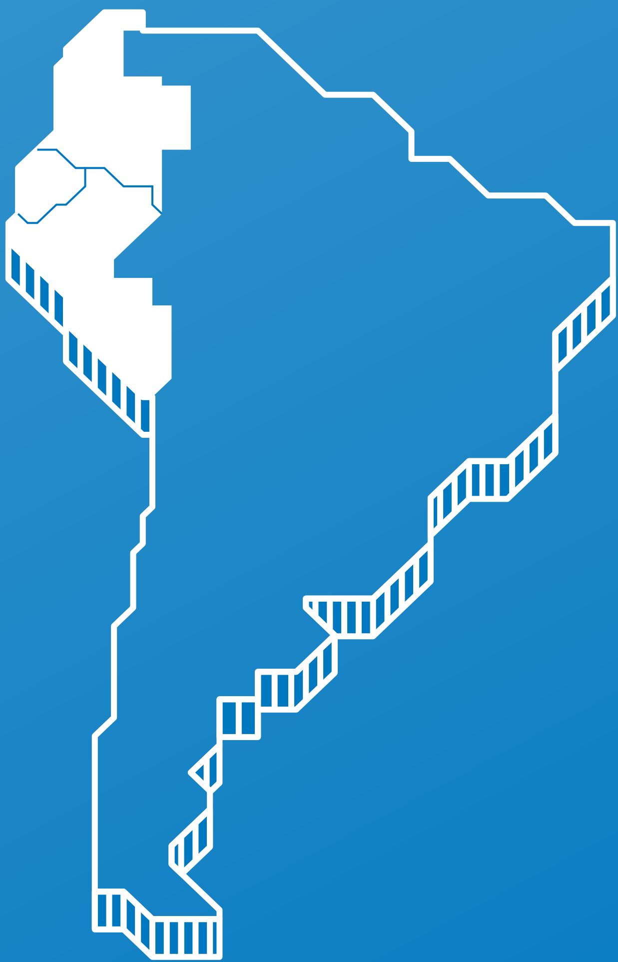
# Executive Summary

Colombia | Ecuador | Peru



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

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

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# List of acronyms

| | |
|---|---|
| CCGT | Combined Cycle Gas Turbine |
| COES | Comité de Operación Económica del Sistema Interconectado Nacional (Peru) |
| COP | Conference of the Parties |
| DNE | Dirección Nacional de Energía |
| EENS | Expected Energy Not Supplied |
| EOH | Equivalent Operating Hours |
| GDP | Gross Domestic Product |
| GHG | Green House Gas |
| HV | High Voltage |
| HVDC | High Voltage Direct Current |
| LATAM | Latin America |
| LCOE | Levelized Cost of Energy |
| MINEER | Ministerio de Electricidad y Energía Renovable (Ecuador) |
| MINEM | Ministerio de Energía y Minas (Peru) |
| NTC | Net Transfer Capacity |
| OCGT | Open Cycle Gas Turbine |
| p.u. | per unit |
| PV | PhotoVoltaic |
| RES | Renewable Energy Source |
| SIN | Sistema Interconectado Nacional (Colombia) |
| UPME | Unidad de Planeación Minero Energética (Colombia) |
| USD | United States Dollars |
| VRES | Variable Renewable Energy Sources |
| XM | Compañía Expertos en Mercados (Colombia) |

# Executive Summary

## 1 General objective of this study

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

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

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

The study answers the following two questions:

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

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

Through sensitivities the study also investigates how different configurations of power systems, such as enhanced use of storage, affect the development of VRES generation.
The analysis is performed for the target year 2030 and starts from a given set of thermal/hydro generation that includes the already existing plants, the ones under construction and the planned ones which will be built before the target year.

The first report of this study was completed in January 2018 and was focused on Chile and Argentina (Cluster 1). The second report – focused on Argentina, Brazil and Uruguay (Cluster 2) – was completed in January 2019. The present Executive Summary presents the main findings related to the analysis of a third cluster of countries in South America, composed by Colombia, Peru and Ecuador (Cluster 3). Finally, there will be a continental report featuring the main findings across the three geographical clusters including all the above-mentioned countries.

# 2 The study process

Aim of the study is the definition of the optimal amount of PV and wind plants in the analysed countries in three main different configurations of the power systems (namely, a Base Case and two Variants) characterized by different assumptions on the demand and the available technologies in the generation fleet. For each of these three conditions, a "Reference Scenario" is identified, which includes the expected amount of generation per source based on the current expansion plans in the different countries at the target year 2030 or for years close to it. The three "Reference scenarios" represent the basis of the optimization process which define, at the end of an iterative calculation, the optimal techno-economic VRES generation deployment in each condition. This amount maximizes the benefits for the system calculated in terms of fuel savings and reduction of the Expected Energy not Supplied (EENS[2]) minus the costs (investments for the new plants and increase of EENS, if any).
Starting from the relevant "Reference scenario", the optimization of the VRES installation has been carried out by modifying the generation expansion pattern optimising the amount of new VRES generation, particularly PV and wind, taking into account their potential across the territory, and their costs and performances. In the optimisation process, we took into account the system operational constraints in terms of reserve to be warranted in each hour of the year, limits in the power transfer capacity in the transmission grid, requirements on inertia and system stability. A development of VRES technologies and the introduction of storage plants 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

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

security of supply. As anticipated above, to better appraise the results of the optimization carried out in the Base Case and assess the stability of the results against uncertainties, some variants to this scenario have been investigated:

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

# 3 Computational tools

The optimisation process is based on a set of deterministic and probabilistic computational tools. In particular, to assess the system adequacy and the risk of over-generation in presence of an increasing share of VRES, the GRARE (Grid Reliability and Adequacy Risk Evaluator) software has been adopted. GRARE is developed by CESI and owned by Terna, the Italian TSO. GRARE is a powerful computer-based tool which evaluates the reliability and the economic operation of large electric power systems. GRARE supports medium and long-term planning studies using probabilistic Monte Carlo approach and modelling in detail the transmission networks.
The probabilistic simulation of one operational year considers thousands of different system configurations (including load, availability of generation fleet and transmission networks, VRES power production), weighted by their probability to happen. With this approach, results depict the expected operation of the whole system, obtained analysing many real possible operational states, and detailed information about each component of the system can be evaluated.
The most interesting results are the expected benefits for the system in terms of variation of generation costs, considering differences in the EENS. The expected production of VRES plants, considering potential curtailments due to system or transmission constraints, provides important information for the evaluation of their profitability and supports the definition of the optimal amount of power to install.
The definition of VRES plants producibility based on geographical information combined with the usage of a detailed transmission system model allows to clearly identify the best areas where PV and wind plants should be developed in order to maximize the benefits for the system.
More information on the GRARE tool is available on www.cesi.it/grare.

# 4 Base Case Reference Scenario and study assumptions

The "Reference scenario" for the Base Case has been built starting from the available public domain information [1]. The three main building blocks of the "Reference scenario" are: the yearly energy demand, the generation fleet and the structure of the transmission grid.

As for Colombia, information on the evolution of the power sector until 2030 has been made available by UPME[3] in the Plan de Expansión de Referencia Generación [2], while for Ecuador, the reference is the Plan Maestro de Electricidad 2016-2025 by Ministerio de Electricidad y Energía Renovable [3]. As far as Peru is concerned, information was retrieved from publications by Ministerio de Energía y Minas (MINEM) and by COES[4] [5].

The scenario at 2030 was completed for all countries by applying, where needed, a load forecast computation considering energy and peak demand as well as main upgrades of the High Voltage (HV) transmission system. The required and optimal generation expansion was computed assessing the technical possibility and the economic convenience to invest money in new VRES (PV and wind) or in thermal power plants.

### 4.1 Reference scenario: Colombia

As mentioned, the demand forecast at 2030 is available and is provided by UPME, articulated in different scenarios. In order to define the Base Case for this study, reference has been made to the "Medium" scenario which foresees a demand of 100.8 TWh and a peak of 13.8 GW. UPME "Low" and "High" scenarios have respectively been considered in the definition of the Reference Scenario of the Variants of this study.

The definition of the hourly time-series to be considered at 2030 has been performed starting from the most recent available data and considering the effects of a strong flattening of the typical daily profile which is evident from last years' trends.

