Executive Summary

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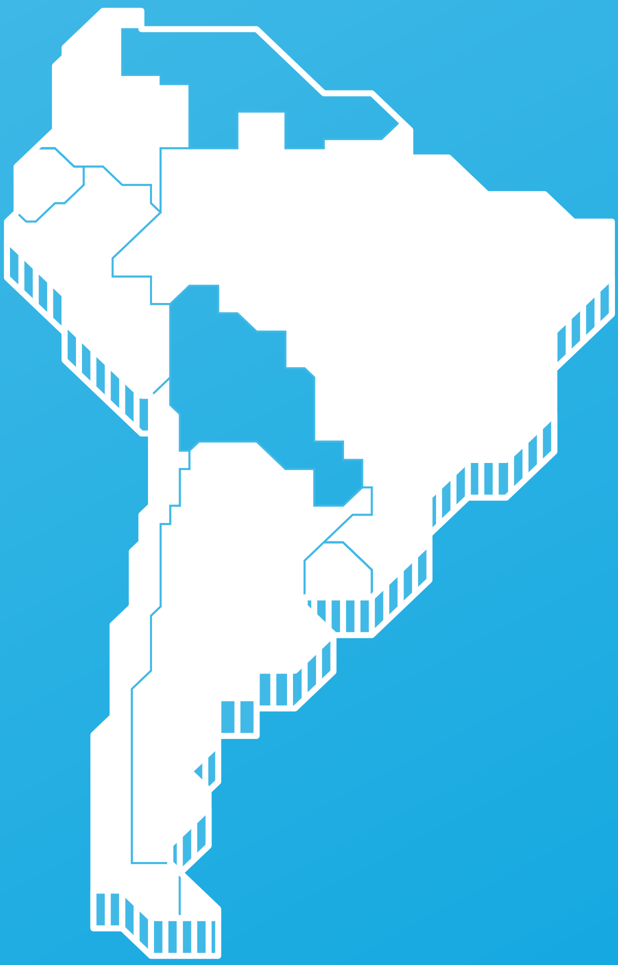
South America



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

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

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List of acronyms

BESS	Battery Energy Storage System
EENS	Expected Energy Not Supplied
EPE	Empresa de Pesquisa Energética
NTC	Net Transfer Capacity
PV	PhotoVoltaic
RES	Renewable Energy Source
VRES	Variable Renewable Energy Source

1 General objective of this study

South America is endowed with outstanding renewable energy resources. The location of new power plants exploiting RES is constrained by the geographical availability of the resources (wind, sun, geothermal, biomasses, hydro). Hence, the integration of a large quantity of RES into the power system 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 from the areas with highest potential or impossibility to balance the system due to the inflexibility of the conventional generation). Limitations to the development of RES generation, particularly the variable generation such as PV and wind, can be overcome, among others, by exploiting the existing interregional or crossborder interconnections, reinforcing the existing ones and building new crossborder corridors.

This study on "*VRES deployment and role of interconnection lines for their efficient exploitation*" aims at examining the optimal technical and economic penetration of Variable Renewable Energy Source (VRES, namely photovoltaic and wind) generation in selected countries, accounting for the possible cross border power exchanges. The analysis focuses on Argentina, Brazil, Chile, Colombia, Ecuador, Peru and Uruguay and the optimal operation of their power systems at 2030.
The research aims at answering the following main questions:

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

2 The study process

The study evaluates the optimal amount of PV and wind plants in the analysed countries in three main different configurations of the power systems characterized by different assumptions on the demand and the available technologies in the generation fleet:

- The ***Base Case*** represents the expected situation in terms of demand growth and generation expansion based on the development plans available for each country. In this configuration, two different optimisations have been carried out, modifying the assumptions on the costs of new VRES plants: in addition to the optimal VRES capacity in the reference Base Case, it is assessed also an ***enhanced VRES installed capacity*** applying a stronger reduction of the investments required for the new installed capacity.

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

Detailed information on the assumptions can be found in [1][2][3].
For each of these three system configurations, a "Reference Scenario" is identified, which includes the expected amount of generation per source based on the examined expansion plans of the different countries at the target year 2030. The "Reference Scenario" represent the basis of the optimization process which defines, through an iterative calculation, the optimal technoeconomic VRES generation deployment in each case. This amount maximizes the benefits for the system calculated in terms of fuel savings and reduction of the Expected Energy not Supplied (EENS[1]) minus the costs (investments for the new plants and increase of EENS, if any). The optimization process takes into account the potential of VRES across the territory, their costs and performances.

Exploitation of generation resources and VRES can be affected by system constraints (such as minimum amount of production due to the characteristics of the thermal and hydro generation fleet and reserve to be ensured) and limits of the power transfer capacity of the transmission grid. A development of VRES technologies and the possible coupling with battery energy storage systems (BESS) have been assumed, so that in 2030 they will be able to provide the system with auxiliary services, like frequency regulation, hence reducing the need for additional upward and downward reserve, and voltage regulation. In this context, it is possible to increase the penetration of VRES while keeping adequate security of supply.

