Final Report

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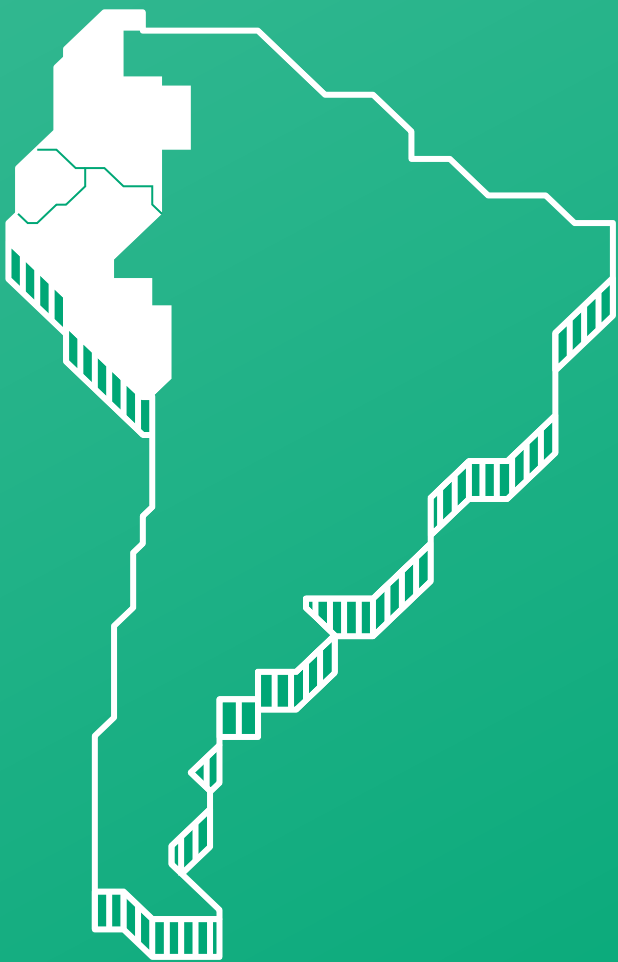

Variable Renewable Energy Sources (VRES) deployment and role of interconnection lines for their optimal exploitation: the **Colombia-Ecuador-Peru** case study

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LIST OF ACRONYMS

CCGT	Combined Cycle Gas Turbine
CELEC	Corporación Eléctrica del Ecuador (Ecuador)
COES	Comité de Operación Económica del Sistema Interconectado Nacional (Peru)
EENS	Expected Energy Not Supplied
EHV	Extra High Voltage
EOH	Equivalent Operating Hours
GHG	Greenhouse gas
GT	Gas Turbine
HVDC	High Voltage Direct Current
LATAM	Latin America
LCOE	Levelized Cost of Energy
MC	Monte Carlo
M$ or MUSD	USD million
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PV	PhotoVoltaic
RES	Renewable Energy Source
RoR	Run-of-River
UPME	Unidad de Planeación Minero Energética (Colombia)
VRES	Variable Renewable Energy Source

1 FOREWORD

1.1 General objective of the study

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

Unfortunately, the location of new power plants exploiting RES is strictly constrained to the geographical availability of the resources (wind, sun, geothermal, biomasses, hydro). Hence, the connection of a large quantity of RES generation shall be carefully examined in advance to avoid operating conditions calling for RES generation curtailment for security reasons (e.g.: overloads due to insufficient power transfer capability; impossibility to balance the system due to the inflexibility of the conventional generation, poor voltage profiles, risk of cascading effects following an outage on a grid component / generating unit, etc.).

The limitation in the development of RES generation, particularly the variable generation such as wind and PV, can be overcome exploiting the existing interregional or cross-border interconnections, reinforcing the existing ones and building new cross-border corridors.
As a matter of fact, Latin America is still fragmented in national or regional power pools: SIEPAC (interconnected pool from Guatemala to Panama), the Andean interconnected system (from Colombia to Peru) and the Brazilian system (SIN) interconnected basically with Uruguay and Argentina. Other countries are still fully isolated, like Guyana, Suriname, French Guyana and Bolivia or very weakly interconnected, like Chile where just one cross-border line is in operation between SING (Chile) and SADI (Argentina): the Salta-Andes line with a power transfer capacity of about 200 MW owing to network constraints, despite this line is designed for a capacity of about 600 MW.
Thus, dedicated studies shall be carried out specifically to identify the feasible penetration limits of variable RES (VRES) generation accounting also for the possible power interchange across interconnection lines so to cope with conditions of power surplus or shortfall. Considering the wide geographical extension of Latin America, the analyses shall be applied at a regional level.

Within the context recalled above, this study "*RES generation deployment and role of interconnection lines for their efficient exploitation*" aims namely at examining the optimal economic penetration of VRES

[1] Almost all Latin American countries signed the Paris Agreement and a large majority of them already ratified the Agreement. See the updated status of Paris Agreement ratification and entry into force on: http://unfccc.int/paris_agreement/items/9444.php

generation (wind and solar) in some Latin American (LATAM) countries and regions within the countries accounting for the possible cross border power exchanges.
The analysis is performed for the target year 2030 and starts from a given set of thermal/hydro generation, defined based on the already existing plants, the ones under construction and the planned ones which will be built before the target year.

The study has been divided in three different clusters focused on limited groups of countries (respectively Argentina-Chile, Argentina-Brazil-Uruguay and Colombia-Ecuador-Peru) defined based on geographical criteria and on the current and future configuration of the power systems, in order to allow a deeper analysis of the operation of the national systems and optimize the VRES development with a more local approach. This report contains the outcomes related to the third cluster of countries which includes Colombia, Ecuador and Peru.

1.2 Contents of the report

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

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

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

This first analysis takes into account the system wide operating constraints such as the needs for upward and downwards secondary and tertiary reserves and the "must run" units, hence ensuring among others a suitable capability for ramp up/ramp down to face the load pattern and the variability of wind and PV. The most critical conditions will be analysed with a deterministic approach.
During this task, it is assumed that the VRES power plants are not able to support the operation of the system with special services (for instance providing downward reserve), thus creating more challenging operational conditions, as traditional power plants are requested to provide the flexibility needed for the security of the system. Moreover, in the analysed conditions, a limited risk of VRES production

curtailments is accepted. At the end of this task, an upper bound of the feasible VRES penetration in the various countries is defined, which does not affect the system operation and is subject to limited curtailment risk.

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

One year of operation at the target year is simulated with a probabilistic approach based on Monte Carlo method for increasing levels of VRES until maximum economic convenience is reached with an adequate generation fleet.

For every simulation, which summarizes the results of thousands of different system configurations weighted by their likelihood to happen, main outcomes are provided, such as:

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

Benefits for the system are evaluated in terms of generation costs, considering where necessary also investment costs, and adequacy of the generation (measured through the possible variation of the Expected Energy Not Supplied index). The comparison of these benefits calculated with different amount of VRES production provides the information necessary to define the optimal configuration.

A similar approach allows to assess also investments in the transmission system, which bring benefits to the system which have to be compared with the costs of the improvement of the network.

At the end of Chapter 3, the optimal amount of VRES power plants is estimated for the Colombian, Ecuadorian and Peruvian power system considering the countries as isolated systems and then considering them as interconnected.

Evaluations of possible benefits for the systems coming from the improvement of the network are presented in case there are significant congestions which limit the VRES generation and increase the overall production costs.

Moreover, the expected operation of the systems with the resulting generation fleet is also evaluated for different hydrological conditions, in order to verify that security of supply does not become critical during adverse years.

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

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

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

2.1 Introduction

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

The analysis takes into account the characteristics of the existing and future generation fleet together with the most restrictive load conditions for RES operation, coherently with the data collected in the Inception Report [1]. The ability of conventional generation to provide the upward and downward reserve needed to face the increasing penetration of VRES production is checked, and it is estimated the maximum VRES installable capacity ensuring that the reserve requirement is fulfilled by the conventional plants in service (in countries with massive presence of hydropower plants, such as Colombia and Ecuador, it is assumed that reserve is also provided by them). According to the said assumptions, PV and wind power plants do not support actively the system operation providing regulation capacity, reserve or other ancillary services.

The VRES taken into account are wind and PV plants. There are several combinations of installed power of these sources that can be integrated in the power system still ensuring that the conventional power plants are able to provide the needed reserve. One of the main outcomes of the analysis is then a description of the allowable combinations of wind and PV installed power.

At this stage, network constraints are not considered, but a system wide analysis is carried out considering the demand and generation mix. This means that a single bus-bar model is used to model the whole power system of each country.

2.2 Methodology

This chapter reports details about methodology and analysis process for a preliminary evaluation of the admissible VRES penetration in each country for the 2030 scenario. This analysis is carried out for every Country assuming the condition of isolated system, i.e. without power exchanges with the neighbouring countries, and by means of a simplified model where each system is represented as a single bus-bar, where load and generation are connected and must be balanced.

Load level and constraints on generation are defined according to the assumptions described in the following paragraphs. The balance in each system must be ensured considering also the secondary and tertiary reserves requirements which are necessary to manage both the uncertainty of the load and the variability of RES generation, without jeopardizing the security of the system.

This procedure is based on a deterministic approach taking into account the critical operating conditions for the power system in presence of VRES generation, generally represented by off-peak load and peak VRES generation. In particular, in off-peak operating hours during night, a high wind installed capacity

forces the conventional power plants to generate energy at a very low level. Even in this condition it should be guaranteed a proper amount of reserve in order to cope with the normal fluctuations of load and VRES.
The same problem occurs during the hours with high levels of solar radiation and low load.