The generation fleet is the one proposed by UPME, based on different available technologies and areas, and the limits of interconnections between them.

In the Reference scenario a significant increase of the installed hydro power is foreseen due to big projects like the Ituango dam being operational before 2030. 1.3 GW Wind and more than 1 GW PV are also included. As assessed by UPME, this generation fleet is adequate to supply the load and cover the peak demand at 2030.

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3 In Colombia, Unidad de Planeación Minero Energética UPME is a special administrative department linked to the Ministerio de Minas y Energía, responsible for the development of the mining and energy sectors.

4 In Peru, the Comité de Operación Económica del Sistema Interconectado Nacional (COES) is a private entity responsible for the coordination of the short-, mid- and long-term operation of the Sistema Eléctrico Interconectado Nacional (SEIN) at the minimum cost, ensuring system security and the best usage of resources, as well as for the planning of the transmission system development.

The transmission system considered in the "Reference scenario" for Colombia includes the reinforcements foreseen in the UPME plan, especially to strengthen the interconnection between the northern regions and the central area. The best exploitation of wind resource in the Caribbean coast (La Guajira region) requires the construction of new 500 kV substations connected to the existing system in the same area, and of a High Voltage Direct Current (HVDC) link used to transfer the power directly to parts of the system closer to Bogotà. Thanks to these significant reinforcements of the connections from the North to the Centre (and corresponding investments), the transfer capacity increases up to levels which overcome critical constraints for the power flows. This means that the Colombian network can be considered as a single system with no particular limiting factors between North and Centre-South.

This study aims to highlight whether some bottlenecks in the transmission capacity can cause a limitation in the VRES exploitation at 2030 and whether other network improvements might be necessary and economically profitable to allow a higher penetration of VRES generation in the Colombian system.

Figure 1 shows a graphical illustration of the main assumptions considered in the Colombian "Reference scenario": electrical energy demand, peak power demand and generation fleet.

**Colombia**

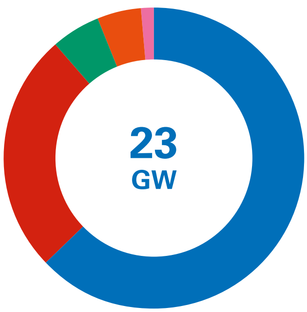
**Electrical Energy Demand**
2030

**100.8**
**TWh**

**Peak Power Demand**
2030

**13.8**
**GW**

**Generation fleet**
2030




| | |
|---|---|
| Hydro | **63.0%** |
| Thermal | **25.7%** |
| Wind | **5.2%** |
| PV | **4.8%** |
| Biogas/Biomass | **1.3%** |

**Figure 1** - Main data of Base Case Reference scenario for Colombia [Source: UPME data elaborated by CESI]

## 4.2 Reference scenario: Ecuador

The long-term demand forecast for Ecuador is available up to 2025, published in the Plan Maestro de Electricidad 2016-2025 (PME) by Ministerio de Electricidad y Energía Renovable (MINEER) [3]. An extension up to 2030 has been carried out by CESI assuming the same growth rate as in the PME, resulting in nearly 49.4 TWh and 7.6 GW peak. The 2030 hourly load profile has been obtained for typical days and weeks.

The PME has also been used as a reference for the generation fleet of the "Reference scenario" of this study, which includes about 10.3 GW of capacity, 60% of which are hydro, the main resource developed from today to 2030. Wind and PV are foreseen in a limited amount (200 MW in total). PME contains also good references for the availability of resources, including wind data from the Atlas Eólico del Ecuador by MINEER [4].

The model of the transmission system takes into account the additional reinforcements of the network foreseen in the next years. No division in different areas is necessary, as Ecuador is a small country and does not show critical congestions limiting the power transmission on the HV network which is the focus of the present study.

Figure 2 depicts the main information on the electrical energy demand and the composition of the generation fleet.

**Ecuador**

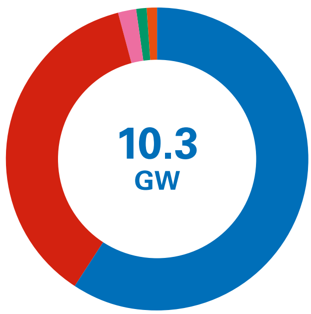
**Electrical Energy Demand**
2030

**49.4**
**TWh**

**Peak Power Demand**
2030

**7.6**
**GW**

**Generation fleet**
2030




| | |
|---|---|
| Hydro | **59.2%** |
| Thermal | **36.9%** |
| Biogas/Biomass | **1.9%** |
| Wind | **1.0%** |
| PV | **1.0%** |

**Figure 2** - Main data of Base Case Reference scenario for Ecuador [Source: MINEER, data elaborated by CESI]

## 4.3 Reference Scenario: Peru

The energy demand forecast and the expected peak power demand for Peru are provided up to 2028 by Ministerio de Energía y Minas (MINEM) in the Actualización Plan de Transmisión 2019 – 2028 [5]. Extrapolation up to 2030 of both values has been performed by CESI reaching respectively 85 TWh and 11.3 GW. As far as generation capacity is concerned, in the Plan de Transmisión a considerable number of plants are analysed and proposed as possible in future scenario, depending also on other important developments of the power system, such as the interconnection with Brazil. In addition to the power plants assumed by COES in the analysis of the power system at 2028, some important improvements of the already existing generation fleet are included in the Reference scenario, increasing the production from natural gas in the Southern part of the country thanks to the conversion to CCGT technology of power plants currently burning oil. The total installed power in the Reference scenario is then equal to 16.2 GW. The cost of natural gas is assumed equal to 4.35 USD/MBTU, a particularly low value due to subsidies granted to national production. The network model is taken from COES, focusing on the year 2024 which includes the upgrades already committed. Some further reinforcements have been introduced where necessary to solve congestions due to the increase of the load[5].

Figure 3 shows the main data of the Base Case Reference scenario for Peru at 2030 (electrical energy demand and generation fleet).

**Peru**

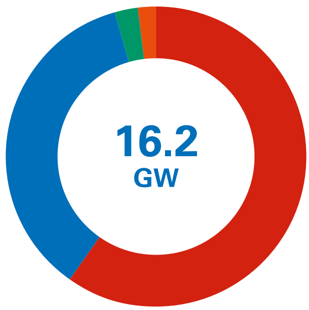
**Electrical Energy Demand**
2030

**85**
**TWh**

**Peak Power Demand**
2030

**11.3**
**GW**

**Generation fleet**
2030




| | |
|---|---|
| Thermal | **59.9%** |
| Hydro | **35.8%** |
| Wind | **2.5%** |
| PV | **1.9%** |

**Figure 3** - Main data of Base Case Reference scenario for Peru [Source: MINEM and COES, data elaborated by CESI]

5 For instance, the network has been reinforced in the area close to Lima because the expected load at 2030 in some conditions causes power flows higher than the capability of the 2024 network. These local problems limiting the load supply are not the focus of the study aims at analysing system constraints and the required reinforcements to ensure the optimal exploitation of VRES production.

### 4.4 International interconnections

In a first step, the assessment of the optimal technical and economic penetration of VRES power plants in the Colombian, Ecuadorian and Peruvian systems is performed on each country, considered as isolated. The assessment takes into account possible transmission network reinforcements aimed at allowing a better exploitation of PV and wind resources. No energy exchanges with neighbouring countries are taken into account, looking for the best development of the VRES penetration to meet energy and peak power demand internally to each country.
Once the solution for each isolated country is found, the operation of the interconnected systems is simulated, to evaluate whether the possibility to exchange power across the borders can increase the optimal amount of installable VRES capacity. The following interconnections are modelled:

Between **Colombia and Ecuador**:
- The capacity of the existing 230 kV and 138 kV lines is considered, with an NTC reaching 535 MW from Ecuador to Colombia and 395 MW in the opposite direction.

Between **Ecuador and Peru**:
- The existing 220 kV line is considered together with the 500 kV single line La Niña-Piura-Pasaje- Chorrillos (part of the Andinean project), which improves the NTC between the two countries up to 660 MW in both directions.