The optimization process has been applied first to the isolated countries, identifying optimal national VRES targets independent from the energy exchanges with neighbouring ones, and then to clusters of countries. The results of these analyses can be found in [4][5][6]. Finally, the optimization has been carried out on the whole system (called "Continental case"), taking into account the outcomes of the previous investigations. The detailed results of the Continental case are presented in [7] and summarized here.

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

3 Computational tools

The optimisation process is based on the assessment of the expected operation of the system in 2030, the relevant costs, the system adequacy and the risk of overgeneration in presence of an increasing share of VRES. In order to obtain these results, it was adopted the GRARE[2] software, which evaluates the reliability and the economic operation of large electric power systems using probabilistic Monte Carlo approach and modelling in detail the transmission networks. It simulates the optimal operation of the system in thousands different configurations (considering load variations, forecast errors, availability of generation fleet and transmission networks, VRES power production), weighted by their probability to happen. The results depict the expected operation of the whole system providing the benefits in terms of variation of generation costs and different generation adequacy, measured by means of EENS indicator. The comparison with the costs of the additional VRES capacity drives the optimization until the optimal condition is found, where the benefits generated by the new plants are equal to the relevant costs.

Moreover, the simulations provide the expected production of VRES plants in each country, considering potential curtailments due to system or transmission constraints. The calculation of VRES plants producibility based on geographical information combined with the usage of a detailed transmission system model allow to clearly identify the best areas where PV and wind plants should be deployed in order to maximize the benefits for the system.

2 More info on GRARE (Grid Reliability and Adequacy Risk Evaluator) tool is available on www.cesi.it/grare.

4 Main assumptions

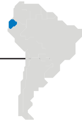
Figure 1 provides a graphical representation of the main data concerning the demand and installed capacity per technology in each analysed country and in the whole system in the Base Case. This data has been defined based on generation expansion plans and demand forecasts of each country, as reported in [1][2][3]. Availability of hydro resource has been defined to represent average hydrological conditions. Sensitivities on dry and wet years have also been investigated.
For the analysis of the two Variants the demand of each country has been increased or lowered according to the scenarios available in the national development plans.

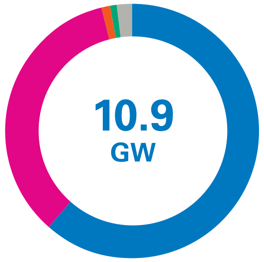
Table 1 summarises the main economic and financial parameters (discount rate, CAPEX, OPEX) assumed at 2030, which affect the cost of the energy produced by PV and wind power plants.

Table 1 - 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
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

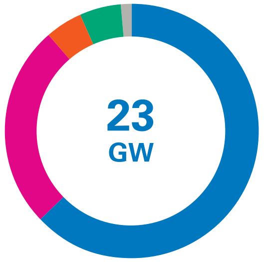
Ecuador (49.4 TWh)





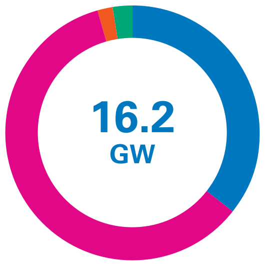
Hydro	6,700
Thermal	3,800
Others	200
PV	100
Wind	100
Nuclear	0

Colombia (100.8 TWh)



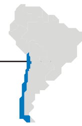
Hydro	14,500
Thermal	5,900
Wind	1,200
PV	1,000
Others	300
Nuclear	0

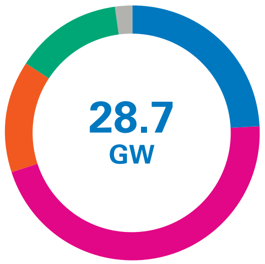
Peru (85.0 TWh)



Thermal	9,700
Hydro	5,800
Wind	400
PV	300
Others	0
Nuclear	0

Chile (108.6 TWh)

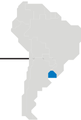


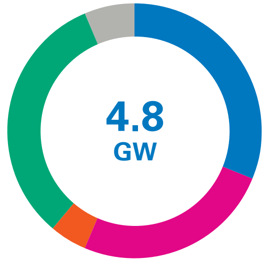


Thermal	13,100
Hydro	7,000
PV	4,100
Wind	3,900
Others	600
Nuclear	0

Figure 1 - Summary of main data assumptions

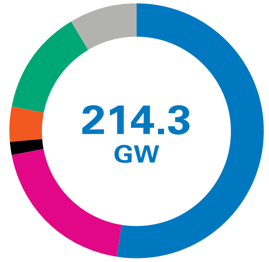
Uruguay (14.7 TWh)





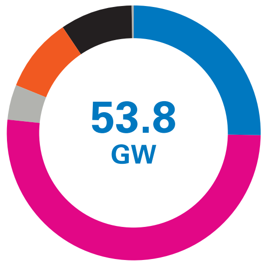
Wind	1,550
Hydro	1,500
Thermal	1,200
Others	300
PV	230
Nuclear	0

