained also with expensive plants, and the cost associated to EENS. RES curtailments (which include VRES plants and a small part of hydro plants) are reduced by about 6.4 TWh, which represents a benefit for the system, as otherwise the thermal generation would have been even higher.

Table 16 - Total additional benefit (costs) resulting from the sensitivity case with dry hydrological conditions

	ELECTRICAL SYSTEM	ADDITIONAL BENEFITS (+) or COSTS (-)
	GWh/year	USD million/year
TOTAL THERMAL GENERATION	100,900	-7,830
RES CURTAILMENT	-6,375	-
TOTAL EENS	417.	-834
TOTAL COSTS	**-**	**-8,664**

In Figure 5 it is possible to note that in the considered dry conditions, there is a massive import of energy in Brazil which is the country suffering the greatest lack of hydro energy: net energy exchange from Argentina passes from 3 TWh to 13.1 TWh and the maximum power flow is reached more than 20% of the time. At the same time, the net exchange with Uruguay increases from 0.5 TWh to 2.6 TWh and the limit is reached ten times more than in the average scenario.

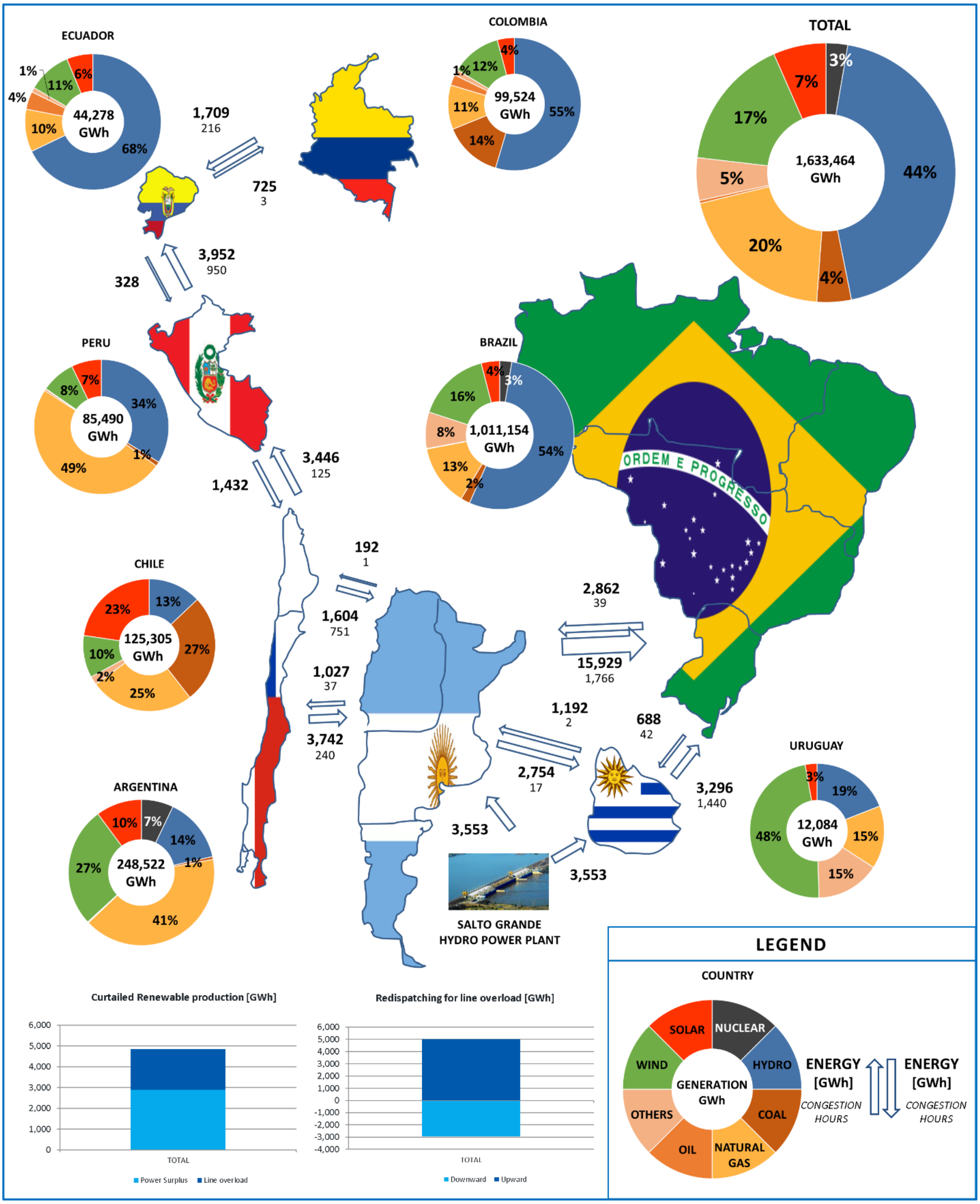

Figure 5 - Total production and energy exchanges at 2030 – Continental case in dry hydrological conditions

2.4.3 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 1.5 GWh (about 1×10^{-6} of the total load).
> - Benefits due to lower *generation costs* are about USD 3,700 million, -20% respect to the optimal scenario with average hydrological conditions because of the higher availability of "free" generation by hydropower plants.
> - Expected *generation by PV and wind* decreases respectively by 3.1 TWh and 9.6 TWh due to more frequent and significant overgeneration conditions. Curtailments for PV and wind plants reach about 6% of the potential production, and considering also hydro, in the system sum up to 32.5 TWh.

The operation of the system in case of wet hydrological conditions is also to be analysed, because it can lead to greater curtailments of VRES and hydropower production than in the Base Case (with average hydrological year) caused by 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 means that the installed VRES capacity is not exploited at its full potential. However, wet years are expected to occur only occasionally along the lifetime of power plants. The consequent risk for the investment is therefore limited, and the impact on the economic viability of the projects is also limited. In any case, it is important to verify that during wet years the production of VRES is not critically affected.

As done for the characterisation 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 85th percentile of the series. Also in this case, attention has been paid to possible different patterns in different 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.

Finally, Colombian plants have been assigned an increase of the available energy equal to about 20 %, while in Ecuador the increase has been set at 15 % and in Peru at 25 %.

The simulation of the scenario with wet hydrological conditions shows that the EENS reaches very low values in the system (1.5 GWh, equal to about 1×10^{-6} of the total load): there is no problem related to lack of resources and the curtailments are all related to line overloading, mainly concentrated in Peru where the transmission system is weaker than in other countries as it is based on the 2024 planning and not up to 2030. However, during real-time operation in presence of abundancy of water resource, it is possible to minimize the impact on the transmission system and consequently on EENS with a proper coordination of the power plants based on short term and more accurate load and production forecasts.

Thanks to the additional availability of hydro resource, there is an increase of hydropower production that causes a reduction of the thermal generation and the related costs. This benefit is estimated at USD 3,700 million, more than 20% of the costs estimated for the optimal scenario with average hydrological conditions. Also CO_2 emissions decrease by 20% with respect to the Base Case, saving 33.5 Mt.