# 5 Optimal VRES penetration

The performed analyses allowed defining the generation fleet at 2030 and in particular the optimal technical and economic penetration of VRES power plants that can be added to the Reference scenario under the Base Case assumptions. Thanks to probabilistic simulations performed with GRARE software, the expected yearly operation of the systems is evaluated considering operational constraints (system reserve, power transfer capacity of the transmission network, uncertainty in the PV and wind production) and production costs, thus enabling the calculation of possible benefits for the systems compared to the "Reference scenario". The results are presented for each country considered as isolated from the others, and then the expected operation of the interconnected system is described, together with benefits and variations in the optimal VRES configuration due to the possibility to have energy exchanges between countries.

### 5.1 Colombia – isolated system

At the end of the computational process, the optimal amount of additional VRES with respect to the installed power already considered in the Reference scenario is more than 1,300 MW of PV and 1,400 MW of wind power plants, with a total of installed battery storage of about 200 MW. The total VRES installed power becomes then higher than 5,000 MW. The investment in such technologies provides benefits for the system of about USD 100 million/year. These benefits are evaluated as the difference between savings in the generation costs compared to the investment costs in new generation. With this additional VRES capacity EENS remains equal to zero, similarly to what already occurs in the Reference scenario. Based on the investment costs and on the relevant production, the expected average LCOE for PV is 45.6 USD/MWh, and for wind 34.5 USD/MWh. Despite wind power plants provide higher absolute benefits to the system with respect to PV, attracting more investments, the amount of additional power turns out to be quite balanced between the two VRES technologies.
This is due to the fact that it is preferable to keep a mix of different sources and the plants distributed in the territory to better exploit them, limiting the system and the local constraints during the operation. And thanks to the substantially lower cost per installed MW typical of PV technology compared to wind, it is possible to install a similar amount of PV power as wind even if the absolute investment in the PV technology is lower.

Table 1 shows the resulting installed capacity per technology in the Colombian system.

**Table 1 - Additional and total VRES installed power in Colombia in the Base Case with optimal economic amount [MW]**

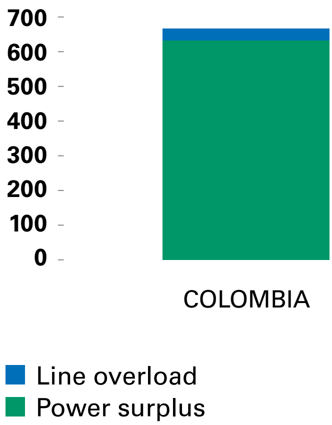
| COUNTRY | PV installed power | | Wind installed power | |
|---|---|---|---|---|
| | Added to reference scenario | Total | Added to reference scenario | Total |
| COLOMBIA | 1,325 | 2,400 | 1,400 | 2,700 |

In this scenario, PV plants produce 4 TWh per year and wind plants more than 11.7 TWh per year. There is a risk of production curtailment, evaluated in 140 GWh for PV and nearly 500 GWh for wind, mainly due to possible overgeneration conditions as Colombia has big hydropower plants in some cases with reduced modulation capacity, and coal plants, with very low production cost and limited flexibility. If externalities were considered, increasing the cost of the energy produced by thermal power plants for instance with the implementation of the carbon tax already present in Colombia, the advantages introduced by VRES plants would be higher, and consequently also the optimal amount of installed VRES power would increase.
In fact, with a higher cost of the energy it would be acceptable to suffer even higher curtailments because the higher benefits in the other periods would compensate them. In a power systems with an already massive presence of hydro (in Colombia 2/3 of the demand is covered by energy generated by hydropower plants) and increasing penetration of VRES, it is necessary to improve the coordination of generation from different sources, in order to limit situations with excess of power, and use the storage capacity made available by reservoirs to improve exploitation of the renewable sources.

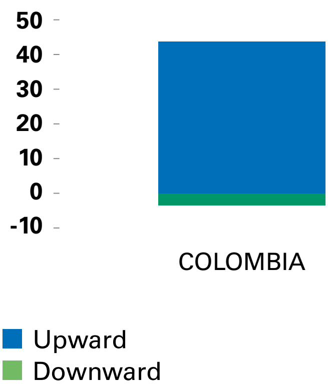
Figure 4 shows the mix of energy sources used in Colombia to supply the load and the risk of RES curtailments with the limited amount of energy required to be redispatched due to network constraints.

## Colombia


### Curtailed RES Production [GWh]




### Redispatching for line overload [GWh]




### Colombia

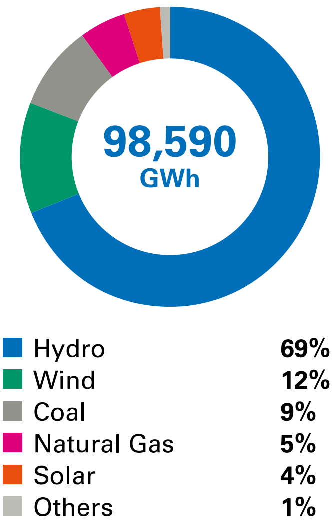



**Figure 4** - Total production and curtailed RES production– Colombian Base Case with optimal VRES amount

### 5.2 Ecuador – isolated system

In the Reference scenario Ecuador is characterized by a strong coverage of the demand by means of hydropower plants (more than ¾ of the total load), and a very expensive thermal generation composed by plants burning natural gas and less efficient plants burning liquid fuels. VRES are an option to replace this expensive generation, but have to face the constraints deriving from the already massive exploitation of hydro and the limited availability of solar irradiation and wind compared to the other countries.

The optimal amount of VRES to be included in the Ecuadorian system turns out to be 1,750 for PV and about 2,000 for wind. There is no need of other power plants to ensure the system adequacy at 2030 in the Base Case scenario with average hydraulicity, but due to the strong dependency from hydro some lack of power occurs in case of dry meteorological conditions calling for the introduction of a 300 MW dispatchable generator able to provide the required energy in case of hydro scarcity. This support might be provided also by additional hydropower plants, and in this case proper assessment of the operational condition in dry years becomes even more important.

In the optimal scenario, PV plants produce 2.2 TWh and wind ones more than 3.7 TWh: together they sum up to about 6 TWh in total, which represents 12% of total demand.Due to lower availability of wind and solar resource, the high curtailment risk and also the higher interest rate which increases the CAPEX of VRES plants, the expected LCOE are quite high compared to other countries, around 95 USD/MWh for wind and 85 USD/MWh for PV, but still convenient compared to the cost of replaced inefficient thermal plants.

Considering the investment costs needed for the new plants and the fuel savings, the total benefit for the system is evaluated in about USD 320 million. No significant network congestions are present.

Table 2 provides the total VRES installed capacity resulting from the optimization process in the "Reference scenario", divided between the technologies and the different areas.

**Table 2 - Additional and total VRES installed power in Ecuador in the Base Case with optimal economic amount [MW]**

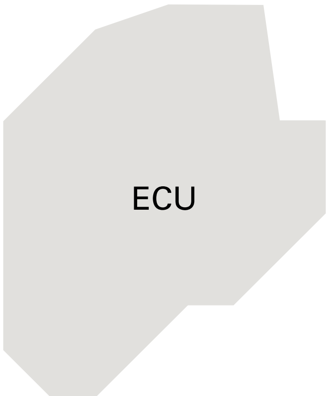
| COUNTRY | PV installed power | | Wind installed power | |
|---|---|---|---|---|
| | Added to reference scenario | Total | Added to reference scenario | Total |
| ECUADOR | 1,670 | 1,750 | 1,930 | 2,050 |

It's worth highlighting that due to the particular condition of the Ecuadorian system, with an already very high presence of hydro power plants and the expensive generation based on liquid fuel, the optimal results are expected to be very sensitive to different demand growth rate assumptions, different efficiency and costs of thermal plants or additional development of new hydropower plants: all these aspects have a significant impact on the advantages and benefits that VRES can introduce in the system, as they modify the amount of load to be covered with generation different from hydro and the corresponding production costs. In case the total load is lower, or the efficiency of the thermal generation higher (i.e. the thermal generation costs lower) the economic advantage of new VRES would significantly reduce, as they would substitute cheaper generation, and the optimal values would be significantly impacted. Due to its small dimension and the very high share of energy already covered by hydropower plants, Ecuador is the country that would be mostly affected by changes – also small – in the assumptions.