2.2.1 Description of the computational approach

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

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

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

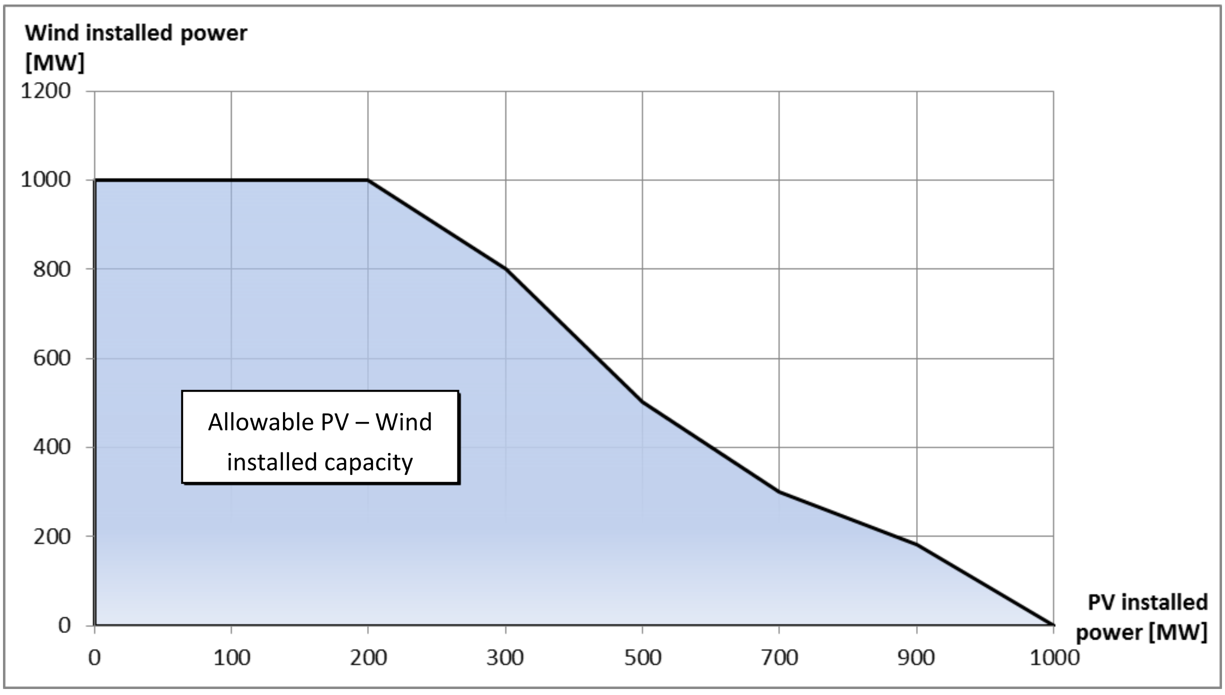

Figure 1 – Theoretical example of the allowable area on the PV/Wind installed power chart

To determine the maximum amount of VRES which can be installed in the system without affecting its security, the analysis focuses on the most critical conditions, which are characterized by low load and high VRES production. It is assumed that also in these conditions the VRES do not support the system with provision of ancillary services for reserve, and their production should not be curtailed.
In this low load condition, the sum of PV and wind production covers a large amount of the load. The residual load is supplied by traditional hydroelectric and thermal plants. These traditional plants operate therefore near their minimum output, although they have to provide the system with all the downward secondary and tertiary reserve required in order to cope with the uncertainty of load and VRES production, guaranteeing the stability and security of the whole system.
A further element that must be taken into account is that the unit commitment of the traditional power plants in the low load condition is not completely free. In fact it must be suitable to provide services to the system such as voltage regulation, inertia, etc. In other words, there is a minimum number of traditional power generation that must be in service. Also the production of plants such as run of the river and biomass cannot be neglected even in low load condition.
The need to guarantee a suitable amount of downward reserve on the traditional plants is then the factor that limits the amount of VRES installed.

The calculation is performed in two steps for wind and for PV power plants.
The maximum wind power production is assessed considering the 10^{th} percentile of the load and no PV production, condition which can happen during the night. The selection of the 10^{th} percentile of the load instead of the absolute minimum is proposed because the acceptance of a risk margin is a common practice during the planning process.
The calculation is performed evaluating the maximum wind power production admissible in the system which does not affect the fulfilment of the reserve constraint. Since the reserve requirements depend also on the amount of wind power production, this maximization is calculated with an iterative method. The corresponding maximum admissible VRES installed capacity is then calculated assuming a contemporaneity factor which is also commonly adopted as the probability that the wind power plants run at full power all together is pretty low.
The procedure is depicted in Figure 2.

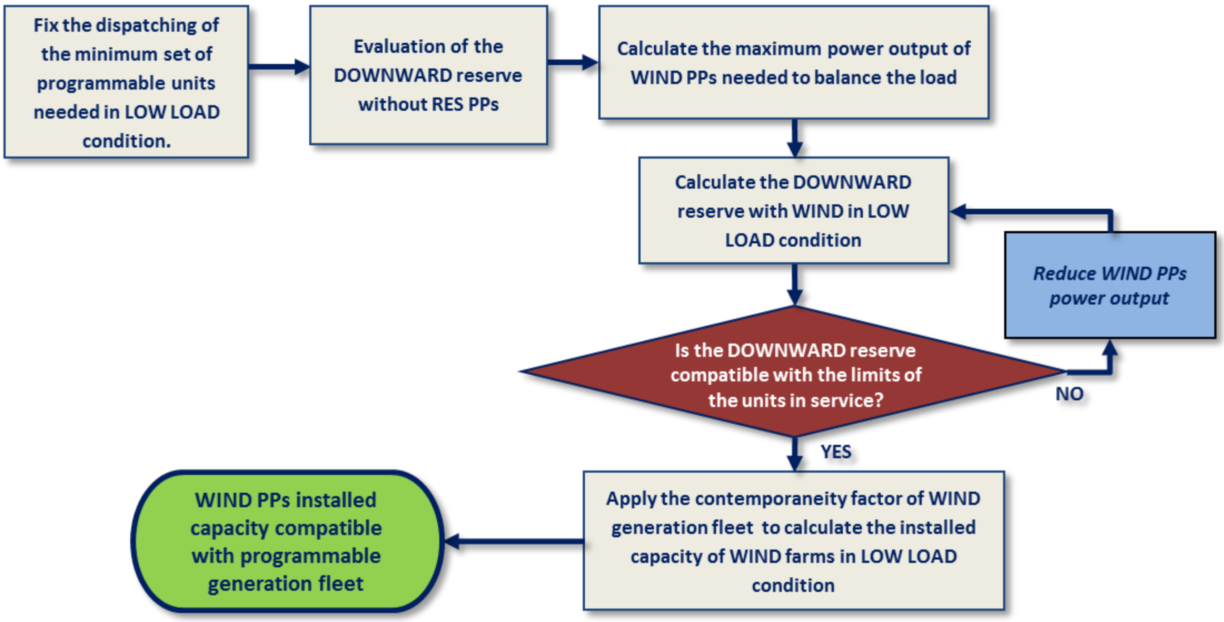

Figure 2 - iterative calculation of max installation of wind power plants

Once the maximum installed wind power is defined, a similar approach is followed to evaluate the maximum allowable PV production which does not require any curtailment due to reserve requirements. Also in this case a low load condition is analysed, selected among the hours in which the PV production is high. In particular, the 10th percentile of the loads that occur during the hours of maximum solar radiation is considered, which is expected to be slightly higher than the value used in the previous step. The calculation of the maximum PV production is performed for different levels of wind production, from the maximum value calculated in the previous step to 0 MW, in order to define the allowable PV/Wind installed power area as depicted in Figure 1.
The two analysed conditions are therefore the following:

- Calculation of maximum PV installable power in presence of the maximum wind installable power defined in the first step
- Calculation of maximum PV installed capacity in presence of no wind installed power

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

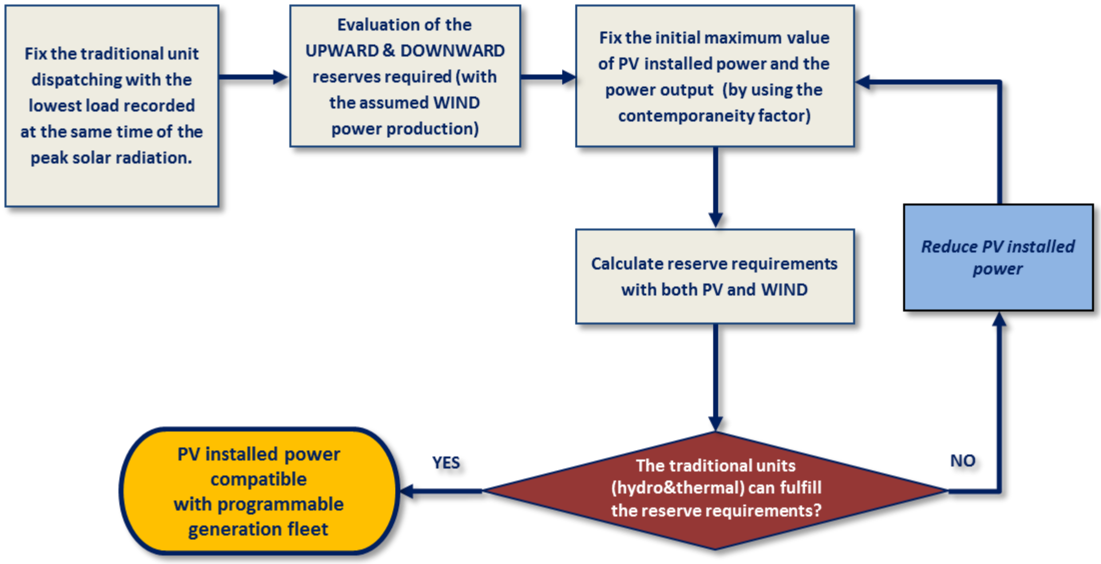

Figure 3 - iterative calculation of max installation of PV once assumed a fixed value of Wind