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 3,100 GWh and by 9,600 GWh with respect to the final optimal scenario with average hydrological conditions. Moreover, some hydro power plants are affected by additional production curtailments, equal to about 300 GWh.
Thus, the risk of VRES curtailments reaches then 23.5 TWh (equal to about 6% of the total potential production), and hydropower plants are also limited by about 9 TWh (slightly more than 1% of the total available energy from hydro), totalling about 32.5 TWh of available clean energy which cannot be exploited. The country most affected by the risk of VRES and hydro production curtailments is Brazil, which reaches 23.8 TWh, followed by Colombia and Argentina (3 TWh and 2.8 TWh respectively) and Chile and Ecuador (1.4 TWh and 1.3 TWh). As already mentioned in the chapter 2.3.1, these values can be reduced in the real operation with special attention to short-term production forecasts and planning. However, it is important that the risk increase is highlighted in long term scenario analyses.

This represents a relevant amount of energy in absolute value, but a limited percentage of the total generation in the system. Taking into account the fact that the analysed wet scenario is likely to happen only few times during the lifetime of the VRES plants, it is possible to state that, even if the curtailments reduce the incomes of the VRES projects in the specific year, the impact on the overall economic convenience of the projects should not result to be critical. This risk must be considered during the development of new plants and the related financial analysis, and should be managed together with other typical uncertainties and assumptions on the expected production and energy costs to assess their profitability[12].

Table 17 summarizes the main figures relevant to the operation of the power system with wet conditions with respect to the scenario in an average hydrological year. The availability of more hydro resource provides a benefit for the whole power system equal to USD 3,700 million.

Table 17 - Total benefit in wet hydrological conditions with respect to average year

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	USD million/year
TOTAL THERMAL GENERATION	-65,240	3,697
RES CURTAILMENT	13,000	-
TOTAL EENS	-2.5	5
TOTAL BENEFIT	**-**	**3,702**

[12] CO_2 costs and other externalities are not included in the economic evaluations carried out in the study, and the positive impact they can have in real operation on the overall economics of the project can be higher than the increase of curtailments in wet conditions.

Figure 6 shows that in the wet conditions, Brazil increases significantly the energy exported towards the neighbouring countries (+13.1 TWh, moving from a net import equal to 3.4 TWh to a net export equal to 9.7 TWh), and the interconnection limit with Argentina is reached for more than 850 h/year.

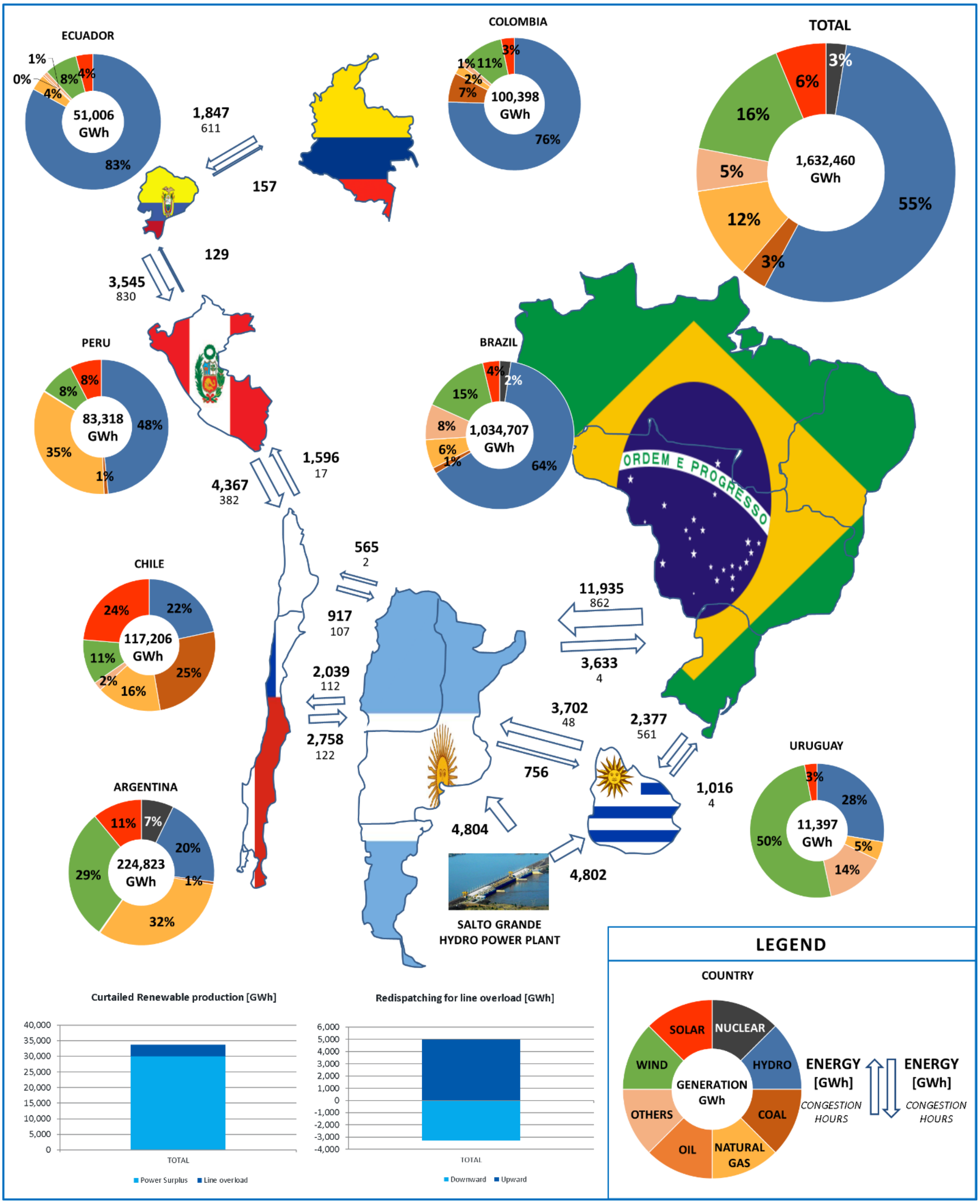

Figure 6 - Total production and energy exchanges at 2030 – Continental case with wet hydrological conditions

3 VARIANTS

In this chapter the results of different scenarios, called Variants, are presented. As introduced in [4][5][6], their aim is to evaluate the behaviour of the system in case some major changes take place with respect to the assumptions of the Base Case analysed in the previous Chapter 2.
By comparing the outcomes of the Variants with those of the optimal configurations resulting from the performed assessments, it is possible to appraise to what extent these fit against possible different evolutions of the power systems: the more flexible are the solutions, the better is for the system planning and potential investors.

3.1 First Variant: Accelerated decarbonization in a strong economic development

3.1.1 Main assumptions

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 optimal configuration of the Base Case are described in the following.