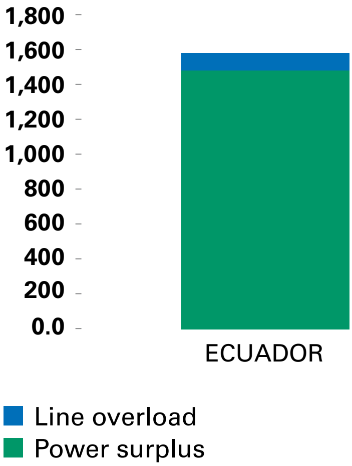
Figure 5 provides a visual summary of the operation of the Ecuadorian system in the optimal scenario, highlighting the generation mix, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

With respect to the "Reference scenario", the PV and wind productions increase from 1% to respectively 4% and 8% mainly replacing energy generated by oil and natural gas plants.

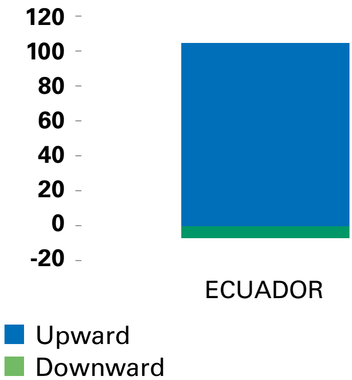
## Ecuador




### Curtailed RES Production [GWh]




### Redispatching for line overload [GWh]




### Ecuador

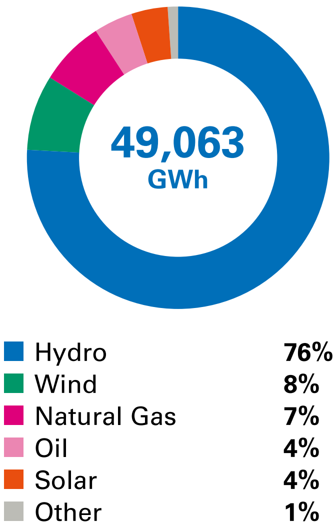



**Figure 5** - Total production and energy exchanges – Ecuadorian Base Case with optimal VRES amount

### 5.3 Peru – isolated system

In Peru the generation fleet assumed in the Reference scenario results to be not adequate for the supply of the demand with acceptable EENS values. This is because the generation fleet and the transmission network are considered the same as in 2024 while growth rates are applied to the load up to 2030, leading to a general lack of power and to load curtailments due to line overloads.
However, the introduction of VRES plants makes it possible to avoid EENS due to insufficient generation availability and modifies the power flows in the system, reducing criticalities in some areas thanks especially to wind power, connected to the system in different areas, from North-West to South and along the coast.
The total amount of optimal PV and wind installed power in the Base Case is reported in Table 3. In addition, also about 320 MW of storage are included.

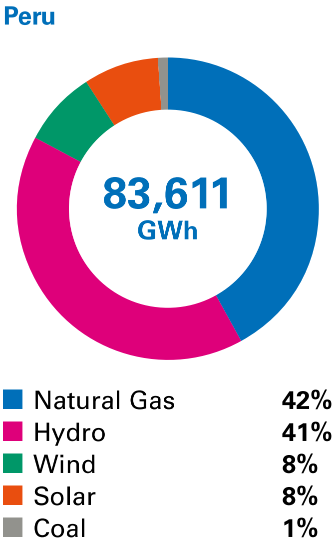
**Table 3 - Additional and total VRES installed power in Ecuador in the Base Case with optimal economic amount [MW]**

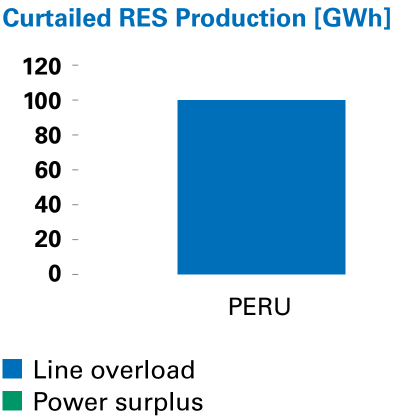
| COUNTRY | PV installed power | | Wind installed power | |
|---|---|---|---|---|
| | Added to reference scenario | Total | Added to reference scenario | Total |
| PERU | 2,465 | 2,750 | 1,290 | 1,700 |

In the final configuration PV produces 6.3 TWh and wind reaches 7 TWh. Risk of VRES curtailments is limited as no overgeneration conditions appear in the system. Only 100 GWh of PV production need to be reduced due to overloading of some lines from South to the centre of the country. Thanks to the excellent availability of resources and the assumed low installation costs, expected LCOE is around 30 USD/MWh for PV and 36 USD/MWh for wind. Total benefits for the system, considering investment costs for new plants and storage and fuel cost saving, amount to about USD 200 million/year.

Figure 6 provides an overview of the main results with respect to the amount of energy and the contribution of different technologies to demand coverage.

## Peru

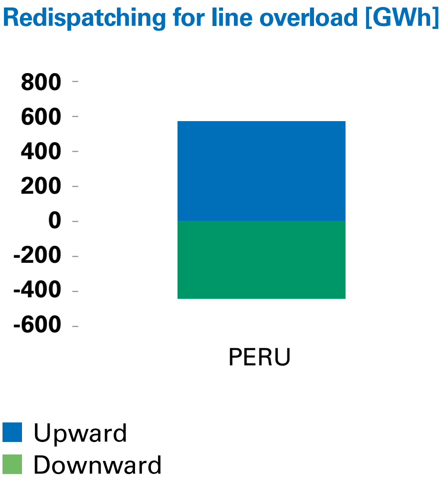




**Figure 6** - Total production and energy exchanges – Peruvian Base Case with optimal VRES amount

An assessment of the optimal amount of VRES plants has been carried out also under the assumption that natural gas market is not regulated by subsidies. According to [1], its cost has been raised from 4.35 USD/MBTU to 6.8 USD/MBTU, and therefore also the cost of energy produced using natural gas as primary source consistently increased. In this scenario, VRES plants become even more attractive as the merit order between VRES and natural gas generation changes with respect to the previous analysis because the cost of energy produced by this source becomes higher than VRES cost, which remains the same. In this scenario it becomes advantageous to install more VRES plants even accepting higher curtailments, or to invest in network reinforcements to solve bottlenecks limiting VRES exploitation.

In case no investments are made on the transmission network, the optimal solution consists in increasing the wind capacity up to 3,500 MW and PV capacity up to 3,000 MW. The additional wind plants are located in the North of the country and along the coasts and thanks to their geographical distribution, they do not stress the grid in only one area, and do not suffer critical curtailments due to local issues. On the contrary, PV plants are located in the South and it is convenient to increase their capacity only by 250 MW to avoid high curtailment risk due to transmission constraints. Thanks to these additional plants, PV and wind power produce more than 20.5 TWh, covering about 25% of the demand, and the benefits for the system exceed USD 500 million per year with respect to the Reference scenario.

If the 220 kV network in the South is reinforced also with controllable devices able to push the power flow to the 500 kV lines and maximize their exploitation, PV can increase more without being limited by network constraints, and the new optimal values both of PV and wind would be 4,000 MW. With this amount of installed power, and thanks to the lower risk of curtailments, the total VRES production would increase up to 24.5 TWh, covering nearly 30% of the load.

Network reinforcements allowing to control power flows are also useful to ensure higher flexibility of the transmission system. In this way, the grid will be better fit for a not yet detailed development of VRES, and capable of accepting significant power injections in nodes different from the originally planned ones. The production of the additional VRES plants which is convenient to install in case the network is reinforced provides benefits for the system quantified in about USD 35 million per year: these benefits have to be compared with the cost of the additional equipment necessary for the optimal exploitation of the transmission grid.

### 5.4 Colombia, Ecuador and Peru interconnected systems

This paragraph presents the results of the analysis of the interconnected systems and the assessment of the benefits that an additional amount of VRES plants can bring compared to the isolated systems. Table 4 reports for convenience the VRES optimal capacity resulting from the optimizations of the isolated systems.