Brazil (874.8 TWh)



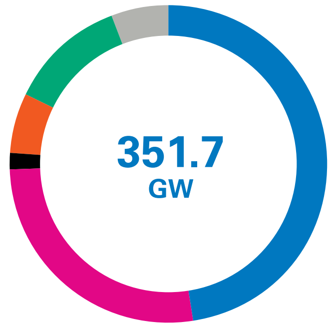
Hydro	113,000
Thermal	41,600
Wind	28,500
Others	18,200
PV	9,600
Nuclear	3,400

Argentina (229.9 TWh)



Thermal	27,600
Hydro	13,700
PV	5,000
Wind	4,950
Nuclear	2,500
Others	100

TOTAL (1463.2 TWh)



Hydro	162,200
Thermal	90,700
Wind	40,600
PV	20,430
Others	19,700
Nuclear	5,900

5 Results

5.1 Base Case

The optimal amount of VRES installed capacity at the target year (2030) in the Base Case reaches almost 50 GW for PV and more than 71 GW for wind. Compared to the targets and forecasts presented in the national generation and transmission development plans (at the basis of the reference scenario 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 (see also Figure 6). 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 forecasts errors in real time operation and enabling peak shifting. In this configuration, the risk of VRES generation curtailments is limited to about 3% of the potential production.

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 capacity.
The presence of the calculated optimal amount of VRES plants and the exploitation of the interconnections reduces the emission of about 85 Mt of CO_2 in the atmosphere per year with respect to the Reference Scenario. The economic benefits deriving from this strong reduction in terms of negative externalities and further possible savings have not been made explicit and taken into account and would push for an even higher penetration of VRES plants.
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. The comparison of the optimal scenario with the one in which countries are not allowed to exchange energy among them shows that, if countries operate as isolated:

- risk of VRES curtailments increases to about 6% for PV and 4% for wind,
- the thermal generators are required to produce 4.5 TWh more,
- fuel costs increase by about USD 680 million due to usage of more expensive thermal plants (equal to about 4% of the total expenses for production based on fossil fuels),
- additional 2 Mt CO_2 emissions are released each year in the atmosphere.

These savings due to the interconnections 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 these 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.

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. Moreover, the value of the risk of RES generation curtailments is reported, specifying the reason.