As far as the demand growth is concerned, the main drivers which can contribute to its increase are:

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

The variation of the demand profile in the big cities due to the presence of e-vehicles has been also considered, concentrating part of the load increase in the night hours.
Based on the data available in each county (forecasts of demand and e-vehicles penetration growth and the national development plans), the load has been increased by about 5% in Colombia, 8% in Argentina, Chile, Brazil and Uruguay, and 12% in Ecuador and Peru.

With regard to the available capacity, the transition towards a “carbon-free” generation has been simulated to minimize GHG emission. All coal power plants have been considered shut down[13], replaced by equivalent VRES power plants or with combined cycle natural gas power plants of the same size in case the increase of VRES plants is not sufficient to substitute all of them keeping a suitable level of generation adequacy.
The main variations of the thermal and hydro generation fleet assumed in Variant 1 with respect to the Base Case are the following:

- 10,400 MW of coal power plants have been removed from the generation fleet in the system, and in Brazil and Chile some combined cycles (respectively at least 2,700 MW and 4,300 MW) have been introduced to limit adequacy issues;
- 5 GW more hydro capacity in Brazil, due to additional installed power in some specific plants identified by the regulator and the system operator.

[13] Only the coal power plant of Bocamina, in Chile, has been kept in service, due to the short operational life which does not make convenient its shutdown.

The transmission network has been also reinforced in some specific areas where the load increase causes local congestions not related to the presence of the VRES plants. This assumption is consistent with the fact that if in a country the demand increases more than forecasted, the transmission system must be anyway improved to follow the higher load conditions limiting excessive stresses and bottlenecks.

3.1.2 Results of Variant 1

The higher demand and the reduction of the thermal capacity create the conditions for a stronger penetration of VRES plants. Table 18 shows the detailed optimal values of VRES, highlighting the variation with respect to the Base Case and the final total values in Variant 1.

PV installed capacity passed from less than 50 GW to more than 75 GW (nearly +50%), while wind installed power from 71 GW to 95.5 GW (+34%). Storage is also increased, reaching 16 GW (+75%).

Table 18 - Total VRES capacity and storage in Variant 1 [MW]

COUNTRY	Increase with respect to Base Case			Total Variant 1		
	PV	Wind	Storage	PV	Wind	Storage
ARGENTINA	1,500	1,530	500	12,100	17,400	3,000
BRAZIL	16,000	20,000	5,600	36,500	61,600	9,300
CHILE	1,100	230	250	12,400	5,500	2,250
COLOMBIA	2,500	1,000	250	4,900	3,700	470
ECUADOR	0	0	0	1,750	2,050	260
PERU	2,500	1,000	320	5,250	2,700	640
URUGUAY	0	450	60	230	2,500	80
TOTAL	23,600	24,260	6,980	73,130	95,500	16,000

The main results of the operation of the interconnected system are represented in Figure 7. The contribution of VRES plants to the demand supply increases considerably: thanks to the additional capacity (almost 48 GW), PV and wind plants introduced in the system cover more than 30% of the total load. The remaining part of the load increase is covered by natural gas and oil, as hydro availability and its absolute production remain unchanged (while its share decreases due to higher total generation).

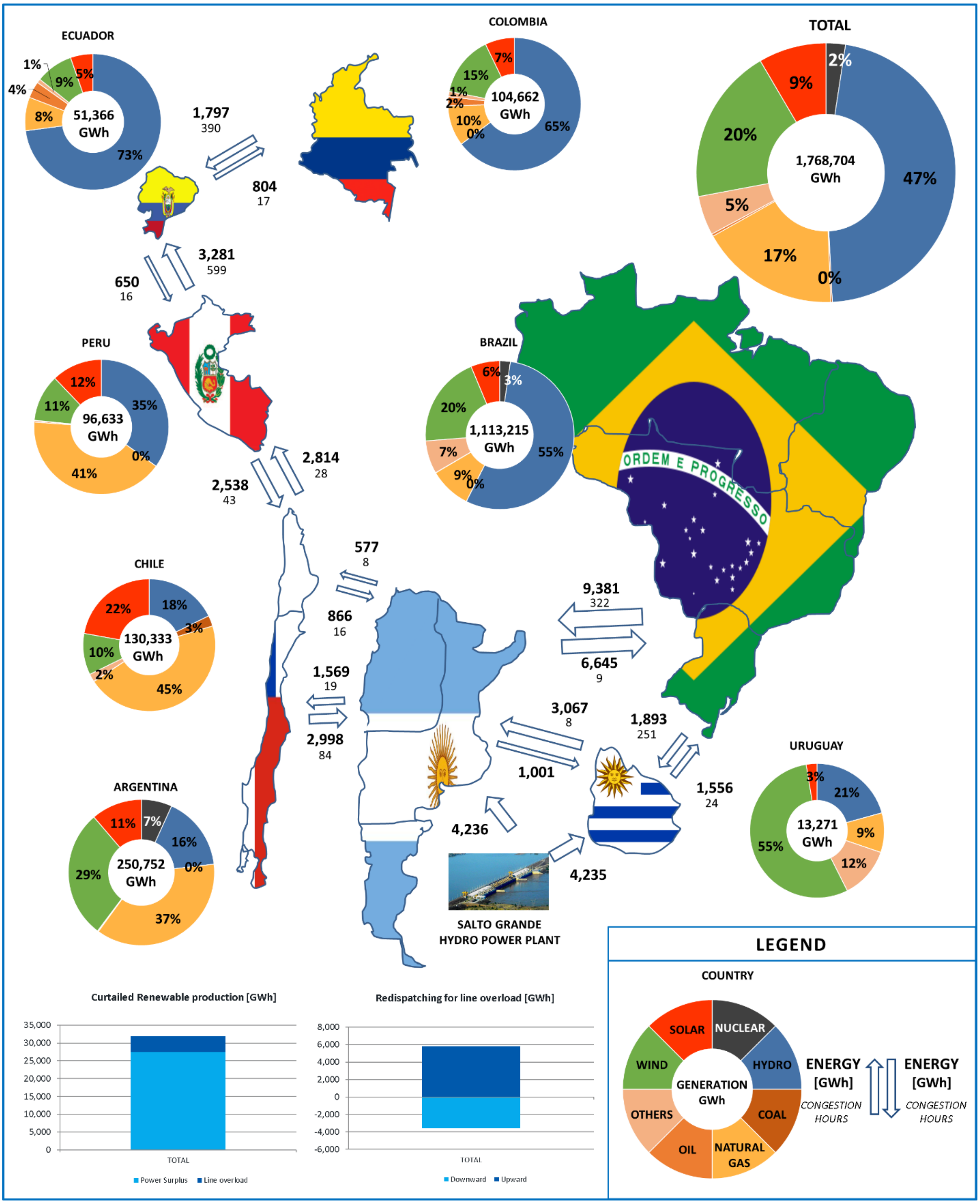

Figure 7 - Total production and energy exchanges at 2030 – Variant 1 – Continental case