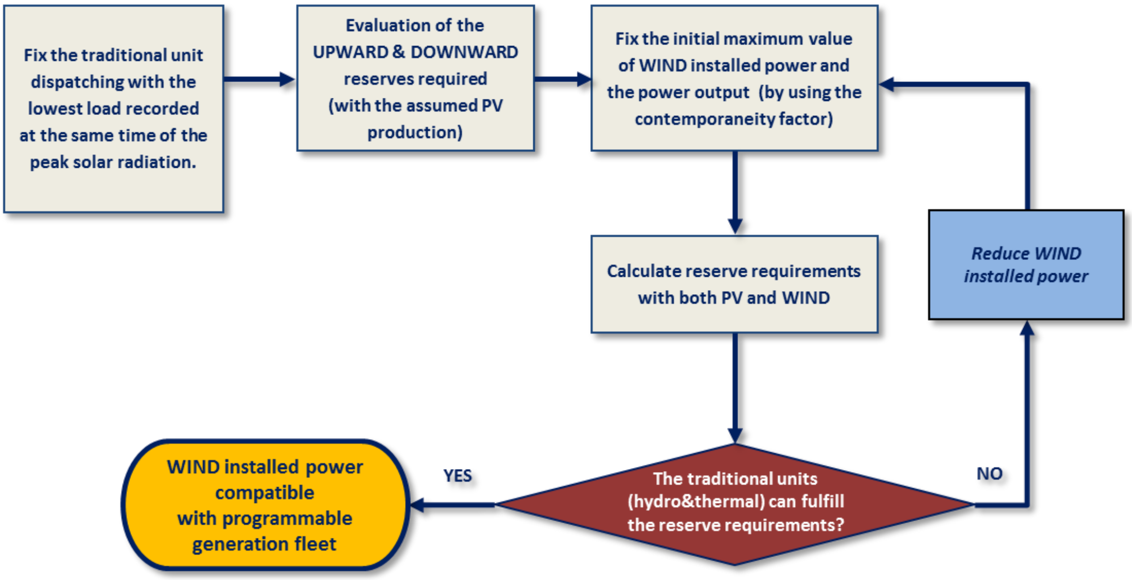

Figure 4 - iterative calculation of max installation of WIND once assumed a fixed value of PV

2.2.2 Assumptions

2.2.2.1 Load

The low load conditions are calculated using for the countries the data presented in the Inception Report. The hourly profiles used for the 2030 simulations (obtained by the available data from past years, rescaled according the foreseen peak value and annual energy demand) allows the identification of the 10th percentile.

Low load during night

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

Low load condition during solar radiation peak

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

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

In Table 1 are listed the load values used for the countries.

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

[MW]	Colombia	Ecuador	Peru
Low load during night	9,400	4,250	8,000
Low load condition during solar radiation peak	10,350	4,650	8,500

2.2.2.2 PV and WIND contemporaneity factor and uncertainty

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

The contemporaneity factor is used in this activity, to estimate the amount of MW which can be installed for the PV or the wind technology which can inject in the system the maximum power production without effecting the fulfilment of the reserve requirements. Given a specific power production, the relevant installed power can be obtained dividing it by the estimated contemporaneity factor.

The contemporaneity factors used in this study are shown in Table 2. These values are established based on experience and on the available resources in each country (in terms of maximum values and also distribution over the territory). For PV, the values take into account also the fact that some installations might be on roofs, with a lower efficiency because with worse exposition to the solar irradiation.

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

	Colombia	Ecuador	Peru
Solar PV	70%	70%	75%
Wind farms	80%	70%	80%

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

The standard deviations used in the analysis related to load and PV and wind production are shown in Table 3. It is important to consider that as the analysis is focused on conditions of high production by VRES, the upward error is in general lower, because the power increase (which require a downward thermal reserve) is limited by the characteristics of the plants and their maximum power.

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

[%]	Error downward	Error upward
Load	2.92	2.92
Solar PV	10	5
Wind farms	20	5

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

For all the analysed countries, the interconnection with neighbouring power systems have not been considered in the basic case or reference scenario. The possibility to export power towards the other countries is taken into account at the maximum possible level (reported in Table 4) in an additional calculation, in order to assess the maximum benefit that the interconnections might provide in terms of reduction of VRES curtailment risks. It is important to highlight that this analysis does not verify the actual ability of the neighbouring systems to absorb the excess of production. This detail will be fully considered in the simulation using the complete generation and transmission network model.

Table 4 – NTCs between Countries [MW]

	A → B	B → A
Colombia - Ecuador	395	535
Peru - Ecuador	660	660

2.3 Results of performed analysis

This section describes the results of the assessment of the limit of VRES due to system operation constraints considering a single bus-bar modelling of the countries, i.e. neglecting the possible internal network constraints.

2.3.1 Colombia

Figure 5 shows the maximum VRES installed capacity considering different combination of Wind and PV generation. The blue line represents the values obtained considering Colombia as isolated system (i.e.: "*Analysis considering the Transmission System in the Reference Scenario*"). The grey line is calculated assuming the usage of the interconnections between Colombia and Ecuador capable of 395 MW (i.e.: "*Analysis considering the Transmission System with the possible reinforcements defined in the Inception Report*"). It provides a clear indication about a maximum value beyond which a significant part of new VRES should be curtailed for operational constraints in low load conditions. In the figure the actual 2016 VRES installed capacity is also indicated as well as the installed capacity defined by UPME at 2030 [2]. It is possible to note that this value has an adequate margin with respect to the calculated limits, so no curtailments are expected during the operation due to system constraints.

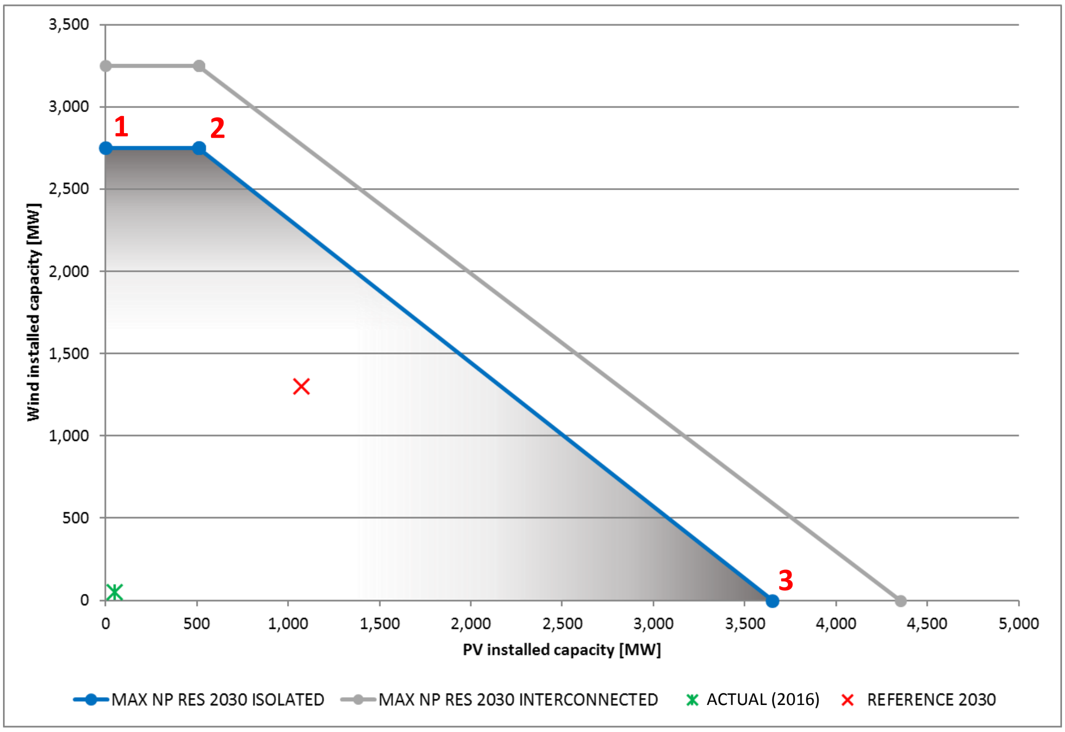

Figure 5 - VRES installed capacity limits due to system operation constraints in Colombia – 2030

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

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

Points 1, 2 and 3 do not represent situations which are likely to happen, because the planned development of VRES generation in Colombia foresees a growth of both PV and wind power installed plants, so at 2030 it is expected that there will be a balanced mix of PV and wind installed capacity and not the predominance of only one technology, as indicated by these points. Even if it is not probable that the system will operate in these conditions, they have been anyway evaluated in order to provide a general overview of the boundaries due to the system constraints.

It is also to be taken into account that if a technology is developed much more than the other (grey areas in the graph) concentrated in the limited portion of the transmission system where there is the best natural resource, local problems might appear due to the constraints in the evacuation capacity and technical minimum.

Finally, it is important to underline how the values provided considering the export capacity towards neighbouring countries (grey line) are indicative, as it is not sure that the other systems are able to absorb the exported energy which would be in excess in Colombia.

In Chapter 3 detailed calculations considering the transmission network model and based on a probabilistic approach will be performed in order highlight possible issues and to quantify the real risk of VRES curtailment considering simulating the expected operation of the systems.

2.3.2 Ecuador

The assessment of the maximum installable PV and wind power in the Ecuadorian system as a whole provides the results shown in Figure 6. As described in previous paragraphs, it represents the relationship between PV and wind installed power which allows to keep the risk of possible VRES curtailments low, considering the reserve requirements and the minimum amount of generation which cannot be shut down.