Electrical energy demand and generation fleet at 2030 – BASE CASE OPTIMAL

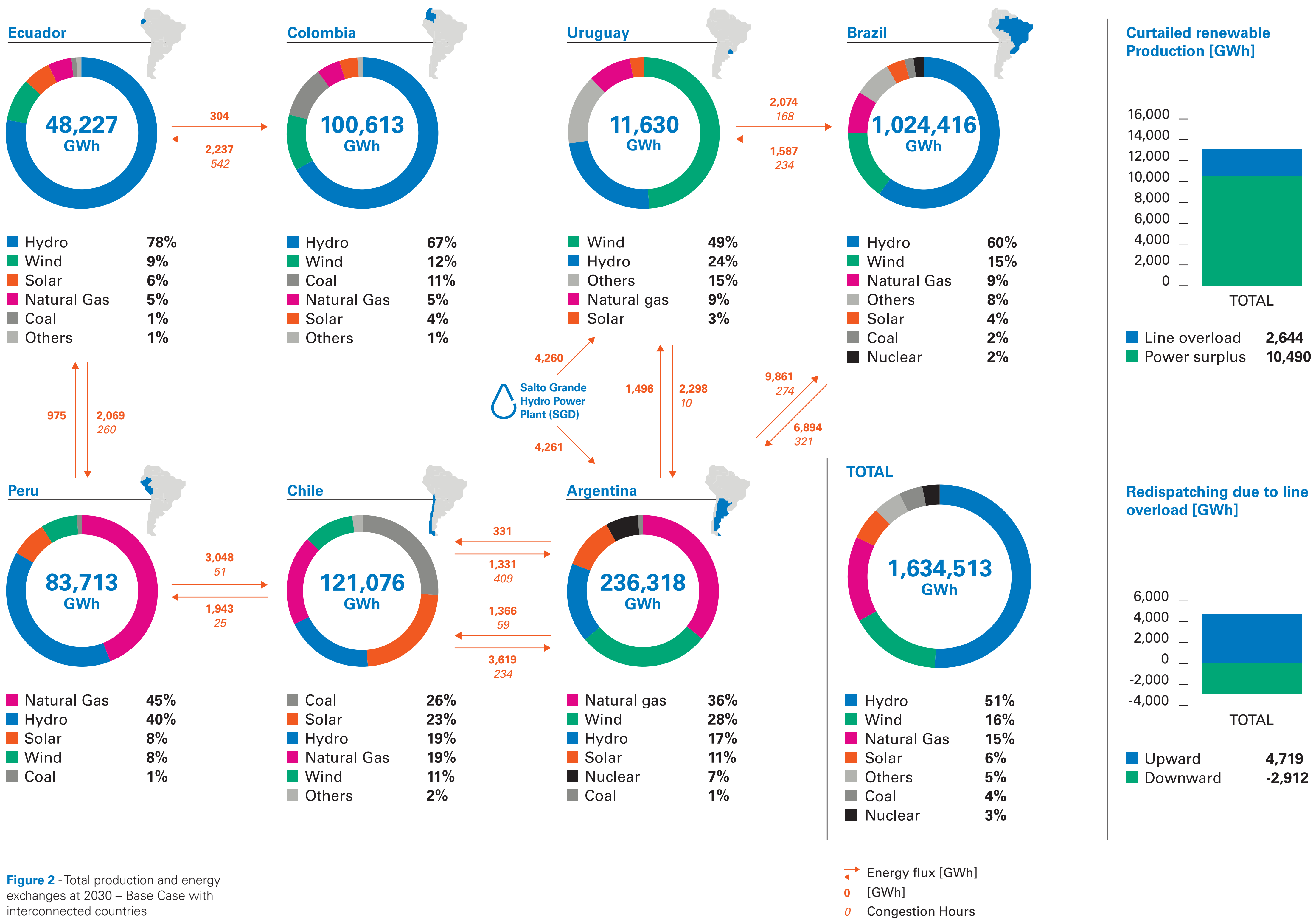


Figure 2 - Total production and energy exchanges at 2030 – Base Case with interconnected countries

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 the other countries it is convenient to import electricity: Brazil (3.4 TWh), Argentina (1.1 TWh) and Ecuador (0.7 TWh) become net importers. 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 interconnection capacity investigated in the study, based on the existing lines and the 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.

5.1.1 Enhanced VRES installed capacity

A sensitivity analysis has been carried out investigating how the optimal VRES installed capacity is enhanced 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, in case of reduced VRES costs:

- 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, bringing the overall demand coverage by VRES up to 28%,
- the additional plants suffer an increased risk of curtailments (about 20% of their 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 decreases 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 generation plans,

A graphical representation of the energy exchanges and of the generation mix in the countries according to this sensitivity analysis is provided in Figure 3.