Table 19 shows the values of EENS resulting from the simulations. Brazil has the lowest adequacy (EENS is equal to about $7x10^{-5}$) and even if in other countries there are resources available[14], the most effective and economic solution to improve the security of supply is the introduction of additional flexible generators (*peakers*) in the most affected Brazilian areas. As described in chapter 3.1.1, 2,700 MW of thermal generation (natural gas) have been included in the simulated scenario to bring the EENS below the $1x10^{-4}$ p.u. threshold. Further plants might be added to further improve the system adequacy. Also different technologies might be considered, for instance additional hydropower plants, provided they are able to ensure the required amount of energy when needed, with good dispatchability. The introduction of additional flexible generators able to cover the load peaks is more convenient than the improvement of the interconnections with other countries, as the areas suffering most EENS are located far from the borders and the reinforcements of the grid over long distances would be too expensive. The Plano Decenal de Expansão de Energia 2026 [9] proposes similar solutions in the planned scenario, suggesting the installation of an even higher amount of plants to ensure the coverage of the peak load. The assessment of the optimal amount of additional dispatchable capacity to be introduced with the increased level of VRES defined in the present study should take into account the target threshold for the adequacy, the costs of the new plants and the availability of primary energy sources.
Other countries do not present criticalities in terms of generation availability, but only minor issues related to local network congestions.

Table 19 - Expected Energy Not Supplied – Variant 1 – Interconnected system

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
ARGENTINA	0	104	0	104
BRAZIL	0	2,391	67,648	70,039
CHILE	0	435	0	435
COLOMBIA	0	0	0	0
ECUADOR	0	88	0	88
PERU	0	39	0	39
URUGUAY	0	0	0	0
TOTAL	0	3,057	67,648	70,705

As far as the PV and wind productions are concerned, Table 20 and Table 21 show the results for each country. PV plants inject in the grid nearly 150 TWh, while wind 345 TWh, together supplying more than 30% of the total demand.
In Brazil, due to the very high installed VRES capacity and the presence of big hydropower plants with limited dispatchability (RoR), there is a VRES curtailments risk higher than 20 TWh (about 7% of the total

[14] The EENS in Table 19 is labelled as "Lack of Interconnection" which means that there are available resources in the system, but, due to the limitation of the interconnections, they cannot be transferred to the Brazilian areas suffering load shedding. The possible solutions would be a) increase the installed capacity of dispatchable plants in the areas; b) increase the NTCs and the transmission capacity form the countries where there is available generation to the areas with EENS. This solution would require higher investments because of the long distances to be covered from one country to the other.

potential production), which still represents the optimal economic value. Considering that Brazilian system also suffers the highest amount of EENS, this fact shows that the operation of the power system might become more challenging in presence of limited flexibility of big generators and the high variability of VRES. Further flexible systems able to provide energy quickly, possibly storing it during overgeneration periods and releasing it when needed, might be useful also to improve the exploitation of the natural resources. Moreover, it is important to underline also that during real-time operation, a proper coordination of the fleet based on short- and medium-term generation forecasts can reduce the actual risk of overgeneration on one hand and lack of resources on the other, minimizing their impact. However, it is important that in a long-term planning investigation, these issues are identified and well addressed in order to define proper countermeasures.

Table 20 - Total production of PV plants at 2030 – Variant 1 – Interconnected system

PV PLANTS	TOTAL NET PRODUCTION [GWh/y]	RISK OF CURTAILMENT [GWh/year]		Installed capacity [MW]	Equivalent hours [MW]
AREA		System constraints	Network constraints		
ARGENTINA	28,262	628	110	12,100	2,345
BRAZIL	70,003	4,820	237	36,500	1,920
CHILE	28,858	683	1,079	12,400	2,337
COLOMBIA	7,499	1,047	0	4,900	1,528
ECUADOR	2,747	44	4	1,750	1,567
PERU	11,728	0	385	5,250	2,234
URUGUAY	345	0	0	230	1,505
TOTAL	149,442	7,222	1,815	73,130	2,044

Table 21 - Total production of Wind plants at 2030 – Variant 1 – Interconnected system

WIND PLANTS	TOTAL NET PRODUCTION [GWh/y]	RISK OF CURTAILMENT [GWh/year]		Installed capacity [MW]	Equivalent hours [MW]
AREA		System constraints	Network constraints		
ARGENTINA	71,400	932	1,745	17,400	4,126
BRAZIL	222,164	17,025	312	61,600	3,606
CHILE	13,196	130	9	5,500	2,410
COLOMBIA	15,442	1,157	122	3,700	4,172
ECUADOR	4,567	33	1	2,050	2,227
PERU	10,895	0	36	2,700	4,035
URUGUAY	7,274	8	33	2,500	2,846
TOTAL	344,938	19,285	2,258	95,500	3,613

Comparing the energy exchanges shown in Figure 7 with the ones resulting in the Base Case (Figure 2) it is possible to notice that the net balance of some country changes significantly. In particular, Brazil becomes a net exporter (more than 3 TWh net energy flow towards Argentina and Uruguay), while Argentina increases the amount of energy imported from neighbouring countries. Peru exports energy towards Ecuador which increases the import as PV and wind resources are lower than in other countries and it is not convenient to increase the VRES penetration. The net balance of Chile and Uruguay remains similar to the one of the Base Case, meaning that the increase of VRES plants in the countries is consistent with the increase of the demand.

The importance of the interconnections between the countries is also visible in the assessment of the benefits deriving from the possibility to exchange excess of energy, sharing the most economic generation and mutually supporting each other.

In fact, in case countries are operated as isolated systems, the risk of VRES curtailments increases considerably: +3.8 TWh for the PV production, and +6.8 TWh for wind (in both cases about 2% of the total available energy), mainly for overgeneration issues due to the impossibility to evacuate the high production from VRES, hydro and minimum set of thermal plants. This energy must be supplied by more expensive thermal plants, which increase their production by 7.4 TWh[15], with relevant higher costs and emissions (about 5 Mt CO_2).

Moreover, also the security of supply would be lower in the countries which have limited resources or generation constraints: in particular in Brazil EENS would increase by 31 GWh (about $3x10^{-5}$ of the load) and in Argentina some adequacy problems would appear with EENS equal to 13 GWh ($5x10^{-5}$ of the load). The other countries experience smaller deterioration of the security of supply.

The total economic benefit deriving from the optimal coupling of electricity markets, the better exploitation of renewable resources and the lower usage of fossil fuels, together with the lower amount of EENS, can be quantified in more than USD 1.6 billion. This value is significantly higher than the corresponding advantage calculated in the Base Case due to the particular configuration of the generation fleet simulated in Variant 1, with reduced thermal capacity (the cheap coal power plants have been only partially replaced with natural gas plants) which requires a more frequent usage of more expensive plants. This impacts the generation costs in particular when the most economic resources cannot be shared through the usage of the interconnections.