**Table 4 - Total VRES installed capacity in Colombia, Ecuador and Peru [MW]**

| COUNTRY | PV installed power [MW] | Wind installed power [MW] |
|---|---|---|
| COLOMBIA | 2,400 | 2,700 |
| ECUADOR | 1,750 | 2,050 |
| PERU | 2,750 | 1,700 |
| TOTAL | 6,900 | 6,450 |

All three countries are operated at 60 Hz, and interconnections are obtained through the usage of AC lines. The Net Transfer Capacities (NTCs) between them, which consider existing and future projects, are reported in Table 5.

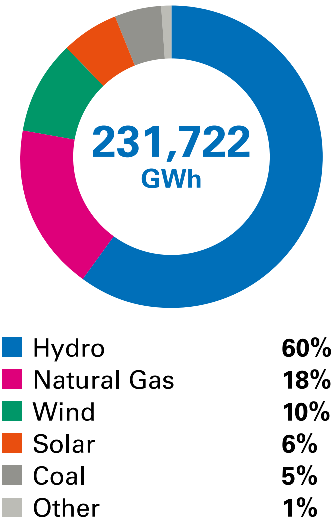
**Table 5 - Net Transfer Capacity between countries [MW]**

| NTC COL-ECU | NTC ECU-COL | NTC ECU-PERU | NTC PERU-ECU |
|---|---|---|---|
| 395 | 535 | 660 | 660 |

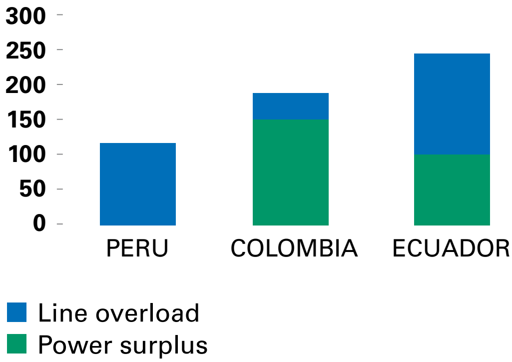
Thanks to the possibility to exchange energy, overgeneration conditions are strongly reduced, and a better exploitation of the VRES plants can be achieved, together with a lower usage of thermal plants which had to replace curtailed VRES energy. More than 1.8 TWh of additional green energy can be injected in the power system compared to what was compatible with the constraints of isolated systems. A more economical dispatch of the thermal fleet can also be applied, further increasing the benefits for the system, while EENS is reduced by 30%, as network constraints can be resolved using plants available in neighbouring countries. The total benefit for the whole interconnected system accounts for USD 335 million. This represents a maximum value achievable in case the power exchanges can be fully optimized from an economic point of view. To this aim, the possibility to exchange energy between the countries must be addressed by a clear regulatory framework, which must set rules, rights and duties of all the involved parties. The more the systems will be operated in a coordinated and flexible way, able to react also to real-time events, the more the benefits for the whole system will increase, thanks to the possibility to share the cheapest generation and supply the demand more effectively.

In these optimal conditions, Colombia exports to Ecuador 2.4 TWh and imports 0.3 TWh, while Peru exports to Ecuador 1.1 TWh, importing about 1.8 TWh. Peru and Ecuador are electricity importers, due to the high cost of thermal generation, while Colombia exports more than 2 TWh thanks to its hydro resources and to a cheaper coal production. Only minor congestions take place on the interconnections, meaning that the assumed NTCs are already high enough to allow the system to exploit the benefits at best. Improvements of the NTCs are expected to give no significant benefits as they would improve the operation of the system only in the limited periods in which the exchanges are constrained.
The energy exchanges might change in case externalities were considered for thermal production, increasing the generation costs to consider effects on the environment. For instance, the application of the carbon tax in Colombia might affect the convenience of coal power plants against other technologies.