Electrical energy demand and generation fleet at 2030 – ENHANCED VRES CAPACITY

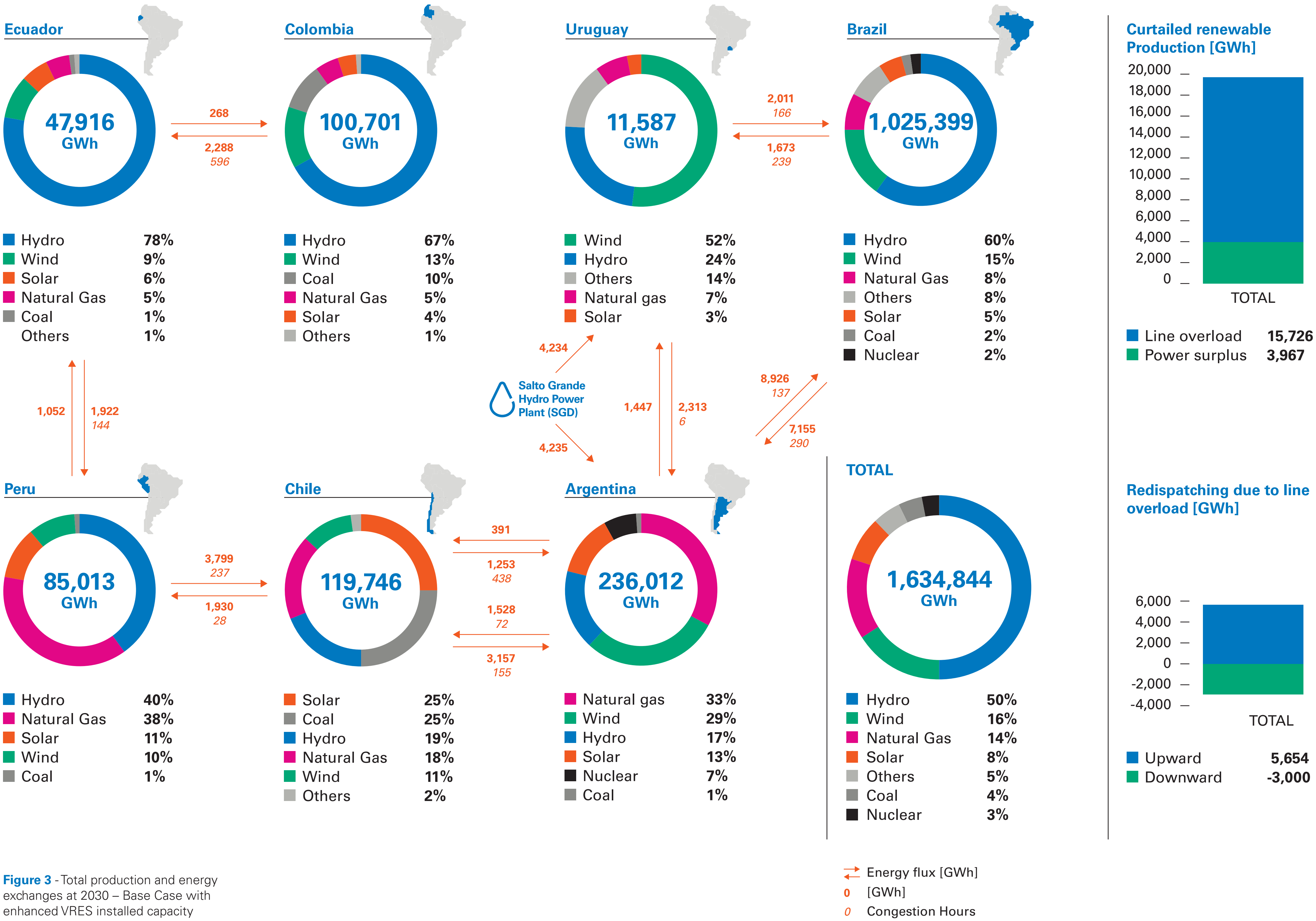


Figure 3 - Total production and energy exchanges at 2030 – Base Case with enhanced VRES installed capacity

5.1.2 Sensitivities on dry and wet hydrological conditions

Moreover, the operation of the interconnected power system with the optimal amount of VRES installed capacity estimated assuming average hydrological conditions has been simulated also in case of dry or wet years 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. Hydro availability has been lowered or increased based on the historical data, in order to simulate conditions representing approximately the 15^{th} and the 85^{th} percentile.

- 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 [8]) should be included in the optimal configuration of the Base Case, as they represent the most effective solution to ensure a proper security of supply in the areas affected by lack of hydro resource.
  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 become 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 use of the interconnections.

5.2 High demand variant

In the first Variant, representing an accelerated decarbonization path in a strong economic development, the electric demand in the countries has been increased also considering a deeper penetration of evehicles, 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 emitting less CO_2 are introduced to ensure the 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. The remaining part of the load increase is covered by natural gas and oil, as hydro availability and its absolute production remain unchanged.
- 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 Variant 1 2,700 MW of flexible thermal generators have been introduced to maintain a an acceptable adequacy level[3]. Higher capacity might be included to reach better adequacy levels.
  In Chile it is necessary to introduce gas fuelled power plants replacing part of the coal plants switched off to ensure adequacy, as the system would suffer excessive lack of dispatchable resources.
- 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.

Also in this condition, 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.

Figure 4 shows energy flows between the countries and the percentage of generation per technology in each country and in the whole system. It is possible to observe the increase of the optimal VRES installed capacity and, consequently, also of the risk of curtailments due to overgeneration conditions in the syste.

3 In this case, it is accepted an EENS equal to 10^4 p.u. of the total demand, while in the other scenario the EENS threshold is set at 10^5 p.u.