Table 22 summarizes the main economic benefits achievable with an optimal exploitation of the interconnections between the countries.

Table 22 - Total benefits achievable with optimal exploitation of interconnections – Variant 1

	ELECTRICAL SYSTEM	ADDITIONAL BENEFITS
	GWh/year	USD million/year
TOTAL THERMAL GENERATION	-7,450	1,570
VRES CURTAILMENT	-10,600	-
TOTAL EENS	-45.6	90
TOTAL BENEFITS	-	**1,660**

[15] The increase of the thermal production is lower than the reduction of the VRES generation due to the lower amount of losses on the transmission system present when the different power systems are operated as isolated and the energy is transferred over long distances between countries.

3.2 Second Variant: enhanced energy efficiency

3.2.1 Main assumptions

In the second Variant a lower demand scenario has been investigated, aimed at assessing how the VRES penetration growth can be affected in this condition and with the given hydro and thermal generation fleet. The key parameters that are modified with respect to the Base Case are described in the following paragraphs.

As far as the demand is concerned, the main drivers which can contribute to a demand lower than the one considered in the Base Case are:

- a possible economic scenario with growth lower than forecasted, condition already examined in many national development plans;
- an improvement of energy efficiency with respect to what was already accounted for, which can reduce the amount of electrical energy needed for specific uses (light, electric motors, industrial processes…)

According to what was defined in [4][5][6] and depending on the levels of energy efficiency already considered in the definition of the hypothesis of the Base Case, the load is reduced by 8% in Uruguay, 10% in Brazil, Chile and Colombia and 15% in Argentina, Ecuador and Peru. The demand reduction is distributed proportionally in all the nodes of the countries.

Only minor changes have been applied to the available thermal and hydro generation capacity with respect to the one considered in the Base Case: the 300 MW dispatchable plant introduced in the Base Case in Ecuador due to adequacy issues has been removed as the security of supply is ensured even without it given the lower demand.
Moreover, in this Variant it is considered the possibility to introduce storage plants (pumping hydro) to ensure a higher flexibility of the generation fleet and increase the minimum load of the systems. This helps limiting the risk of overgeneration which can cause higher VRES generation curtailments with respect to the Base Case. The option for new pumping storage plants has been introduced in Chile, as in this country it is analysed also in the generation expansion studies presented by the Coordinador Eléctrico Nacionál in the last years. On the contrary, this possibility has not been applied in other countries because of the presence of an already significant amount of hydropower plants or due to difficulties in their possible realization for instance because of environmental issues.
Finally, the transmission systems and the interconnections between the countries are kept the same as in the Base Case.

3.2.2 Results of Variant 2

Table 23 shows the resulting optimal values of PV and wind capacity in the different countries, and the variation with respect to the assumptions of the Base Case based on the plans set up by each country (reported in Table 2). In Chile two pumped storage plants (300 MW each) have been introduced in the SING area and close to Santiago, to increase the flexibility of the generation fleet and the minimum demand.

The optimal values of VRES capacity in this scenario reach almost 29 GW for PV and 47.8 GW for wind, showing an increase by 25% of the quantities planned by the countries.

Even in a condition with lower demand and high capacity of hydro and thermal power plants there is room for additional VRES in the areas with highest potential. Nonetheless, countries with already a high availability of hydro resource with limited flexibility (run-of-river plants) and with significant demand reduction (like Brazil) show no convenience to increase the planned amount. Countries with strong interconnection capacity with other systems can more easily introduce additional VRES plants[16].

Table 23 - Total VRES capacity and storage in Variant 2 [MW]

COUNTRY	INCREASE WITH RESPECT TO INITIAL ASSUMPTION		TOTAL VARIANT 2		
	PV	Wind	PV	Wind	Storage
ARGENTINA	1,520	4,000	6,520	8,950	780
BRAZIL	0	0	9,600	28,500	0
CHILE	4,500	1,000	8,600	4,900	1,400
COLOMBIA	200	500	1,300	1,700	50
ECUADOR	100	100	200	200	20
PERU	2,200	1,100	2,500	1,500	290
URUGUAY	0	500	230	2,050	60
TOTAL	8,520	7,200	28,950	47,800	2,600

Compared to the Base Case, the optimal VRES capacity in many countries is lower because a significant portion of the needed energy is already produced by hydropower plants. For this reason, the demand to be covered with thermal and VRES plants is actually subject to a much stronger relative reduction than the ones applied to the overall demand, impacting more significantly the results of the optimal VRES capacity.

EENS is null in the system thanks to the abundancy of energy sources and plants with respect to the peak load.
Similarly, RES curtailments due to network congestions almost disappear as the transmission system is less loaded in this low demand Variant. In parallel, the curtailments due to system constraints remain similar to the ones in the Base Case, but affecting less PV and wind plants and more the hydropower ones.
The total PV production is equal to 63.7 TWh, suffering curtailments lower than 1%, while the wind generation sums up to more than 177 TWh, taking into account about 3% limitations mainly concentrated in Brazil.
The risk of VRES and hydro curtailments is located mainly in Brazil (almost 11 TWh), while for Argentina, Colombia and Chile it sums up to about 0.6 TWh in total.

[16] Uruguay, which has a strong interconnection towards Argentina and Brazil compared to its peak load, can maintain the same VRES installed capacity as in the Base Case because can export its (small) excess of production given the strong decrease of the VRES capacity in the neighbouring countries. However, similar benefits for the system can be obtained when the VRES decrease is partially shared between Argentina and Uruguay

In this Variant 2, the optimal amount of VRES is lower than in the Base Case[17] because there is more availability of relatively cheap thermal generation. However, there is a lower risk of curtailments. Two considerations are particularly important:

- In a lower demand scenario, it is possible that not all the hydro and thermal power plants planned at 2030 are actually developed and built, because they might result to be not technically necessary or not economically viable or might incur more difficulties during the authorization process. In this case, VRES would become more competitive and their optimal capacity higher than the one resulting from the present investigation.
  In such a context, flexibility, modularity and shorter installation time of VRES plants with respect to other technologies, in addition to the low costs, 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.
- Externalities (such as emissions of CO_2 or other pollutants) are not considered in the economic assessment performed in the present study. If they were included in the analysis, the thermal generators would show higher costs and VRES would become even more competitive and attractive, increasing their optimal capacity.

Figure 8 shows the main figures of the operation of the interconnected system in Variant 2. Hydropower resource, which is assumed to be the same as in the Base Case, increase its share from 51% to 57% as the demand is lower. Thermal generation maintains similar shares, reducing the absolute production.
From the graphs it is possible to note that the countries where VRES capacity has the lowest increase with respect to the initial assumptions (Brazil, Colombia, Ecuador) are the ones where hydro resource is the highest. In Argentina the optimal VRES amount is limited by the stronger assumption on demand reduction compared to the other countries.

[17] As explained in Chapter 3.2.1, Variant 2 is characterized by a lower demand and the same generation fleet. This means that the load not supplied by hydropower plants is significantly lower, and that cheaper thermal generators become the marginal unit which would be replaced by VRES generation.