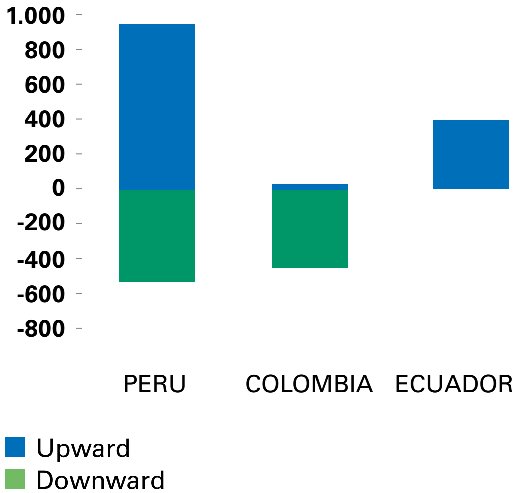
**Total**




**Curtailed RES Production [GWh]**




**Redispatching for line overload [GWh]**



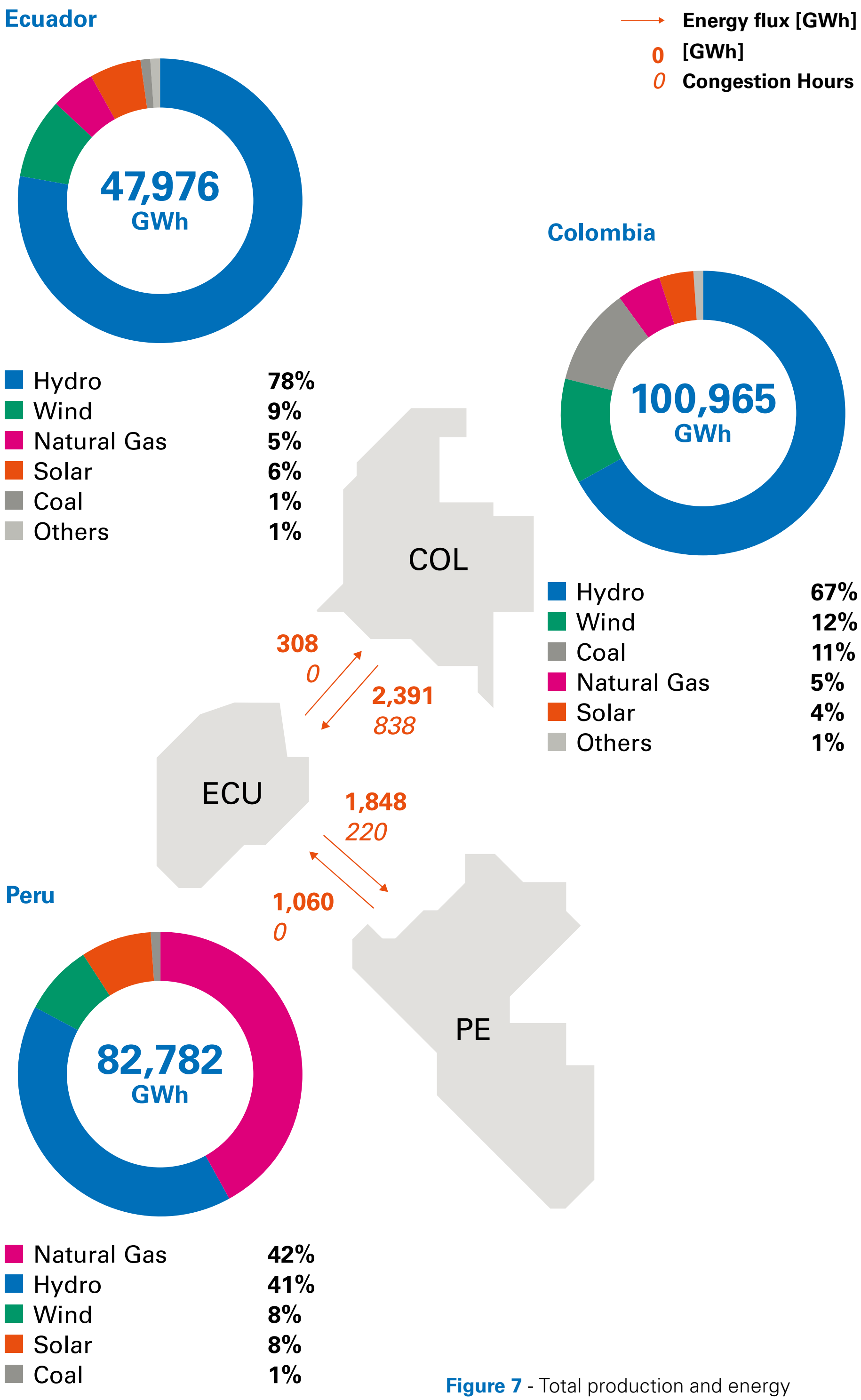



**Figure 7** - Total production and energy exchanges – Base Case Interconnected scenario with optimal VRES amount

Interconnections always improve the technical possibility to exploit VRES, and in this case they make it possible to increase the production of VRES plants by reducing system constraints and related curtailments. In this way, they bring a positive economic advantage into the system, pushing for further deployment of plants in these countries. Interconnections also enable a more effective exploitation of cheap thermal generation[6], reducing the overall generation costs and making VRES competing against cheaper resources. This fact would have a negative impact on the economic advantages that VRES introduce on the system as they would replace energy generated at lower cost. Depending on which effect is stronger, the interconnections might create or not conditions for the economic convenience of additional installations of VRES plants. In the interconnected scenario, calculations have been performed with additional PV and wind plants in the most favourable areas in Peru and Colombia: results showed that the investments for these new plants are aligned with the benefits they introduce and are therefore a no-regret option, even considering only fuel costs reduction. If externalities - which increase the cost of the energy produced using fossil fuels due to the polluting and GHG effects - are also assessed and considered, the advantage of installing new VRES plants in the areas with best resources would become more significant.

In conclusion, interconnections do not increase the optimal economic amount of VRES capacity, which remains aligned with the values of the isolated countries, but allow a better exploitation of the VRES plants (+1.8 TWh) as the system constraints are partially relaxed due to the possibility to import/export energy and risk of curtailments is reduced. Moreover, they improve the security of the system and create the conditions for the exploitation of additional VRES capacity which might be further introduced to reduce the environmental impact of thermal generation. The optimal configuration for VRES installations includes a total of 6,900 MW of PV power plants and a total of 6,450 MW of wind power plants as reported in Table 4. They produce 13 TWh and 23.5 TWh respectively, corresponding to about 6% and 10% of the total demand. These VRES plants and the related storage systems contribute to cover the load increase up to 2030 mostly with carbon-free generation: in fact VRES and hydropower plants represent 90% of the additional power introduced in the systems with respect to the existing fleet, and only thermal plants already planned to be built on short term have been considered in the analysis. Hydro power plants continue to play the most significant role in the analysed power systems. Thanks to the flexibility ensured by reservoirs, they can provide a positive contribution to the deployment of VRES plants, but on the other hand they might become also one of the limiting factors due to the availability of big amount of energy generated at low operational cost and the low flexibility of run-of-river plants. Interconnections also improve the flexibility of the systems, reducing constraints and allowing a better exploitation of VRES plants, but also make available cheaper resources against which VRES plants have to compete. In case externalities were considered for fossil fuel generation and costs are increased for the pollution and GHG effects, VRES would become even more attractive in areas with best availability of resources.

6 It is important to recall that the economic assessment is based on fuel costs savings, and no externalities are considered for thermal generation. This approach increases competitiveness of thermal power plants and provides a conservative estimation of the advantages introduced by VRES.

## 5.5 Sensitivity analyses on final optimal configuration of Colombia-Ecuador-Peru interconnected system

The optimal VRES capacity reported in the previous Chapters has been calculated starting from the Reference scenario which considered an average availability of the hydro resource, representative of conditions of different years, and the expected composition of the generation fleet.
In order to check how the power system including the optimal amount of VRES plants operate in conditions which differ from the average and the expected ones, some sensitivity analyses have been performed on the final optimal configuration of the interconnected system, focused mainly on:

- Variation of hydrological conditions;
- Variation of generation fleet.

No sensitivities on different NTC values have been performed because, despite the good amount of energy exchanged between the countries, interconnections reach their limits in a limited number of cases and therefore do not represent critical constraints for the optimal operation of the whole system.

Sensitivity analyses on **hydrological conditions**, simulating the expected operation of the whole system in a dry and a wet year, are very relevant for this cluster of countries which covers a significant share of the demand with hydro plants.
In fact, the optimal amount of VRES has been defined considering an average production of the hydroelectric power plants but it is necessary to ensure that in different hydrological conditions, such as dry periods, the system has enough generation available to supply the load, avoiding a dramatic deterioration of the adequacy, which would cause a high EENS value. In these conditions, there must be other generation resources, even expensive ones, to be used to cover the demand. In case the simulation shows critical results, some countermeasures, based on thermal generation or other technologies, should be considered in the power system planning to limit the negative effects of scarcity of hydro resource.

The "dry hydrological condition" has been defined based on historical series and assuming the availability of water resource typical of the 10th-15th percentile of the series. Following this approach, the dry year has been modelled with a reduction of the energy available from hydropower plants equal to about -25% in Colombia, -20% in Ecuador and -15% in Peru.
As expected, the simulation of the scenario with lower availability of hydro resource shows a limited increase of the EENS, up to 3 GWh, which remains acceptable in the system, and a significant increase of generation costs of thermal plants, which must produce nearly 26 TWh not available from hydro. However, the system remains adequate and no critical risk of lack of power is highlighted, meaning that there is enough generation capacity, even if expensive, to face dry periods. Interconnections support the good operation of the system, allowing Peru, which has the highest share of thermal generation, to export a big amount of energy (nearly 4 TWh) towards the other countries which suffer more the scarcity of water.

On the contrary, in case a *"wet year"* happens (still defined based on historical series assuming the conditions of about the 85th90th percentile corresponding to 20% more water in Colombia, 15% in Ecuador and 25% in Peru), the system has abundancy of generation from hydro. In this condition EENS remains very limited and due only to local network congestions, thermal generation costs reduce to about 2/3 compared to the average condition, and the risk of curtailments for VRES plants increases. In fact, due to the higher generation by hydropower plants, PV and wind power plants must cut their production in overgeneration conditions respectively by about 750 GWh and 2 TWh, corresponding to respectively more than 7% and 9% of their total possible production. These curtailments reduce the revenues of the VRES plants, nonetheless it is expected that the overall impact on the economics of the projects is limited, as this wet scenario takes place only for a very limited amount of their lifetime.

As far as the **generation fleet** is concerned, a simulation in which some new thermal power plants or important upgrades are not present has been performed, in order to assess whether in the interconnected system with the additional VRES plants there might be some benefits in terms of possible avoided investments. The investments that have not been considered in this sensitivity are related to the planned thermal plants which are not already in an advanced phase of development (including the dispatchable plant which resulted necessary in Ecuador to ensure adequacy in dry conditions), and also the conversion of the big plants of Nepi and Puerto Bravo in the South of Peru from liquid fuel to CCGT.
In total, in this sensitivity the installed power of cheap thermal plants is reduced by about 1,100 MW, and in addition about 1,400 MW in Peru are switched from natural gas to liquid fuel. In this new condition, EENS does not change significantly, while generation costs increase by more than 35% with respect to the original case: from a technical point of view, the new thermal generators are not necessary to cover the load with a good adequacy in an average hydrological condition, thanks to the presence of the VRES plants which provide a significant share of the energy. The strong cost increase highlights that if the lack of the listed thermal generators had been assumed also in the Reference scenario, there would have been additional room for VRES, as the advantages deriving from VRES plants would have been more consistent. Similarly, if externalities were considered in the calculation of the cost of electricity produced by thermal plants, with consequent higher cost for the load supply, VRES would become even more attractive.

### 5.6 Geographical location of VRES plants and connection process

The best mix of PV and wind installed power determined for the Base Case represents the optimal solution in a long term planning. In case of network constraints, the optimal solution can be slightly adjusted to ensure that constraints are not violated. However, the detailed roadmap for deploying a massive VRES installed capacity as the one resulting from the optimization depends on specific constraints such as land availability and the authorization time needed for the project development and the connection to the transmission grids. This latter issue is of utmost importance. In fact, the actual development of VRES plants will have to deal with the need to effectively connect them to the transmission network since the difficulty to get an access point to the grid where to inject the power might increase the cost of the projects. Many local network improvements also at lower

voltage levels will be probably needed to enable the new power plants to reach the transmission system, and this detailed evaluation is part of the activities that need to be performed during the short/mid-term planning of the system.
Looking also at examples from other countries where the VRES penetration have been already increasing for the last years, it is reasonable to foresee that new substations on the 500 kV lines will be required to make available more frequent points of possible access to the transmission system. This is valid in particular in the areas with high solar irradiation or wind availability where the lines are long and the amount of power that should be transferred is high, as for example the areas along the Peruvian coasts. Colombia already developed an ambitious plan for the connection of the great number of windfarms expected in la Guaijra region, with the constructions of new substations ("Colectoras") and the long HVDC line directly connected to the transmission system more in the Centre of the country.