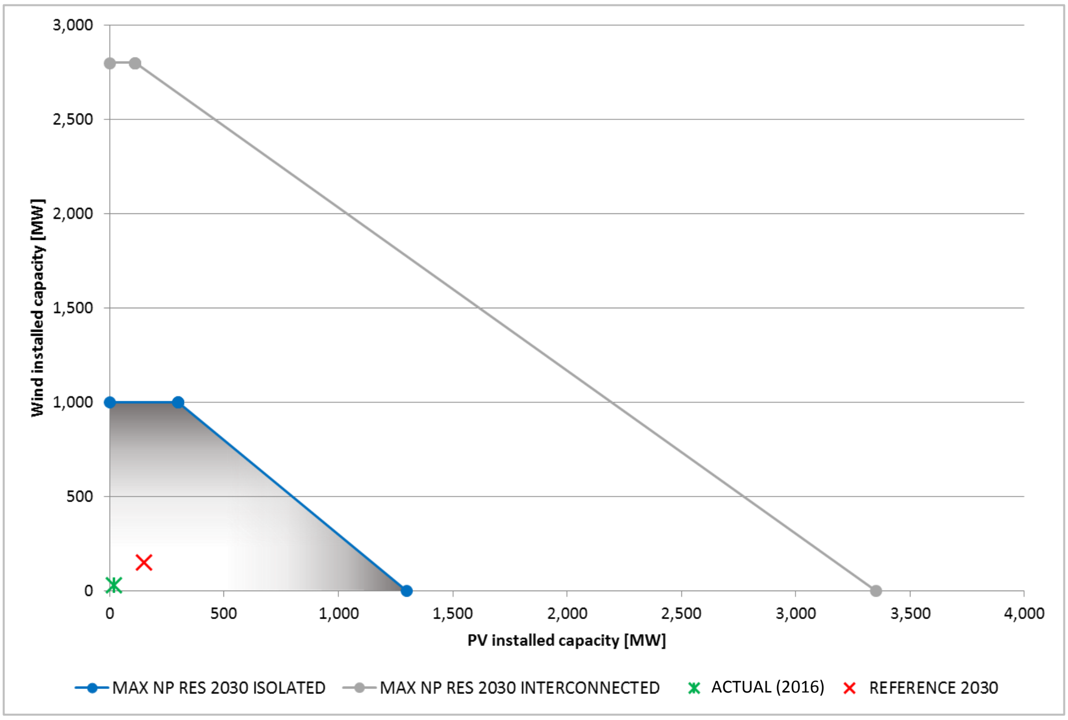

Figure 6 - VRES installed capacity limits due to system operation constraints in Ecuador – 2030

In the Ecuadorian case it is possible to see how the resulting VRES installed power is limited in case of isolated country due to the reduced amount of the thermal load. Ecuador is in fact the country with the smallest demand and with the highest share supplied by hydropower plants, in many cases RoR, and this leaves a small room for additional generation, in particular new VRES. The presence of the interconnections introduces big variations in the results, as the maximum exportable power is high compared to the internal load which can be supplied by VRES, even higher than it. Looking at these results, it is possible to expect a big difference in the operational constraints limiting the VRES production when considering the Ecuadorian system as isolated or when interconnected to the other countries.

2.3.3 Peru

The Peruvian power system is characterized by the presence of a higher share of thermal power plants and lower coverage by hydro with respect to Colombia and Ecuador. In general, this can be an advantage for a higher penetration of VRES, as the system can present more residual load to be covered with generators other than hydro, “must-run” or minimum power. Moreover, the high flexibility ensured by hydropower plants with reservoirs increase the ability of the system to accept new VRES plants.

Figure 7 shows the resulting values, which confirm the expectations with a possible total amount higher than 5,000 MW. As for the other countries, it is expected that it is not convenient to have an expansion strongly shifted towards only one technology, as it might cause local network problems.

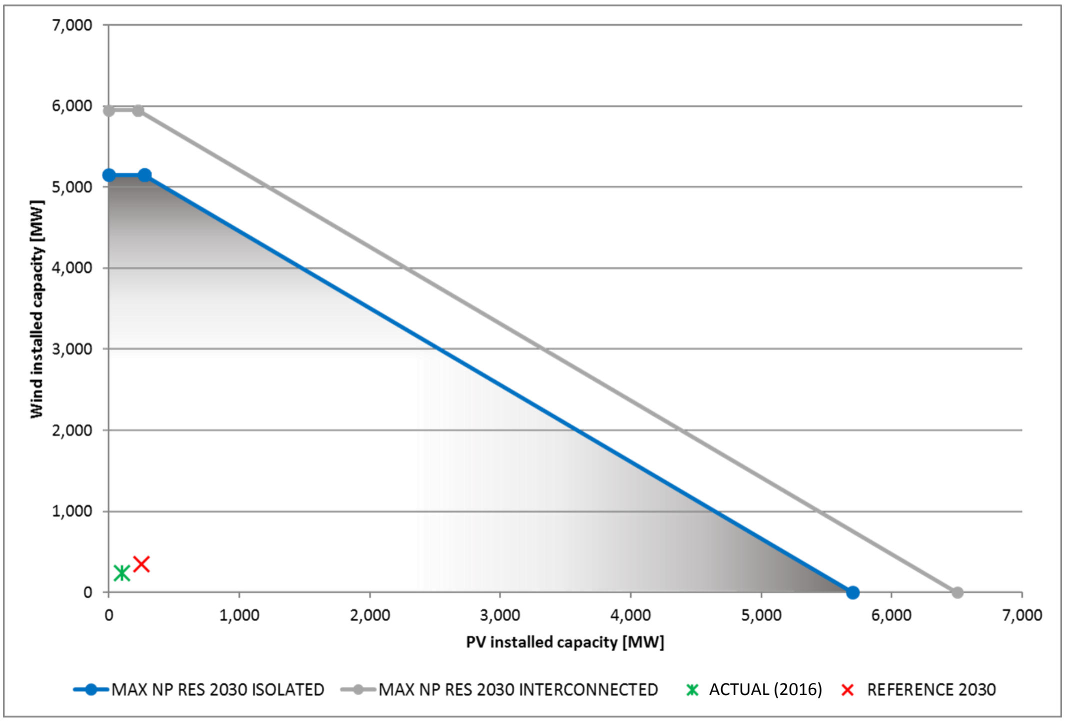

Figure 7 - VRES installed capacity limits due to system operation constraints in Peru – 2030

The interconnection towards Ecuador seems to have a limited effect ion the maximum VRES installed power, due to its reduced transfer capacity with respect to the values obtained in the isolated case.

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

3.1 Introduction

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

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

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

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

The most interesting results are the expected benefits for the system in terms of lower generation costs, taking into account the variation of the Expected Energy Not Supplied (EENS[2]), but also the expected production of the VRES plants, considering possible curtailments due to system or transmission constraints. These curtailments, which might become necessary to solve overloads that cannot be resolved by a different dispatching of the traditional generation or to meet very low load conditions when the thermal generation is already at the minimum production, reduce the production of the new VRES plants, reducing their profitability.

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

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

3.2 Methodology

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

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

[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)

provides highest benefits. The procedure adopted is illustrated in Figure 8 and is made by different steps and iterations that will be described in the next paragraphs.

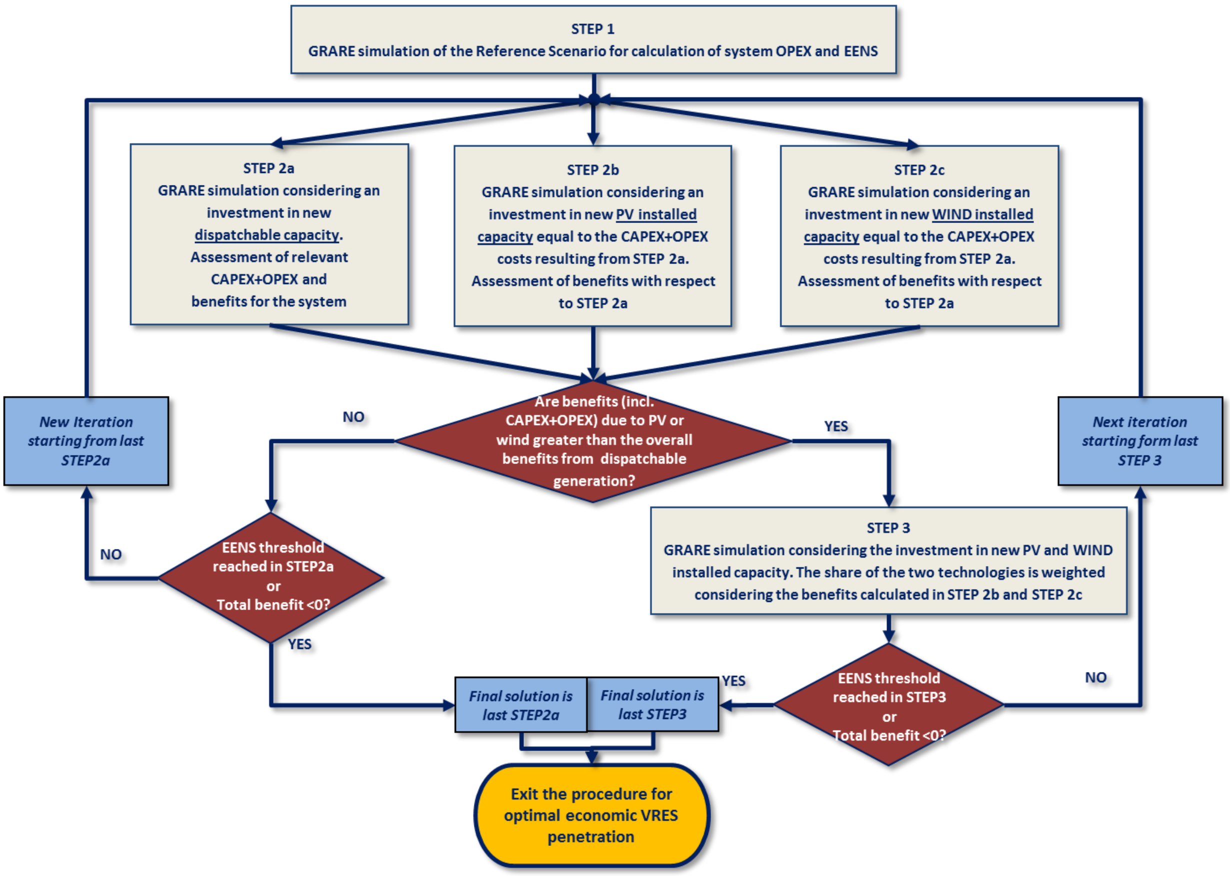

Figure 8 - Procedure for the calculation of the optimal economic VRES penetration

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

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

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

The construction of the Reference Scenario is based on the information described the Inception Report [1].