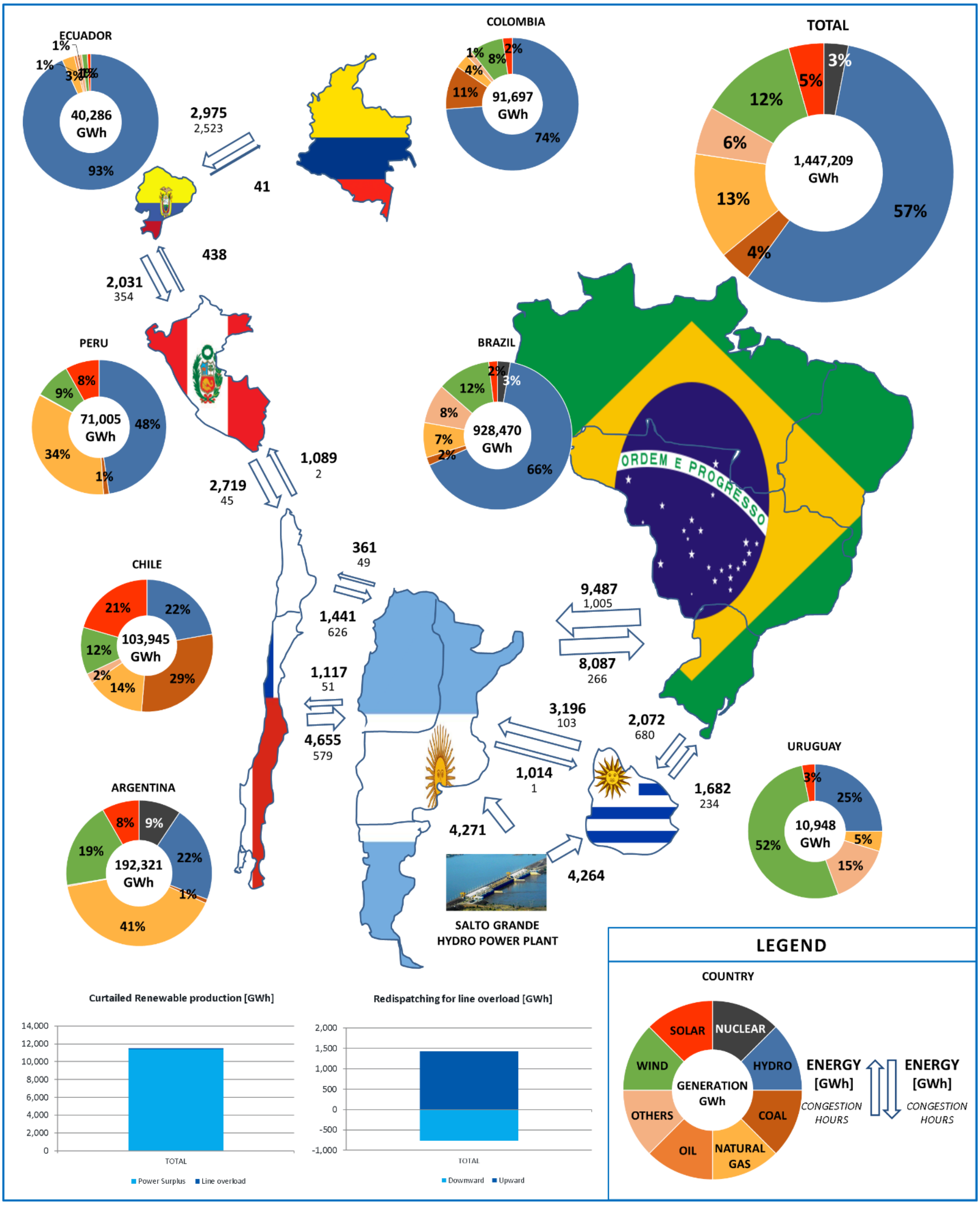

Figure 8 - Total production and energy exchanges at 2030 – Variant 2 – Continental case

From the comparison of the energy exchanges depicted in Figure 8 with the ones of the Base Case (Figure 2), countries with strong presence of hydropower plants increase their exports towards the ones with a generation fleet more based on more expensive thermal plants: in particular Argentina has a net import equal to more than 8 TWh and the energy exchanges with Brazil are nearly inverted.

As done for Variant 1, the benefits for the system ensured by the optimal utilization of the interconnections have been evaluated simulating also the operation of the system not allowing energy exchanges between countries.

Due to the low demand, countries have enough generation resources to avoid EENS, even when operated as isolated. On the contrary, when evacuation of the production towards other countries is not allowed, VRES curtailments would be 1.4 TWh and 4.1 TWh higher for PV and wind (corresponding to respectively an increase of 250% and 75%) due to risk of overgeneration. Hydropower production is also affected, with limitation increasing by 4.3 TWh.

Taking into account the variation of the losses in the system, which are higher when the energy can be exchanged between countries, in the interconnected scenario the final production by thermal generation is expected to be about 5.5 TWh lower than in the isolated case, corresponding to fuel savings equal to nearly USD 1 billion[18]. Moreover, CO_2 emissions also decrease by about 2.8 Mt thanks to better utilization of the generation fleet.

The total benefits achievable with the optimal exploitation of the interconnections in Variant 2 are summarised in Table 24.

Table 24 - Total benefits achievable with optimal exploitation of interconnections with respect to isolated case – Variant 2

	ELECTRICAL SYSTEM	ADDITIONAL BENEFITS
	GWh/year	USD million/year
TOTAL THERMAL GENERATION	-5,560	978
VRES CURTAILMENT	-5,530	-
TOTAL EENS	0.0	0
TOTAL BENEFITS	**-**	**978**

[18] Fuel savings include both the benefits from lower thermal generation (because replaced by RES) and the optimal exploitation of the fleet, which can supply more demand using the cheapest plants.