# 6 Variants

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

- Electric demand;
- Generation evolution;
- Possibility to have big electrical storage systems.

Both Variants have been investigated on the system with interconnected countries featuring the amount of PV and wind plants resulting from this optimization.

## 6.1 First Variant

In the first Variant a higher demand scenario has been evaluated, under the hypothesis of a stronger economic growth of the countries and a high penetration of e-mobility in the biggest cities. Based on the data available in the different forecasts released in the countries and summarized in [1], the overall demand is increased with respect to the Base Case by 5% in Colombia and 12% in Ecuador and Peru. In addition, the load pattern has been modified especially during the night as a consequence of the presence of electrical vehicles.
Another important change in the generation fleet has been taken into account to introduce the transition to a carbon-free condition of the system: coal plants (accounting for more than 2 GW, mainly in Colombia) have been tentatively replaced by equivalent VRES power plants. In case the increase of VRES does not ensure a suitable level of generation adequacy, part of the coal plants can be then replaced by natural gas power plants with higher efficiency and lower specific $CO_2$ emissions, which thanks to their dispatchability can compensate the variations of PV and wind resources.
Also the need of storage systems has been evaluated related to the installation of new VRES power plants, to increase the flexibility of the overall system, reducing the constraints on the minimum production level and increasing also the ability to cope with the peak load.
Even without any additional generation plant, the system does not suffer EENS due to lack of power, but only shows limited issues, within the acceptable thre-

shold, due to line overloads. However, in this condition generation costs become very high because even very inefficient plants must be operated to supply the high load: it is then expected that further installation of VRES plants is advantageous from an economic point of view, replacing expensive generators.

Simulations showed that in this Variant 1 there is convenience to install additional 5 GW of PV plants and 2 GW of wind, distributed in areas with highest resources in Colombia and Peru. The total installed power is then nearly 12 GW for PV and 8.5 GW for wind, as reported in Table 6.

**Table 6 - Additional and total VRES installed power in Variant 1 [MW]**

| COUNTRY | Additional PV power plant [MW] | Total PV power plant [MW] | Additional wind power plant [MW] | Total wind power plant [MW ] |
|---|---|---|---|---|
| COLOMBIA | 2,500 | 4,900 | 1,000 | 3,700 |
| ECUADOR | - | 1,750 | - | 2,050 |
| PERU | 2,500 | 5,250 | 1,000 | 2,700 |
| **TOTAL** | **5,000** | **11,900** | **2,000** | **8,450** |

The additional plants generate more than 16 TWh and cover about 80% of the load increase assumed in Variant 1, achieving more than 20% of the total supply. VRES curtailments are estimated in about 1.7 TWh (3% of the total possible production, higher than 55 TWh), and even if the value is higher than in the Base Case, it results to be convenient because the average marginal cost of the thermal generation is higher. Limiting factors are also in this case represented by system constraints (and in particular risk of overgeneration conditions when VRES produce at their peak) and by some network bottlenecks.

In this condition, Peru exports to Ecuador about 3 TWh, with a significant change with respect to the Base Case where it was a net importer, and Colombia exports more than 1 TWh, slightly less than in the Base Case. In fact, due to load increase and no additional generation capacity, Ecuador needs more energy from other countries as its thermal plants are in general expensive. Peru increases the production of its thermal plants which have low generation costs due to the subsidies for natural gas, in order to supply the load increase not covered by the additional VRES.

### 6.2 Second Variant

In the second Variant a lower demand scenario has been considered, under the assumption of a generally reduced economic growth and an increase of the energy efficiency. Considering the plans of energy efficiency already available and committed in the national development plans of future systems and what already included in the Base Case, the load is reduced by -10% in Colombia, -15% in Ecuador and -15% in Peru, for a total of 29 TWh.

The generation fleet assumed as a reference for Variant 2 is the same as in the Reference scenario of the Base Case of each single country. As far as VRES are concerned, lower optimal values are expected as the demand is reduced while the amount of energy available from hydropower plants is the same, then requiring less production by other technologies. For this reason, the calculation of the new VRES optimal values is launched from the original values assumed in the Reference scenario of the Base Case. The resulting optimal values of installed power per technology to be added in the different countries are reported in Table 7. For convenience, also the total values are calculated.

**Table 7 - Additional and total VRES installed power in Variant 2 [MW]**

| COUNTRY | Additional PV power plant [MW] | Total PV power plant [MW] | Additional wind power plant [MW] | Total wind power plant [MW ] |
|---|---|---|---|---|
| COLOMBIA | 220 | 1,300 | 400 | 1,700 |
| ECUADOR | 120 | 200 | 80 | 200 |
| PERU | 2,220 | 2,500 | 1,090 | 1,500 |
| **TOTAL** | **2,560** | **4,000** | **1,570** | **3,400** |

With this additional capacity, system adequacy remains good, and generation costs are reduced by 25% thanks to the injection in the system of about 11.8 TWh produced by VRES plants and not by thermal ones.
Risk of curtailments remain limited because in this scenario the limiting factor to a wider expansion of VRES plants is the low cost of the generation against which they have to compete, which keeps the economic advantages of VRES relatively lower. It is worth recalling that costs accounted for thermal generation are mainly based on fuel costs and no externalities are included. If additional costs for emissions and pollution are considered, the average generation cost increases and benefits due to the introduction of VRES plants also become higher, fostering their penetration in the power system.
Even without considering the latter, the optimal configuration of Variant 2 includes almost 7.5 GW of PV and wind plants in the system, much more than as of today.

The optimal amount of PV and wind plants would increase in the countries with best resources in case some of the non-VRES power plants (thermal, hydro, biomass…) considered in the generation fleet foreseen at 2030 will not be developed because not profitable in a scenario of lower demand growth (as they would be operated a lower number of hours) or because they might incur difficulties during authorization process. In such a context, flexibility, modularity and shorter installation time of VRES plants with respect to other technologies, in addition to the competitive LCOE, can foster the penetration of PV and wind plants in the generation development plan also in a lower demand scenario.

# 7 Conclusions

The analysis was aimed at assessing the optimal economic and technical amount of PV and wind power in the Colombian, Ecuadorian and Peruvian systems at 2030 taking into account the transmission system characteristics. It has been assumed that new VRES technologies can actively support the system, sharing the burden for balancing and reserve usually assigned only to the dispatchable plants. Storage systems have been allocated to new installed VRES plants, aimed at mitigating the variability of their production, which negatively affects the operation of the electric power system, and providing required ancillary services.
The results showed that in these countries there is the opportunity for a massive deployment of VRES generation. The best mix of new generation varies in the countries, depending on the availability of natural resources and on the expected installation costs.