For some Countries, it might turn out that there is an inadequate installed generation for peak demand supply due to the misalignment between the year considered for the development of the generation and the one considered for the load. For instance, the generation in Peru is compliant with committed projects at 2024 while the load in the analysed scenario refers to 2030. In this case the demand increase from the year relevant for the generation to 2030 needs to be compensated by further installed generation.

Local congestions on transmission lines due to concentrated load increase are identified and eliminated, including reinforcements which are required to supply the load. Such reinforcements are not the object of the present study, which is focused on the improvement of transmission system to ensure the optimal exploitation of VRES.

The whole transmission network is modelled to ensure a correct calculation of the power flows on the lines, but only constraint on Extreme HV lines (500 kV) and 220 kV are considered. It means that overloads are evaluated only on these voltage levels which are responsible of the power transfer over long distances and between different areas, since the lines with lower voltage have a limited capacity and a more local effect. Constraints on voltage levels equal or below 150 kV are taken into account only when deemed appropriate.

Once the Reference Scenario to be simulated is defined, a run is carried out to evaluate the operation of the system in this starting condition.

The main information taken from the results are related to:

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

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

In the second step, simulations are carried out to determine the best economic generation mix which ensures the minimization of the system operational costs, taking into account also the cost of EENS and aiming at an adequate level of generation adequacy.

The main parameters considered to calculate the amount of new generation capacity to be added in the systems are the annual costs of the system, including OPEX and CAPEX of the new power plants and the EENS. In order to find the best mix of new generation, three different simulations will be performed to compare different technologies, assuming that an equal amount of money is invested in dispatchable or PV or wind plants.

As shown in Figure 8, the first simulation of the second step (Step 2a) will consider the introduction of an amount of new dispatchable generators, defined case by case for each country depending on the lack of power and energy resulting from Step 1. The outcome of this first run will be the evaluation of the benefit for the system and the costs (CAPEX[3] and OPEX) of the new added plants. This cost will be taken

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

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

where *n* is the economic life of the plant.

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

Once the amount of money which can be invested in new generation is available, calculated as CAPEX+OPEX of the dispatchable generation analysed in Step 2a, simulations in Step 2b and Step 2c are carried out, assuming respectively that an equivalent investment is done in PV or wind technologies. In both cases, part of the investment will be assigned to the introduction of storage devices which allows the VRES technologies to provide active support to the operation of the systems, on one hand reducing the reserve need to cope with their variations, and on the other increasing the dispatchability of their production, with positive benefit on the exploitation of the renewable source and on the system adequacy. The PV and wind plants are supposed to be installed in the different regions in a way which reflects the distribution foreseen in the available generation expansion plans: this allows to take into account the preference for areas with higher availability of resource and with an easier feasibility of the plants also in terms of permissions or accessibility. This approach is maintained until critical network problems appear, which require to increase the installations in areas with lower producibility but less constraints.
The economic benefits for the system are assessed both at the end of Step 2b and Step 2c, and compared with the one obtained with the dispatchable generation (Step 2a).
When the benefits[4] resulting from the introduction of VRES are higher than the ones due to dispatchable generation, the results of the of Step 2b and Step 2c simulations are used to define the best combination of the technologies, weighting the investments in PV or wind by the respective benefits provided to the system with respect to Step 1. Thanks to this approach, the resulting optimal mix considers an investment in both PV and wind, and not only in the most effective generation technology, to diversify the resources, reducing uncertainty and risks, but keeping an economic merit order.

As can be seen in Figure 8, the Step 2 is part of an iterative process which considers progressive increase of generation until it is economically viable or a proper adequacy level is reached.

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

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

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

The benefits for a total investment in each of the two technologies separately can be measured as a reduction of system operational costs ($Benefits_{PV}$ and $Benefits_{wind}$) and it is calculated based on the results of the simulations carried out in Step 2.

The final simulation of each iteration is performed in the Step 3 considering the combined investment in PV and wind calculated in a proportional way with respect to the benefits brought to the system, i.e. if wind has twice benefits than PV, the investment in VRES in the Step 3 scenario will be 2/3 in wind generation 1/3 in PV generation. In this way it is kept the same investments that would be required also to install and operate the new dispatchable generators and there is a diversification of the VRES technologies keeping an economic merit order between them.

As explained above, the new PV and Wind plants are installed in the area with highest potential.

3.2.4 Iterations

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

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

As mentioned, the amount of generation introduced in the systems in each iteration as well as the new VRES to be considered is calibrated considering the specific characteristics of the power system allowing to obtain the optimal solution in a limited number of iterations.

When the process ends the following information about the optimal economic VRES penetration can be obtained and compared with the outcomes of the reference case:

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

It is worth recalling here that the operational costs of thermal generation are mainly based on fuel costs, and no externalities are considered. This represent a conservative approach in this analysis as the cost of thermal generation remains lower than in case carbon pricing mechanisms are included, and consequently also the benefits introduced by VRES. If externalities were taken into account, the thermal production would become more expensive, and the advantages achieved by its replacement with VRES generation would be higher, meaning that a higher penetration of VRES in the system would result optimal.

3.2.5 LCOE of Renewable resources

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

- Capital costs
- Operations and Maintenance cost

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

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

3.2.6 Role of Transmission

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

3.2.6.1 Inter-Area transmission lines in isolated country

The first step consists in considering the inter-area reinforcement, still with isolated countries.
This has to be performed only in case critical congestions happen on inter-area sections or close to them, which cause high redispatching costs or RES curtailments. In the adopted models, only Colombia is divided in two areas, the North and the Centre-South. Currently this section is critical, and it might become even more as in the Caribbean region there are most VRES (in particular wind) and this might increase the need for energy exchange between areas. On the other hand, it is important to underline that a huge investment in new transmission lines is supported by UPME [2] and present in the network model, so the limitations due to critical operating conditions might disappear. In case there are no congestions and in case the country limit for VRES installation has been reached, no new line is needed.

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

3.2.6.2 International Interconnection lines

After internal reinforcements have been identified, the focus is moved on international interconnection lines. A GRARE simulation will be run on the interconnected countries considering the planned international interconnection lines.

The main outcomes of the analysis of the cross-border transmission lines are the following:

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

3.3 Results of Base Case

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

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

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

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

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

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

The evaluation is carried out on an annual basis, calculating the annuity of the investments as defined in 3.2.1 (footnote 3). This method allows the comparison of the benefits obtained from different scenario and the selection of the most convenient one.

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

General information:

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

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

Tables with information relevant to the Expected Energy Not Supplied

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

Tables with information relevant to generation production and costs:

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

3.3.1 Colombia

In this Chapter the main results regarding the Colombian power system are presented. First of all the results of Reference scenario are illustrated; then scenario with optimal economic amount of additional VRES is analysed and compared with the reference one.

3.3.1.1 Reference scenario

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

- A ***good adequacy*** of the analysed system, with no expected problems of EENS.
- Overall ***generation costs*** are about ***950 M$***. No strong redispatching activity is required, as the transmission system does not limit the economic generation and the supply of the load.
- Expected ***generation by PV*** power plants around 1,840 GWh (a bit more than 1,700 EOH) without generation curtailment.
- Expected ***generation by wind*** power plants close to 5,870 GWh (more than 4,500 EOH) without generation curtailment.
- Nearly no cases where the power flows through the ***section*** between the Northern and the Central-Southern areas reaches the NTC limit.

The operation of the Colombian system in the Reference scenario, isolated from the neighbouring countries, has been simulated.

The main results are presented in this paragraph. The system presents a very high adequacy and the transmission network is already capable to transmit the power from the generation power plants to the loads without any critical issue. In this context, it is important to remember that the Reference scenario is built based on the system defined by UPME at 2030, and this analysis confirm that it is already well dimensioned.

Table 5 shows that there is no EENS thanks to the proper availability of generation power plants and transmission lines.

Table 5 - Expected Energy Not Supplied - Colombian Reference scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	0	0	0

Table 6 shows the total energy produced in the country and the related costs, which are only due to thermal power plants. In this reference scenario total costs are around 950 M$/year, with nearly no need of redispatching activities.

Table 6 - Total production and fuel costs - Colombian Reference scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	98,476	949	0	-1	1	0

As regard PV generation (Table 7), total production is around 1,840 GWh/year and about 60% is located in the Northern regions, close to Caribbean sea, where the availability of resource is better (about 2,000 EOH), while the rest is located in other areas with lower potential and EOH below 1,500 hours. No PV energy curtailment is present in this scenario.

Table 7 - Total production of PV plants - Colombian Reference scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	1,839	0	0	0	1,711

As regard wind generation (Table 8), total production is higher than 5,850 GWh/year and concentrated only in the northern region and in particular in La Guajira. Considering that the total installed capacity is 1.3 GW, the equivalent operating hours are a bit higher than 4,500 h/year. The wind energy curtailed is null.

Table 8 - Total production of Wind plants - Colombian Reference scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	5,866	0	0	0	4,519

In the study, a limit of the transmittable power between the north and the central-south region has been considered, but the results of the simulations show that this limit is never reached thanks to the strong network reinforcements planned up to 2030 (NTC between the areas is higher than 2,700 MW). This means that there are no criticalities and that the generation fleet can be optimized with no constraints due to transmission system, and for this reason in figures in the rest of the report the separation between the two areas in Colombia will not be highlighted. There is no need to analyse possible further reinforcements, as they would bring no benefits in terms of better exploitation of the generation fleet.