4 CONCLUSIONS

At the end of the studies focused on different clusters of countries in South America, an analysis on the whole system including Argentina, Brazil, Chile, Colombia, Ecuador, Peru and Uruguay has been carried out, to assess how the possibility to exchange energy between the power systems improves their operation and allows a better deployment and exploitation of PV and wind power plants.
Main results are listed below:

- The optimal amount of VRES installed capacity in the target year (2030) reached almost 50 GW for PV and more than 71 GW for wind and was estimated taking into account the costs of the plants, the availability of the resources and the risk of curtailments due to system or transmission constraints. Compared to the targets and forecasts presented in the national generation and transmission development plans (at the basis of the reference scenario defined in [4][5][6] from which the investigation has started), the new optimal values correspond to an increase by 150% of PV installed capacity and by 75% of wind power plants.
  The relevant production exceeds 105 TWh for PV and 265 TWh for wind, covering together about 25% of the total demand. Associated to the new plants also about 9 GW of battery storage systems are introduced, which ensure a smoother and more flexible dispatching of VRES generation reducing errors between forecasts and effective production in real time operation and enabling shifting the energy in periods with higher demand.
  Risk of VRES generation curtailments is limited to about 3% of the potential production, while it increases to about 6% for PV and 4% for wind in case the power systems of the countries are operating without the possibility to exchange energy.
  The benefits generated by the additional plants sum up to about USD 3.6 billion at the target year, considering the fuel savings and the annuity of the investments needed for the additional VRES.
- The interconnections contribute to the optimal operation of the system allowing the usage of cheapest generation resources and limiting the risk of RES production curtailments. If countries were not allowed to exchange energy and support each other, thermal generators would be required to produce 4.5 TWh more as consequence of increased curtailments of RES power plants and fuel costs would increase by about USD 680 million due to usage of expensive thermal plants (equal to about 4% of the total expenses for production based on fossil fuels). About 2 Mt of extra CO_2 each year would be also released in the atmosphere.
  These savings have to be considered as the maximum value achievable at the target year with a full integration of the different electricity markets and coordination of the operation. In order to obtain the maximum benefits, regulations and market rules should promote as much as possible the joint operation of the different power systems, enabling the usage of the cheapest resources and exploiting the greater flexibility available in a more interconnected system.
- Interconnection capacity investigated in the study, based on the existing lines and suggested future projects, ensures adequate NTCs between countries: the limit of the transmission capacity is reached more frequently on weak interconnections (between Colombia and Ecuador and from North of Chile to North of Argentina), nonetheless this condition takes place less than 5-6% of the time.
- In the interconnected configuration, Chile, Colombia and Uruguay become exporters towards Brazil, Argentina and Ecuador. Peru shows an almost net balance between imports and exports also because the cost of generation from natural gas is kept low for the internal demand thanks to subsidies.

- The presence of the optimal amount of VRES plants and the exploitation of the interconnections make possible to avoid the emission of about 85 Mt of CO_2 in the atmosphere per year with respect to the condition which would happen when only the amount of VRES plants foreseen in the current national targets is developed. The economic benefits deriving from this strong reduction in terms of negative externalities and further possible savings have not been taken into account and would push for an even higher penetration of VRES plants.

A sensitivity analysis has been carried out investigating how the optimal VRES installed capacity changes in case of VRES costs reduction, in particular for PV, which experienced the strongest decrease over the last decades. In this condition, VRES become even more competitive than before, able to replace cheaper thermal generation and can also accept higher risk of curtailments due to the lower economic impact.
The new VRES optimal capacity increases especially for PV technology in the areas with highest resource, lower system and transmission constraints and more expensive thermal generation to be replaced. The results show that it is optimal to insert in the system 11.7 GW of additional PV plants and 1.8 GW of wind, which produce respectively 20 TWh and 5.9 TWh. These plants suffer an increased risk of curtailments (about 20% of the possible production cannot be injected in the grid for system or network constraints), but it is still convenient to install them due to the reduced costs. This VRES generation further reduce the CO_2 emissions by more than 12 Mt per year, totalling a reduction of almost 100 Mt with respect to the case in which the installed capacity will be limited to the targets set by the countries in their currently available development plants.

Moreover, the operation of the interconnected power system has been simulated also in case of dry or wet conditions through a sensitivity analysis, in order to assess possible adequacy issues in case of lack of hydro resource and the risk of increased VRES curtailments in case of abundance. This information is necessary for a proper planning of the generation expansion and the evaluation of the convenience of high penetration of VRES plants.

- In the dry scenario, EENS increases considerably, in particular in the Brazilian areas not interconnected with other countries, highlighting the need here for some additional power plants or solutions able to compensate the missing hydro production with respect to the Base Case. Due to the long distances, the effective reinforcement of the transmission system up to areas with available resources would be a very expensive solution. Even if they are not economically optimal in the average hydrological year, more flexible generators or even pumped-storage plants, further storage systems, additional hydropower capacity in selected locations (already proposed in the Plano Decenal de Expansão de Energia 2026 by EPE) should be included in the optimal configuration of the Base Case, as they represent the most effective solution to ensure proper security of supply in the affected areas.
  VRES suffer less curtailments, increasing their production by 6.2 TWh, while thermal generators are required to produce about 100 TWh more, increasing the related costs by nearly 50%. CO_2 emissions are also 30% higher.
- In the wet scenario, on the contrary, the abundance of hydro eliminates the EENS due to lack of resources, and only the one due to small local congestions remains. The risk of curtailments of renewable generation increase by 13 TWh (reaching in total about 6% of the potential production), and at the same time more than 65 TWh produced by thermal plants can be avoided, replaced by the additional hydro. Countries with high presence of hydropower plants, such as Brazil, Colombia

and Ecuador, increase their export towards the others, with a consequent higher loading of the interconnections.

Two Variants have also been analysed, aimed at evaluating the variation of the optimal configuration in case some major changes on the demand and on the generation fleet take place with respect to the assumptions of the Base Case.

In the Variant 1, representing an accelerated decarbonization path in a strong economic development, the demand in the countries has been increased also considering a deeper penetration of e-vehicles, and the coal power plants have been tentatively switched off and replaced by VRES plants. Where necessary, some thermal power plants fuelled with natural gas and with reduced CO_2 emissions are introduced to ensure minimum levels of security of supply.

- In this scenario, PV and wind optimal installed capacity resulted respectively 50% and 34% higher than in the Base Case, reaching 75 GW and 95.5 GW. Furthermore, storage associated to these new plants reaches 16 GW to ease the integration of VRES plants.
- VRES production covers more than 30% of the total demand.
- Some EENS appears in Brazil, where additional dispatchable generators are needed to compensate the high variability of the huge amount of VRES (almost 100 GW). Similarly to the results obtained in the dry sensitivity of the Base Case, solutions for the coverage of the peak load already proposed in the existing generation expansion plan should be taken into account. In the optimal configuration of the Variant 1 2,700 MW of flexible thermal generators have been introduced to maintain the EENS below the 10^{-4} threshold. Higher capacity might be included to reach better adequacy levels.
  Eventually, in Chile 4,300 MW of natural gas plants are introduced to ensure adequacy after considering also the shut-down of the coal plants.
- The stronger penetration of VRES plants increases the risk of production curtailments, especially in the countries characterized by the presence of big hydropower plants with limited dispatchability (run-of-river) and high installed VRES capacity. The optimal economic amount is reached with a risk of curtailments around 7% of the potential VRES production.
- Interconnections play a significant role improving the security of supply, limiting the risk of VRES curtailments (which would be more than 10 TWh higher without the possibility to export excess of generation), optimizing the usage of the generation fleet and reducing CO_2 emissions by about 5 Mt per year.

In Variant 2, an enhanced energy efficiency scenario has been set up, reducing the demand in the countries also according different targets available at national level. Generation fleet has been assumed substantially aligned with the one of the Base Case and the availability of energy from hydro resource is maintained the same.