**Base case**
The main findings are the following:

- In Colombia, the installation of 2,400 MW of PV and 2,700 MW of wind power plants, plus storage systems for about 200 MW represent the optimal values. These values are respectively about 1,300 MW and about 1,400 MW higher than the amount foreseen in the assumed Reference scenario of the Base Case based on the UPME forecasts. The main limiting factor is the presence of a high amount of cheap energy (hydro and coal) which already covers a significant share of the demand and introduces some minimum power constraints on the generation. In the analysis, no environmental externalities are considered for thermal generation, and the assessment is based mainly on fuel costs. If cost of energy produced by thermal plants were increased to take into account externalities such as carbon emissions, the optimal amount of VRES also would increase as there would be higher benefits deriving from the replacement of thermal generation.
  Some risk of VRES production curtailments is present in the optimal solution (more than 600 GWh, corresponding to more than 7% of the production of the additional plants) even with the flexibility ensured by hydropower plants with reservoirs and additional storage. This value still represents the economic optimum as the energy produced in the rest of the operational conditions brings higher benefit to the system.
  With the introduction of the additional amount of VRES plants, PV and wind sources are able to cover 16% of the Colombian load.
- In Ecuador, it is convenient to install 1,750 MW PV and 2,050 MW wind, mainly located in the South area with highest potential but also exploiting regions with lower wind resource. An amount of 280 MW of storage has been also introduced, helping the reduction of overgeneration conditions which are the main technical issue due to the strong dependency of the Ecuadorian system on hydropower plants. High risk of VRES production curtailments (up to 20% of the energy generated by the additional power plants) is present, but the solution still represents the optimal economic condition due to the high costs of thermal generation. In the final configuration the amount of load supplied by VRES reaches about 12%.
- The Peruvian system is characterized by the lowest share of hydropower plants among the analysed countries, and the presence of a big portion of

energy supplied by power plants fuelled with natural gas available at a subsidized cost. Moreover, in the Base Case, the generation fleet and the transmission system are considered the same as in 2024 while growth rates are applied to the load up to 2030. Due to this particular condition, in this scenario some inadequacy of the generation is highlighted: EENS due to Lack of Power is higher than 10 GWh (more than $10^{-4}$ p.u of the load).
In the optimal scenario, the PV installed power reaches 2,750 MW (concentrated in the South), while wind is equal to 1,700 MW (along the coast and in the Northern part of the country) and produce respectively 6.2 TWh and 7 TWh, covering 16% of the demand. Lack of Power disappears thanks to their production, and only a limited curtailment of PV plants due to line overload is present.
In case subsidies to natural gas are not considered, resulting in higher cost of electricity produced from that source, VRES become even more attractive, as they replace more expensive generation, and the new optimal values would become 4 GW both for PV and wind. In this case some network reinforcements and the investments in additional special equipment in the South area are necessary, aimed at reducing the congestions on 220 kV lines caused by PV and controlling the power flows on the 500 kV lines for an optimal evacuation of the produced power. If only limited reinforcements are put in place without the possibility to control the loading of the 500 kV lines, it is convenient to install only 3 GW of PV due to the risk of congestions and limited capacity to evacuate PV production from South to North.

- Interconnections allows a better exploitation of the generation, especially VRES and hydro. Thanks to the possibility to exchange energy between the countries and to evacuate excess of power, the overgeneration conditions are strongly reduced and the curtailments of VRES plants decrease by 80% (1.8 TWh), mainly in Ecuador; total maximum benefits for the system are higher than USD 300 million, due to the possibility of a more optimal economic dispatch of the generation.
  Only minor congestions take place on the interconnections, and improvements of the NTCs are expected to give no significant benefits in the energy market.
- The presence of the interconnections does not modify the optimal VRES values because, even if it allows their better exploitation reducing curtailment risks, it also makes available cheaper generation from other countries, reducing the overall cost of the generation and consequently the benefits generated by the replacement with VRES plants. If other factors which cause an increase of the thermal generation costs (for instance, externalities such as costs of carbon emissions, absence of subsidies to natural gas in Peru, absence of some cheap generation…) were considered, the optimal value of VRES would also increase and interconnections would play an even more significant role for their best exploitation.

The following Table 8 shows the final optimal amount of installed PV and wind power and the corresponding production in the Base Case.

**Table 8 - Total VRES installed capacity and production in final optimal scenario (Base Case) for the interconnected system**

| COUNTRY | Installed power [MW] | | | Production [TWh] | | |
|---|---|---|---|---|---|---|
| | PV | Wind | Total | PV | Wind | Total |
| COLOMBIA | 2,400 | 2,700 | 5,100 | 4.1 | 12.1 | 16.2 |
| ECUADOR | 1,750 | 2,050 | 3,800 | 2.7 | 4.5 | 7.2 |
| PERU | 2,750 | 1,700 | 4,450 | 6.2 | 7.0 | 13.2 |
| **TOTAL** | **6,900** | **6,450** | **13,350** | **13.0** | **23.6** | **36.6** |

**Sensitivities**

Three sensitivity analyses have been carried out aimed at checking how the power systems with the amount of VRES plants defined in an average scenario operate in different hydrological conditions (dry or wet) or in case of changes of the generation fleet due to lower investments in new cheap plants.

- In dry conditions it is necessary to use resources other than hydro to supply the load: Colombia and Peru are able to maintain a good adequacy thanks to the availability of thermal plants, while in Ecuador an additional dispatchable generator is needed. Generation costs increase dramatically due to the usage of more expensive plants necessary to avoid high EENS. In these conditions, overgeneration does not occur, and VRES plants are not curtailed anymore; in Peru some small additional reduction of PV plants is necessary due to different loading of the transmission network. Moreover, Peru becomes a strong exporter (4 TWh) and Colombia reduces to 1 TWh its export to Ecuador.
- In wet conditions there is abundancy of hydro resource, which causes more frequent overgeneration, with consequent higher risk of curtailments of VRES and hydro productions. The amount of VRES energy to be reduced increases by 2.7 TWh (the most affected resource is wind in Colombia), equal to more than 7% of the overall PV possible production and 9% of the wind. However, the impact on the whole profitability of the plants is expected to be low, as wet years happen only few times in the projects lifetime.
- Finally, in the sensitivity with less investments in thermal generation this is reduced by 1,750 MW, removing two new coal plants in Colombia, the additional dispatchable plant needed for adequacy in dry condition in Ecuador and not considering the switch to CCGT of two big plants in the South of Peru. Results showed still a good adequacy: in the average hydrological conditions these plants are not necessary to supply the load thanks to the additional generation by VRES. A strong increase of the generation costs has been found, as cheap generators have been removed: this cost increase might create further room for additional VRES plants as they would replace more expensive generation.

**Variants**

In addition to the Base Case, two Variants have been examined, characterized by higher or lower load and differences in the generation fleet, and relevant VRES optimal values have been defined.

- In the first Variant, the demand increases by 5% in Colombia and 12% in the other countries and coal plants are shut down. In these conditions, there is economic benefit to introduce additional 5,000 MW PV and 2,000 MW wind (reaching respectively 11,000 MW and 8,450 MW in total), which are able to produce the energy needed to supply half of the load increase without using coal plants. Their deployment is limited by the risk of production curtailments, which increases to 1.7 TWh as the hydro resource remains the most significant source in the system and introduces constraints in periods of high VRES availability.
- The second Variant considers a lower demand, keeping the same generation fleet of the Base Case. In this condition, the introduction of additional VRES plants results less attractive, as more than 2/3 of the total demand is already covered by hydro production and VRES would replace very cheap thermal generation (mainly coal in Colombia and natural gas in Peru, whose cost is kept low by subsidies). The results show that a total amount of 4,000 MW PV and 3,400 MW wind is possible. VRES plants are distributed mainly in Peru (country with the highest share of production from fossil fuels) and in Colombia, especially for wind, thanks to the very high capacity factor. On the contrary, Ecuador remains with a limited amount of VRES, due to the lower availability of solar and wind resource and higher share of hydro.
  In case in this low load scenario some non-VRES power plants (thermal, hydro, biomass…) foreseen at 2030 will not be developed because not profitable with a lower demand growth, VRES plants might represent a good alternative, thanks to their competitive LCOE and to flexibility, modularity and relative speed in the execution of the projects with respect to other technologies.

As a summary, the analysis carried out in the present study on the interconnected system constituted by Colombia, Ecuador and Peru showed a big potential and economic advantages for a development of PV and wind in the regions with highest resources or with most expensive thermal generation. VRES can play a significant role in the load coverage at 2030, limiting or avoiding the need of new thermal generation and related investments. Planned transmission systems in the different countries are able to support the development of VRES and do not introduce critical bottlenecks. The availability of huge amount of hydro resource has a significant influence on the optimal VRES amount, with two opposite effects: on one hand it fosters the development of VRES plants, because hydropower plants can compensate their variability reducing the negative impact on the systems; on the other hand it represents a limiting factor because of the possible overgeneration conditions and because VRES production would compete with generation without fuel costs.

Interconnections between countries contribute to the optimal exploitation of VRES as they reduce the system constraints in the countries thanks to the possibility to import/export energy, lowering the risk of generation curtailments due to overgeneration conditions and increasing the overall system adequacy and its flexibility.

# 8 References

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