The following Figure 9 provides a visual summary of the operation of the Colombian system in the reference scenario, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

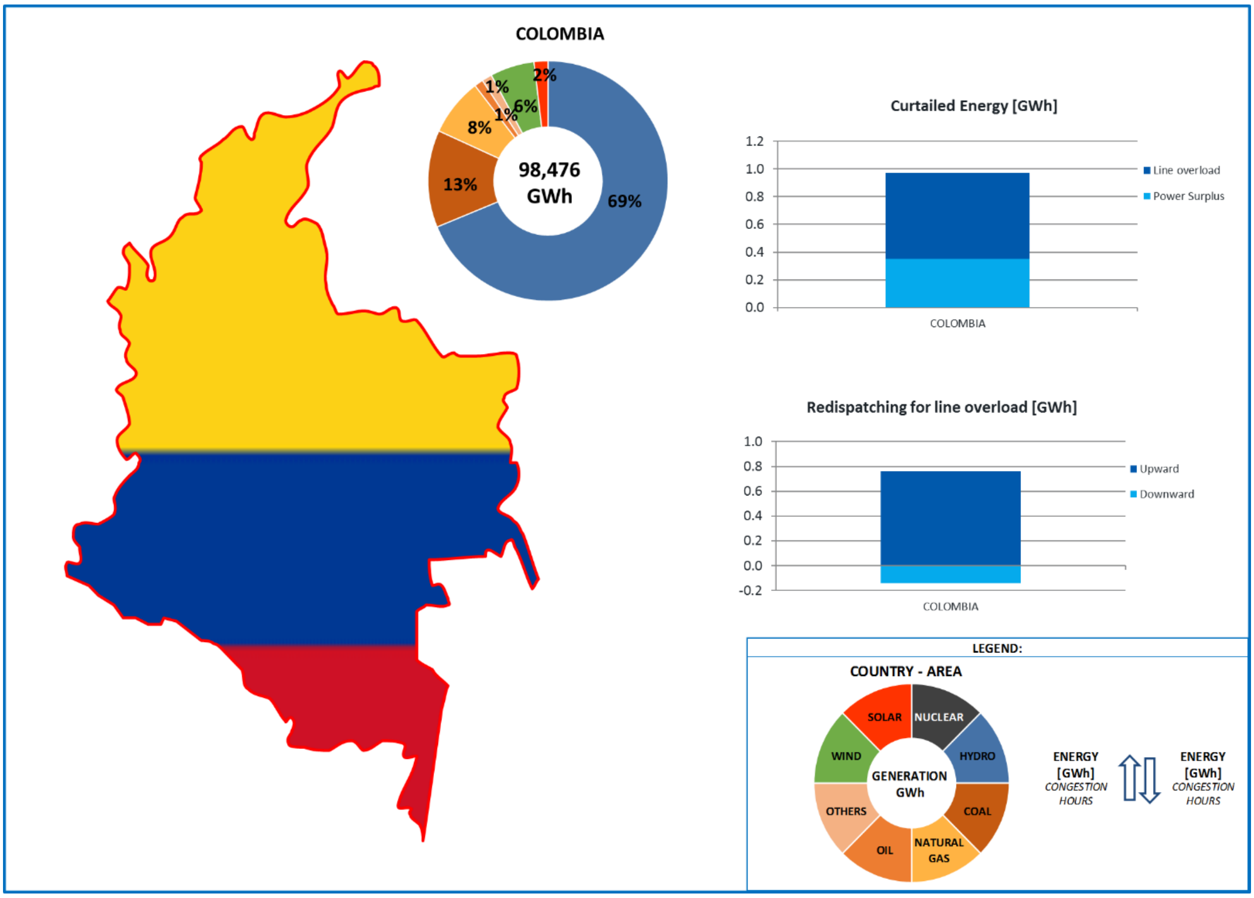

Figure 9 - Total production and energy exchanges – Colombian Reference scenario

3.3.1.2 Scenario with optimal economic amount of additional VRES

At the end of the computational process depicted in Figure 8, the ***optimal amount of VRES*** is about ***2,400 MW of PV*** and ***2,700 MW of wind*** power plants (which corresponds to an increase of more than 1,300 MW PV and 1,400 MW wind with respect to the installed power already considered in the Reference scenario), and a total of installed ***storage*** of about ***215 MW***.
The investment in such technologies provides net benefits for the system of USD 95 million/year (thanks to savings in the generation costs and in EENS higher than investment costs)[5].
The ***expected LCOE*** for PV is 45.6 USD/MWh, and for wind 34.5 USD/MWh.
The amount of additional power turns out to be quite balanced between the VRES technologies because in general wind power plants have a lower LCOE and higher production but PV is cheaper in terms of annuity per installed MW, so more power plants can be installed with a lower amount of money.
In this new scenario:

- The ***EENS*** remains null.
- Overall ***generation costs*** decrease to USD 554 million thanks to the VRES production which replaces thermal generation, with a slight increase of the need for redispatching.
- Expected ***generation by PV*** plants higher than 4,000 GWh, but the EOH decreases to 2,400h due to curtailments which increase up to 140 GWh (about 3.4% of total PV production).
- Expected ***generation by wind*** power plants higher than 11,700 GWh (more than 4160 EOH) and a curtailment of about 470 GWh (3.9% of the total wind generation).

The analysis performed following the procedure described in Figure 8 provides an optimal amount of additional VRES installations in Colombia equal to more than 1,300 MW in PV and 1,400 MW in wind power plants. Table 9 provides the detail of the added PV and wind installed power in each area with respect to the Reference scenario and the final resulting values, which in total exceed 5 GW of VRES.

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

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

The results of the simulation of one year of operation of the system with this new amount of VRES installed power are shown in detail below.
The Colombian power system with the increased VRES production maintain the null EENS as in the Reference scenario

[5] It is worth recalling here that in the present study benefits are calculated with a conservative approach comparing investment costs only with fuel savings, while externalities are not included. As the Colombian system is characterized by the presence of cheap coal power plants, benefits might increase if costs for emissions and pollutants were considered, as it happens for instance with the introduction of a carbon tax.

Table 10 sums up the total annual production and the thermal costs. With respect to the costs of the Reference scenario reported in Table 6, the total thermal costs decrease considerably (- 400 USD million, equal to a reduction of more than 40%) mainly resulting by lower fuel consumption because part of the load is supplied by the new VRES plants and not by thermal plants. An increase of redispatching needs is observable which however does not have significant economic impact.

It is interesting to note that some curtailment of production appears due to the OverGeneration (OG) condition (i.e. conditions in which the VRES production plus the one coming from hydropower plants, "must-run" units and the minimum technical power of the thermal generators in service is higher than the load). The need for curtailments is not surprising, as the total amount of VRES installed in this scenario is much higher than the technical limits calculated in Chapter 2.3.1 and summarized in Figure 5, which wanted to describe a condition with limited OG risk.

Table 10 - Total production and fuel costs - Colombian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	98,589	553	626	-43	43	1

In Table 11 the results in term of PV generation for the optimal amount of additional VRES are presented; Table 12 shows the difference of total PV production respect to Reference scenario.

There is an increase of more than 2,150 MWh in the annual production, and the final production equal to 4 TWh is more than twice the Reference scenario.

The results show a solar production curtailment equal to 142 GWh (3.4 % of the produced energy) due to overgeneration conditions.

The increase of the curtailments has the effect to reduce in the equivalent operating hours with respect to the Reference scenario by about 40 hours.

Table 11 - Total production of PV plants - Colombian optimal scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	4,002	142	0	0	1,668

Table 12 - Difference of total production of PV plants between Colombian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	2,163	142	0	0	-41

In Table 13 wind production results of the optimal scenario are presented; Table 14 shows the difference of total wind production respect to Reference scenario.

The annual wind production reaches 11.7 TWh, also in this case twice the Reference scenario. The results show a wind production curtailment equal to 470 GWh (3.9% of their total produced energy, 8% of the new added plants).
The increase of the curtailments has the effect to reduce in the equivalent operating hours with respect to the Reference scenario, EOH are about 4,340 h/year, 180 h less with respect to the Reference scenario.

Table 13 - Total production of Wind plants - Colombian optimal scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	11,723	471	-10	0	4,338

Table 14 - Difference of total production of Wind plants between Colombian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	5,857	471	-10	0	-180

Figure 10 shows the generation mix, the curtailed VRES production and thermal redispatching needed to solve network congestions in the scenario with the optimal amount of VRES installations. The comparison with Figure 9, which provides the same information for the Reference scenario, highlights the increase of the PV and wind production in the system and the relevant reduction of thermal generation, and an increase of the operations required to solve network constraints.

The curtailments due to overgeneration conditions are necessary in the periods with low load and high generation by hydro and VRES, taking into account also the minimum power of thermal power plants in service. During the real operation of the system it is possible that excess of generation is reduced thanks to a more optimized short-term planning of the plants, in particular the hydro ones. In fact, in a system which covers about 2/3 of its demand with energy generated by hydropower plants, it is possible to use the flexibility that this resource provides in case big or even small reservoirs are present, in order to ensure the coverage of the demand limiting the waste of energy produced by VRES.
The present analysis however highlights that in case the VRES penetration increases, for the optimal exploitation of the renewable resources (including hydro) it is necessary that the short-term production planning by different technologies is properly coordinated by a system operator, in order to ensure that costs and risk of curtailments are minimized. Also during real-time operation, fast regulating power plants such as some hydro ones, must be available to compensate possible significant variations of VRES production with respect to forecasted plans and actual generation.