- Optimal PV installed capacity is estimated at 29 GW while wind reaches almost 48 GW, corresponding to a general increase by 25%, if compared to what was planned by the countries. Also in a condition with lower demand there is room for additional VRES in the areas with highest potential, even if limited by the lower load to be supplied and the competition against cheaper thermal generators.
- Total production by PV and wind plants is equal to almost 64 TWh and 177 TWh. Risk of curtailments affects only a low percentage of the potential production.

- Interconnections contribute to the optimal economic operation of the system as, among others, they allow the exploitation of the cheapest resources, avoiding 5.5 TWh VRES curtailments. Thermal production decreases by about 5 TWh (fuel savings higher than USD 1 billion), reducing CO_2 emissions by 2.8 Mt.

If in a low demand scenario not all the generation capacity planned at 2030 is developed because not technically necessary or economically viable, more VRES plants become part of the solution, and, thanks to their low costs, flexibility, and short installation time, increase their penetration.

Table 25 provides a summary of the optimal PV and wind installed capacities in the countries resulting from the performed analysis.

Table 25 - Summary of optimal VRES capacity in different analysed scenario at 2030 [MW]

COUNTRY	GENERATION EXPANSION PLANS		BASE CASE OPTIMAL		ENHANCED		HIGH DEMAND		LOW DEMAND	
	PV	Wind	PV	PV	Wind	Wind	PV	Wind	PV	Wind
ARGENTINA	5,000	4,950	10,600	15,870	13,600	16,370	12,100	17,400	6,520	8,950
BRAZIL	9,600	28,500	20,500	41,600	26,500	42,100	36,500	61,600	9,600	28,500
CHILE	4,100	3,900	11,300	5,270	12,300	5,270	12,400	5,500	8,600	4,900
COLOMBIA	1,100	1,200	2,400	2,700	2,600	2,900	4,900	3,700	1,300	1,700
ECUADOR	100	100	1,750	2,050	1,750	2,050	1,750	2,050	200	200
PERU	300	400	2,750	1,700	4,250	2,200	5,250	2,700	2,500	1,500
URUGUAY	230	1,550	230	2,050	230	2,150	230	2,500	230	2,050
TOTAL	20,430	40,600	49,530	71,240	61,230	73,040	73,130	95,500	28,950	47,800

In conclusion, the study has shown a great potential for VRES deployment in the analysed South American countries, thanks to the excellent availability of natural resources, the demand growth and the expected decrease of VRES costs. Figure 9 provides a graphical representation of the net demand coverage by VRES plants achieved thanks to their optimal penetration in the different scenarios. Together with the hydropower resource (which covers from 50% to 60% of total demand depending on the case), the optimal VRES capacity would allow to supply more than 75% of the system load with renewable energy. Existing and suggested interconnection capacities allow the best exploitation of VRES plants thanks to the possibility to export excess of generation and the mutual support between countries. Regulations should promote the integration of VRES plants at national and international level enabling higher flexibility and coordination in the operation of the different power systems to ensure that the benefits can be fully achieved.

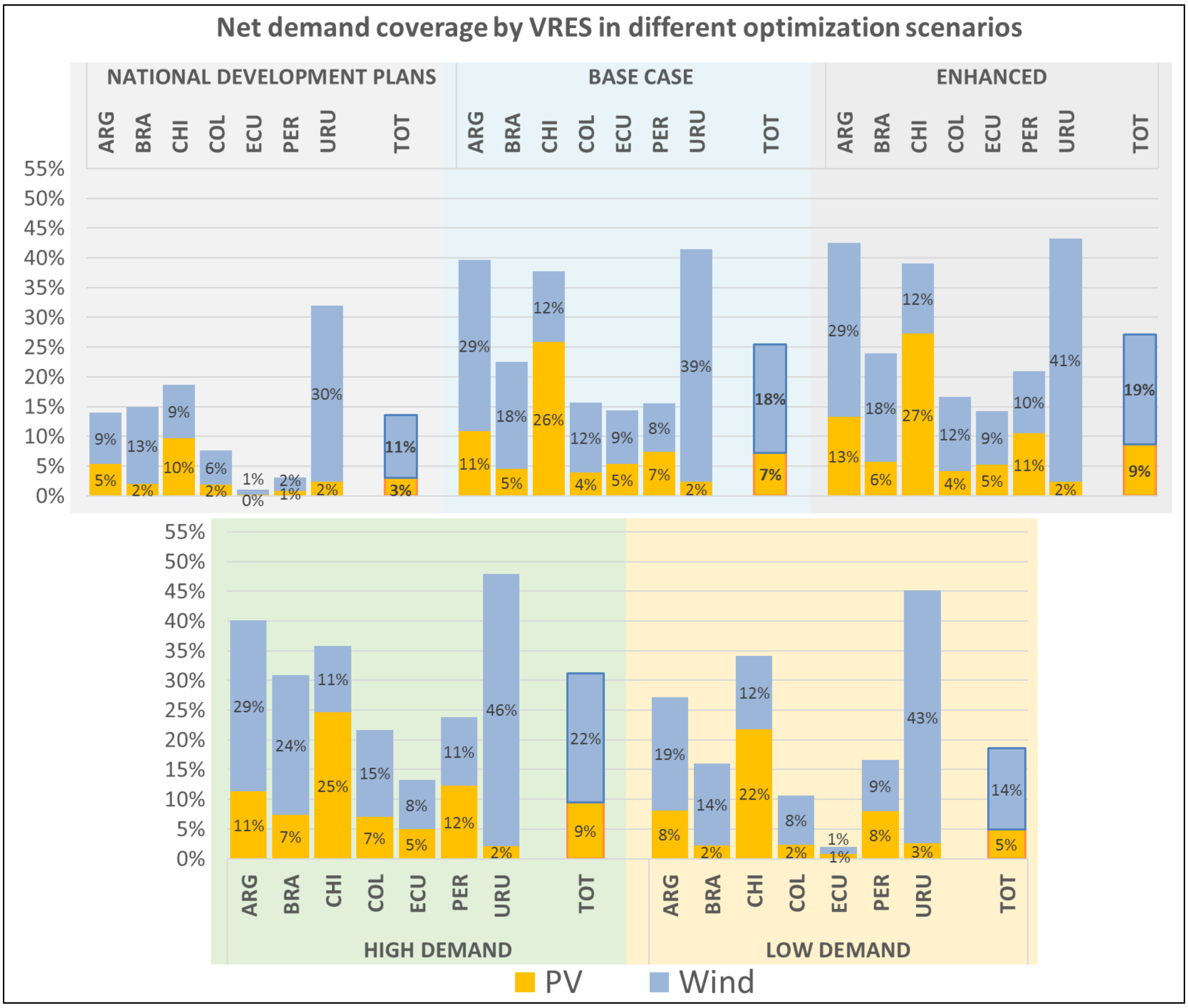

Figure 9 - Net demand coverage by VRES in different optimization scenarios at 2030 – Continental case

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