Electrical energy demand and generation fleet at 2030 – HIGH DEMAND

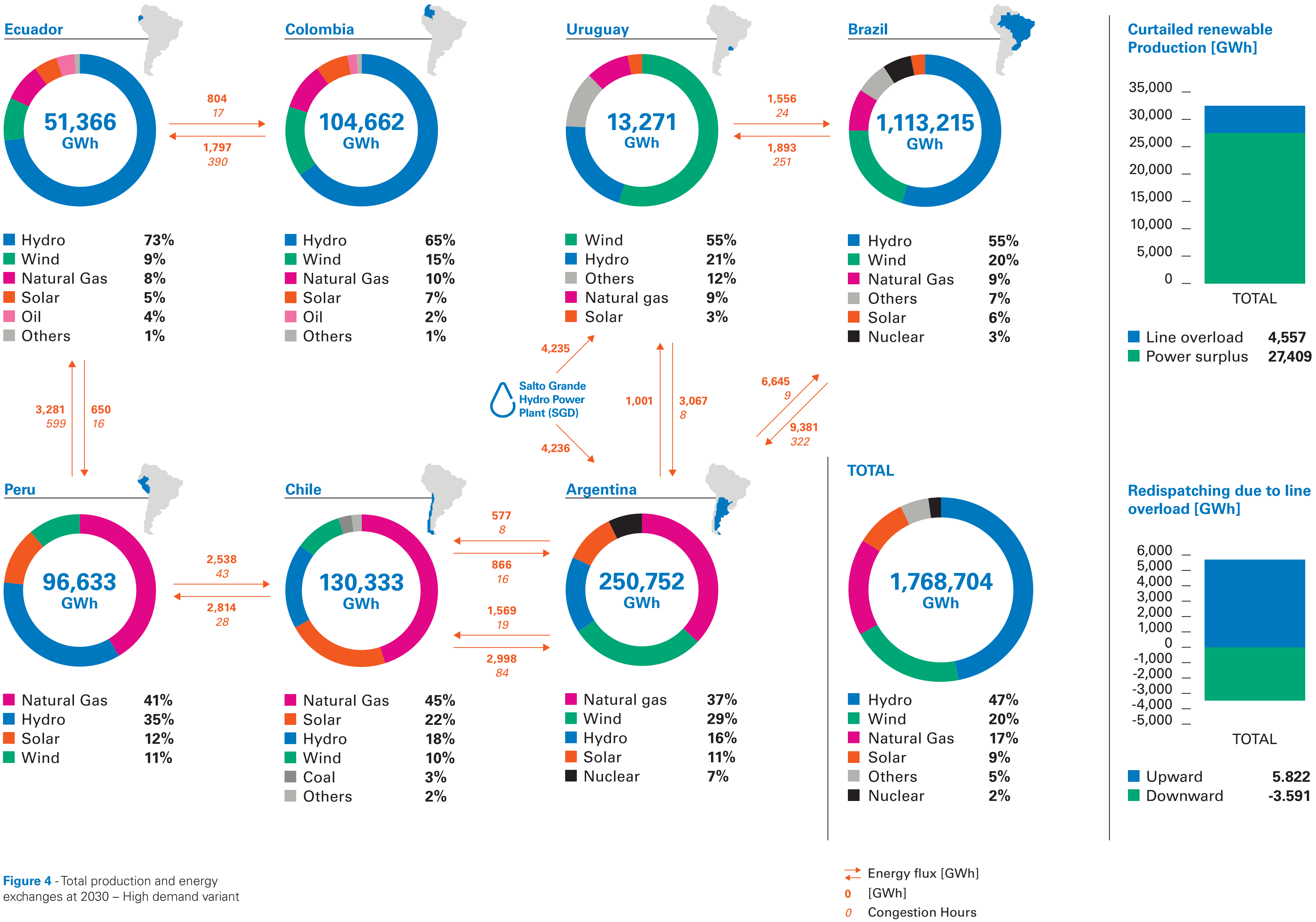


Figure 4 - Total production and energy exchanges at 2030 – High demand variant

5.3 Low demand variant

In the second Variant, an enhanced energy efficiency scenario has been set up, simulating a reduction in the electricity demand also according to the different targets available at national level. Thermal and hydro generation fleet has been assumed substantially aligned with the one of the Base Case, as well as the availability of energy from hydro resource. Under these assumptions:

- Optimal PV installed capacity is estimated at 29 GW while wind capacity 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 the highest potential, even if limited by the lower load that needs to be supplied and by the competition against cheaper thermal generators.

- Total production by PV and wind plants is equal to almost 64 TWh and 177 TWh (covering about 19% of the demand). 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 of VRES curtailments. Thermal production decreases by about 5 TWh (fuel savings higher than USD 1 billion), reducing CO_2 emissions by 2.8 Mt per year.

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.

Figure 5 provides a graphical summary of the operation of the system in this low demand variant. Due to lower demand and generally less loaded network, the risk of VRES curtailments due to network constraints is strongly reduced compared to the other simulated scenario.