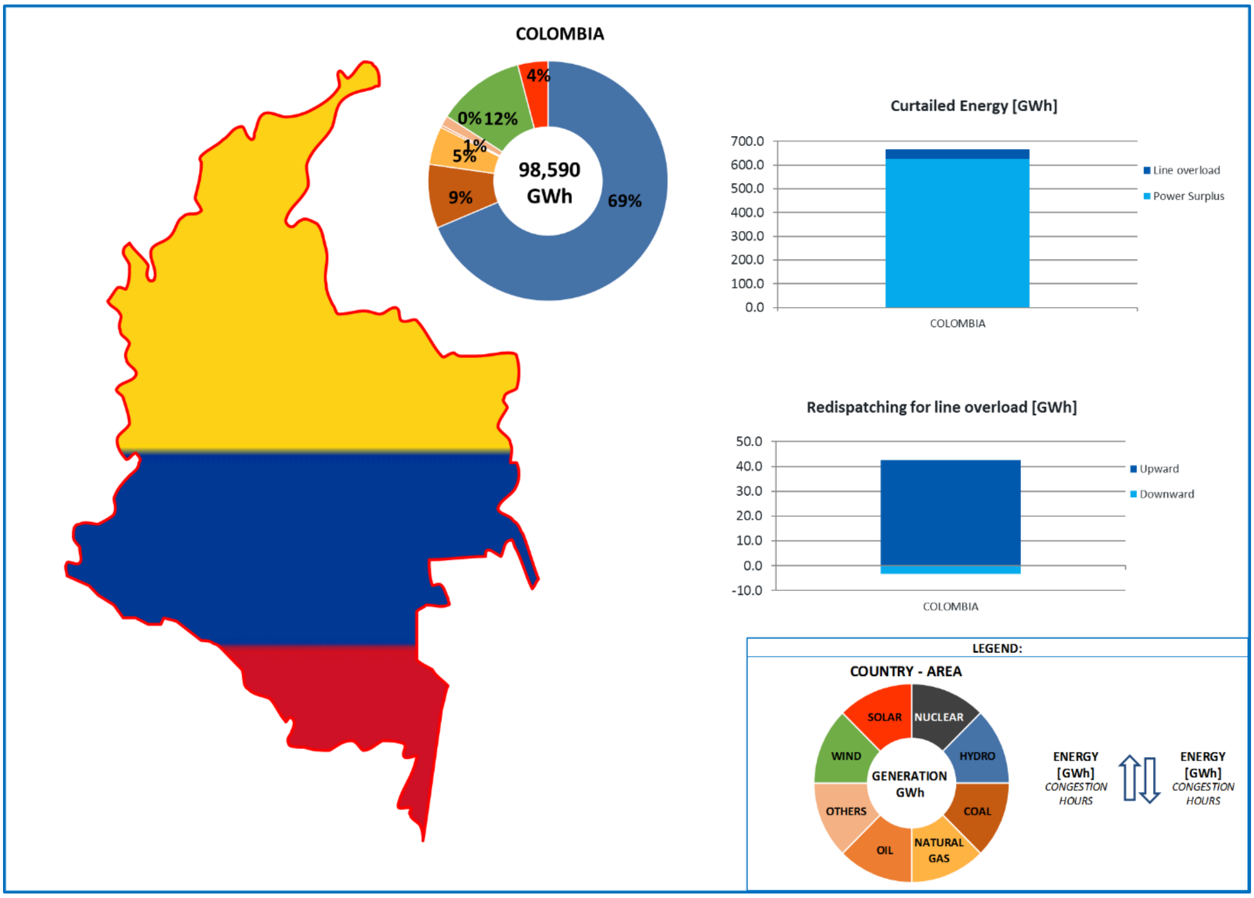

Figure 10 - Total production and energy exchanges – Colombian scenario with optimal VRES amount

The analysis of the results obtained by the simulation of the operation of the system with the additional 2,725 MW of VRES power plants is completed with a table that summarizes the total benefit evaluated with respect to the Reference scenario, so expressed as a difference between optimal scenario and the reference one.

The Table 15 reports the main differences in terms of:

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

These values are expressed in GWh/year.

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

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

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

Table 15 - Total benefit – Colombian optimal scenario with respect to Reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	2,725	-288
STORAGE	215	-12
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-7,860	395
RES CURTAILMENT	624	-
TOTAL EENS	0.0	0
TOTAL BENEFIT	**-**	**95**

BENEFIT/MW VRES [kUSD/year]	**35**

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

- LCOE for PV power plants: 45.6 USD/MWh
- LCOE for wind power plants: 34.5 USD/MWh

3.3.1.3 Final considerations on Colombian isolated system

The optimal solution for additional VRES installations defined in the previous paraghaph, which maintains the high expected adequacy of the Colombian system, includes 2,400 MW of PV, 2,700 MW of wind power plants and storage of about 215 MW. These values might be even higher in case additional costs for coal are considered, derived from carbon taxes which are applied. As the price of energy produced by coal plants would increase, benefits introduced by VRES would be also higher, and the installation of some additional VRES plants might become convenient as possible higher curtailments might be still advantageous as the VRES replace more expensive generation.
Dispatchability of the energy sources is essential to reach a high level of system adequacy and can be obtained and improved thanks to the integration of different technologies and the usage of storage systems. Investment in storage systems might be not economically profitable if they are considered as stand-alone systems, but it is necessary to ensure proper conditions for a considerable growth of the VRES penetration.
Concerning the transmission system, the new lines currently planned by UPME in the last “Plan de expansión de referencia Generación – Transmisión” [2] and assumed in the analysed scenario allow a

good development of VRES plants in the areas with highest potential. No criticalities have been highlighted during the analysis, and no EENS nor VRES generation curtailments due to transmission constraints are present.
The presence of big hydropower plants in many cases also with big reservoirs ensures a high level of flexibility to the system which is then able to accept higher amount of VRES plants also concentrated in limited areas in the North where the best resources are present. The HVDC planned by UPME to transfer the power from La Guajira region to the centre of the system is necessary and allows a good increase of the wind penetration.

3.3.2 Ecuador

Expected operation of Ecuadorian system has been simulated without considering interconnections to the neighbouring countries.

The simulations have been carried out considering the detailed model of the generation fleet and the transmission network, looking for possible overloads on the 500 kV and 220 kV lines.

3.3.2.1 Reference Scenario

The simulation of the ***Reference scenario*** for Ecuador shows the following:

- The analysed system is ***adequate*** with EENS around 0 MWh.
- Overall ***generation costs*** are about **USD *1,400 million***, which include the small costs due to redispatching needed to solve curtailments equal to 3 M$.
- Expected ***generation by PV*** power plants around 121 GWh (about 1,420 EOH) with 7 GWh of generation curtailment.
- Expected ***generation by wind*** power plants close to 343 GWh (nearly 3,900 EOH) with the presence of overproduction for 19 GWh.

In the Reference scenario, the Ecuadorian system shows a generation adequacy: the total EENS is nearly null, with only a very limited load curtailment due to a line overload (5 MWh reported in Table 16).

Table 16 - Expected Energy Not Supplied – Ecuadorian Reference scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
ECUADOR	0	5	0	5

In this context, the generation costs are high (about 1,400 MUSD/year) due to the usage of also expensive plants fuelled with oil and with low efficiency which are often required to cover the peak demand. On the other hand, it is possible to observe that there are already few conditions with overgeneration, due to the presence of a big amount of hydropower plants in many cases with limited reservoirs. These conditions cause some limited curtailments of the generation, which however in the real operation of the system might be reduced with a more optimized short-term planning of the power plants. It is anyway important to highlight that the curtailments due to overproduction might become the limiting factor for the installation of big amount of VRES plants.

Table 17 - Total production and fuel costs - Ecuadorian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
ECUADOR	48,882	1395	62	-21	21	3

Concerning VRES production, Table 18 and Table 19 show the main figures related to PV and wind plants respectively. Also for these technologies curtailments due to overgeneration conditions are already present. The equivalent hours are considerably lower with respect to the other countries due to the lower availability of resource.

Table 18 - Total production of PV plants - Ecuadorian Reference scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
ECUADOR	121	7	0	0	1,503

Table 19 - Total production of Wind plants - Ecuadorian Reference scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
ECUADOR	343	19	0	0	2,646

The following Figure 11 provides a visual summary of the operation of the Ecuadorian system in the reference scenario, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions. The demand is mainly supplied by hydropower plants, and the rest by thermal plants using natural gas or oil, which are very expensive due to low efficiency and high fuel cost.

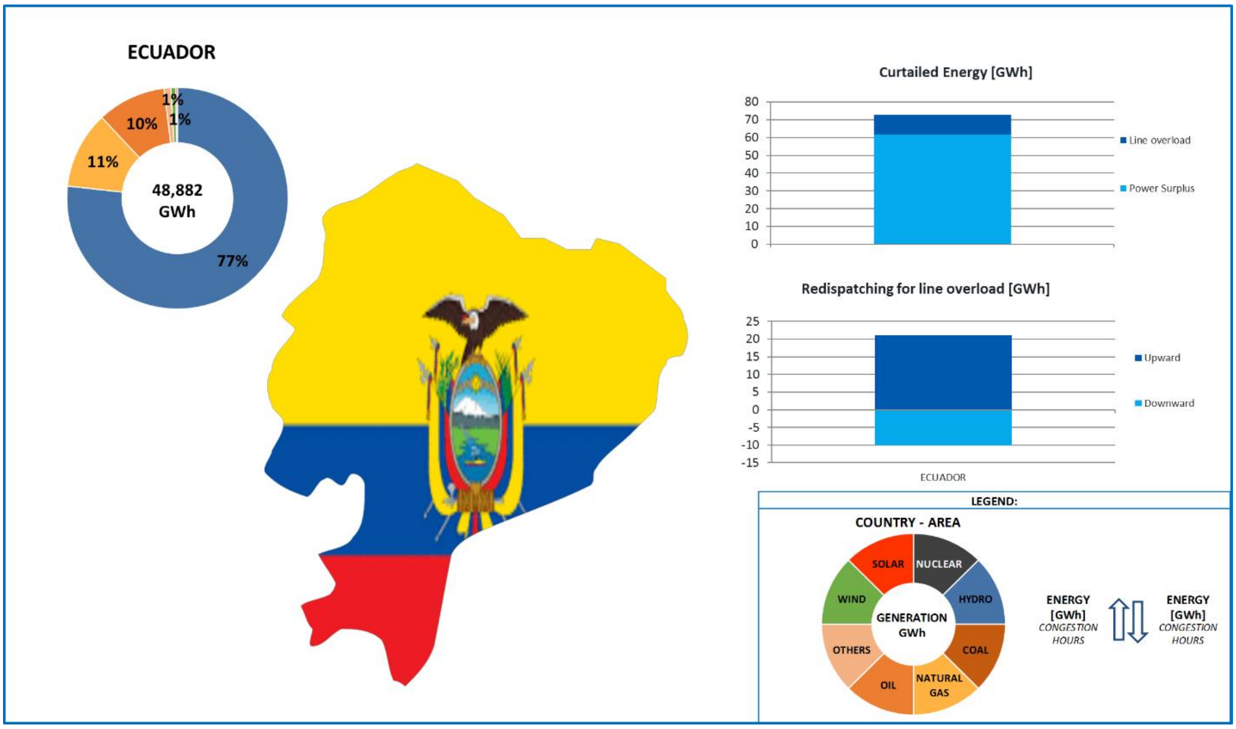

Figure 11 - Total production and energy exchanges – Ecuadorian Reference scenario