Electrical energy demand and generation fleet at 2030 – LOW DEMAND

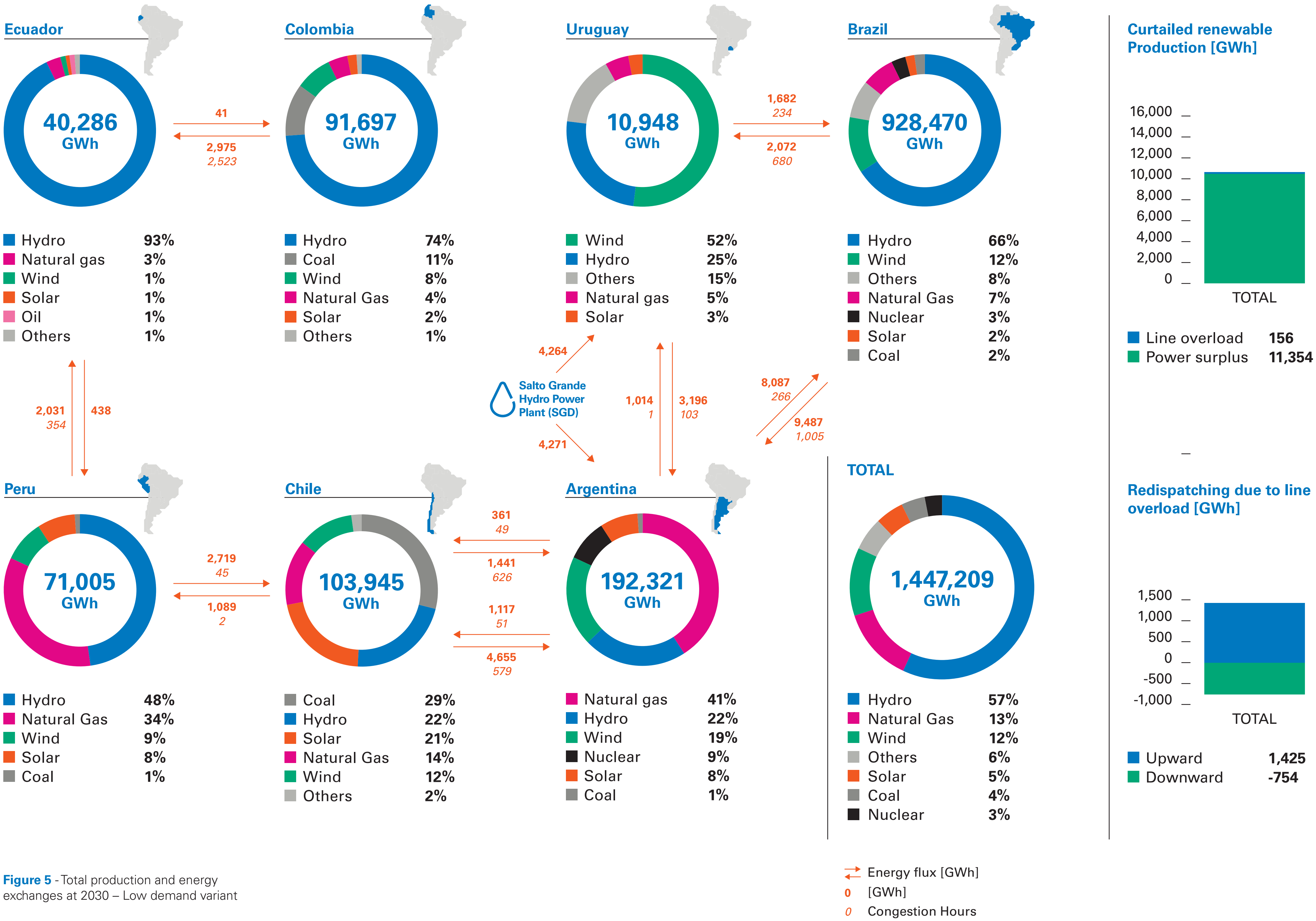


Figure 5 - Total production and energy exchanges at 2030 – Low demand variant

6 CONCLUSIONS

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.
Table 2 provides the summary of the optimal PV and wind installed capacities in the countries resulting from the performed analysis.

Table 2 - Summary of optimal VRES capacity in different analysed scenario at 2030 [MW]

COUNTRY	GENERATION EXPANSION PLANS		BASE CASE OPTIMAL		ENHANCED VRES CAPACITY		HIGH DEMAND		LOW DEMAND	
	PV	Wind	PV	Wind	PV	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

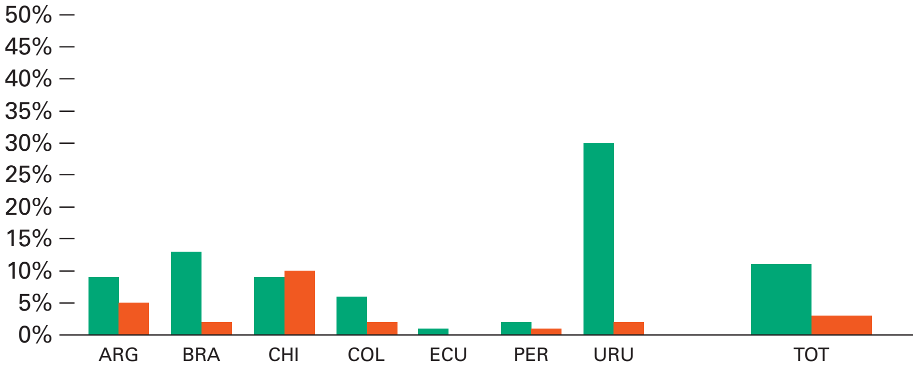
Figure 6 shows the net demand coverage by VRES plants achieved thanks to their optimal penetration in the different scenarios, compared to the results reached with a generation expansion according to the most recent national development plans. The percentage of demand supplied by VRES is provided for each country and for the whole system. In Chile and Peru, which have the best solar irradiation, PV covers a share aligned to or higher than wind, while in the other countries and in the whole system wind resource is more exploited. Countries with highest hydro generation (such as Colombia, Ecuador and partially Brazil) in general show lower optimal penetration of VRES.

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.

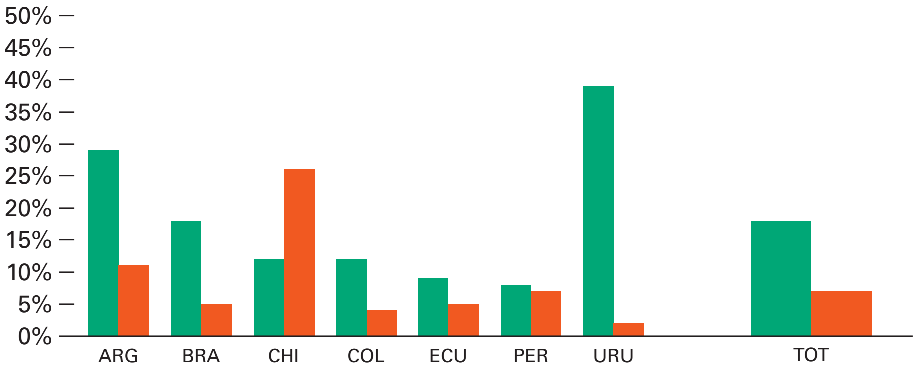
Regulations should promote the integration of VRES plants at national and international level enabling higher flexibility and coordination in the operation of the different power systems to ensure that economic and technical benefits can be fully achieved.

Net demand coverage by VRES in different optimization scenarios

GENERATION EXPANSION PLANS



BASE CASE OPTIMAL



ENHANCED VRES CAPACITY

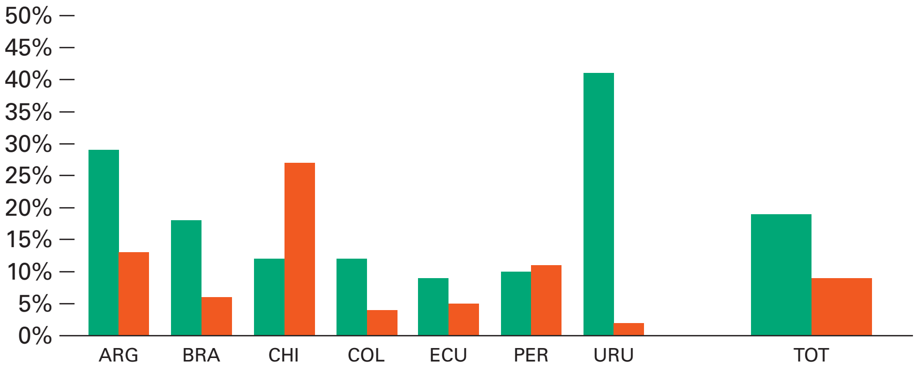
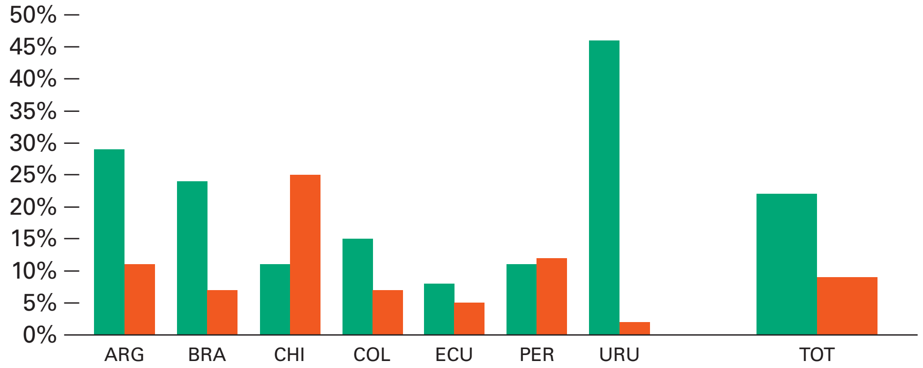


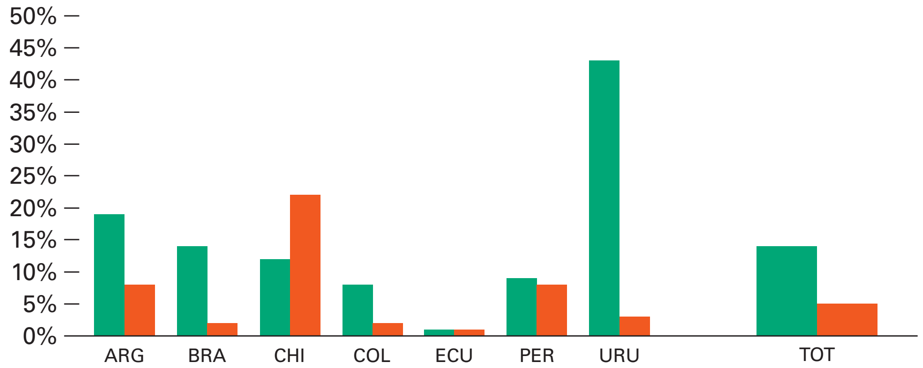
Figure 6 - Net demand coverage by VRES in different optimization scenarios at 2030 – Continental case

Wind
PV

HIGH DEMAND



LOW DEMAND



7 References

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

[2] CESI, B8009716 Inception Report – Data Collection and Scenario for Argentina-Brazil-Uruguay case study.

[3] CESI, B9007163 Inception Report – Data Collection and Scenario for Colombia-Ecuador-Peru case study.

[4] CESI, B8000343 Economic and technical analyses to evaluate optimal economic amount of additional Variable Renewable Energy Sources generation in Argentina and Chile at 2030.

[5] CESI, B8016111 Economic and technical analyses to evaluate optimal economic amount of additional Variable Renewable Energy Sources generation in Argentina, Brazil and Uruguay at 2030.

[6] CESI, B9018217 Economic and technical analyses to evaluate optimal economic amount of additional Variable Renewable Energy Sources generation in Colombia, Ecuador and Peru at 2030.

[7] CESI, C0002250, Optimal economic amount of additional Variable Renewable Energy Sources generation in South America at 2030

[8] Empresa de Pesquisa Energética (EPE), Plano Decenal de Expansão de Energia 2026.

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