3.3.2.2 Scenario with optimal economic amount of additional VRES

At the end of the computational process depicted in Figure 8, the ***optimal amount of additional VRES*** with respect to the installed power already considered in the Reference scenario is about ***1,670 MW of PV*** and ***1,930 MW of wind*** power plants, with a total of installed ***storage*** of about ***280 MW***. The total amount reaches nearly 3.8 GW, divided 45% PV and 55% wind.
There is **no need for new thermal generation**, and the load increase from 2025 (target year for the planning by CELEC [3]) to 2030 can be covered with VRES plants only.
With these additional VRES power plants the system maintains a ***very good adequacy*** with a value of EENS around 0 MWh.
The investment in PV, wind and relevant storage provides benefits for the system around 320 M$/year thanks to savings in the generation costs.
The amount of additional power turns out to be quite balanced between the VRES technologies because in general wind power plants have higher production but PV is cheaper in terms of annuity per installed MW, so more power plants can be installed with a lower amount of money.
In this new scenario:

- The total ***EENS*** reaches 0 MWh.
- Overall ***generation costs*** decrease to USD 580 million thanks to the VRES production which replaces thermal expensive generation. The part of costs due to the presence of network congestions remains around 50 M$.
- Expected ***generation by PV*** plants is almost 2.25 TWh (4.6% of total load), with curtailments increasing up to 500 GWh (about 20% of total PV production).
- Expected ***generation by wind*** power plants higher than 3.7 TWh (more than 1,800 EOH) and a curtailment of about 880 GWh (about 20% of the total possible wind generation).

At the end of the calculation of the optimal economic amount of additional VRES plants with respect to the Reference scenario, the resulting values are the ones listed in Table 20.

Table 20 - Additional and total VRES installed power in the Scenario with optimal economic amount [MW]

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

PV installed power becomes more than 1,700 MW and wind more than 2,000 MW from reference to optimal scenario.
There would be no need to introduce additional dispatchable generation to guarantee the system adequacy which can be obtained thanks to the new energy produced by the VRES plants and a different utilization of the hydro resource, which can be more concentrated in the periods when VRES plants show a lower production.

Nevertheless, due to the high dependency of the Ecuadorean system on the hydro resource, it has been checked that in case of a dry condition with a significantly lower production by hydro plants[6], the generation fleet would be not able to ensure an adequate coverage of the demand, and the generation costs also would increase dramatically as all the generators, even the most expensive ones, would be required to operate to supply the load. For this reason, in the optimal scenario it has been included in the system also a dispatchable 300 MW plant. This plant might represent a thermal plant, for instance an efficient CCGT configuration, or an equivalent hydropower plant able to provide the additional required energy also in dry conditions to ensure the system adequacy.

EENS that was already low in the Reference scenario remains null, and the small issue related to the line overload is resolved, showing that the additional VRES generators can also increase the availability of thermal plants which can solve overloading.

Table 21 - Expected Energy Not Supplied - Ecuadorian optimal scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
ECUADOR	0	0	0	0

The generation costs are strongly reduced by the presence of new VRES plants. As usual in power systems with increasing penetration of VRES, the need for redispatching increases but the relevant costs remain a small part of the total. The amount of curtailed production due to minimum production constraint is near 1.5 TWh, about 3% of the total production. This amount might be reduced in the real operation of the system thanks to a more detailed short-term planning of the thermal fleet and a coordination in the operation of the VRES and the hydroelectric plants.

Table 22 - Total production and fuel costs - Ecuadorian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
ECUADOR	49,039	569	1,474	-107	107	9

Table 23 shows the new production of the PV power plants, the total amount becomes significantly higher than the Reference scenario, more than 2.2 TWh. The curtailments due to overproduction conditions are almost 550 GWh, that means about 20% of the total production. Table 24 highlights the differences with respect to the Reference scenario, where it is possible to see the impact of the curtailments due to overgeneration on the additional production. The value of curtailments is very high, nonetheless the usage of VRES plants still is advantageous compared to the high cost of liquid-fuelled thermal generators.

[6] Based on the available information, the dry year has been simulated with an availability of the hydro resource 20% lower than in the Reference scenario.
A detailed sensitivity dedicated to the dry conditions will be presented in Chapter 3.4.1.

Table 23 - Total production of PV plants - Ecuadorian optimal scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
ECUADOR	2,233	543	0	0	1,276

Table 24 - Difference of total production of PV plants between Ecuadorian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
ECUADOR	2,112	536	0	0	-227

As far as wind power plants are concerned, Table 25 and Table 26 report the main figures.
They produce more than 3.7 TWh, with an increase of almost 3.4 TWh with respect to the Reference scenario. The curtailments also reach the significant value of 880 GWh, corresponding to a about 20% of the total produced energy. The same considerations done for high curtailments of PV plants apply for wind.

Table 25 - Total production of Wind plants - Ecuadorian optimal scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
ECUADOR	3,718	879	0	0	1,814

Table 26 - Difference of total production of Wind plants between Ecuadorian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
ECUADOR	3,375	860	0	0	-1,032

The expected LCOE for wind and PV are then quite high, around 95 USD/MWh for wind and 85 USD/MWh for PV.

Table 27 shows the main figures in terms of costs and benefits for the system which summarize the difference between the Reference scenario and the one with the optimal amount of VRES. It is possible to see that the advantages for the system are significant, mainly thanks to the replacement of expensive thermal generation.

Table 27 - Total benefit – Ecuadorian optimal scenario with respect to Reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	3,600	-481
NEW STORAGE	280	-18
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-5,200	820
RES CURTAILMENT	1,395	-
TOTAL EENS	0.0	0
TOTAL BENEFIT	**-**	**320**

BENEFIT/MW VRES [kUSD/year]	89

The following Figure 12 provides a visual summary of the operation of the Ecuadorian system in the optimal scenario, highlighting the generation, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions. With respect to the Reference scenario (Figure 11) the wind production increases from more or less zero to 8%, PV to 4%. PV and Wind mainly replace energy generated by liquid fuel, which decrease from 10% to 4% and Natural Gas plants, from 11% to 7%.

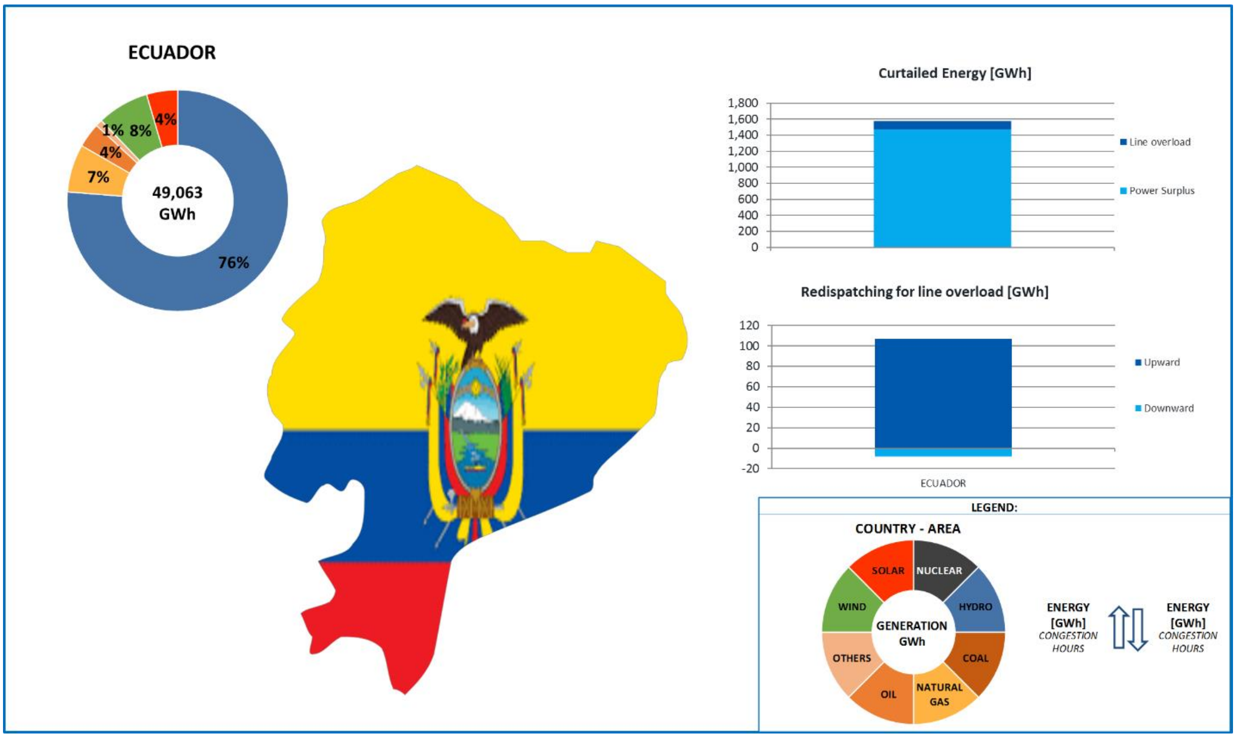

Figure 12 - Total production and energy exchanges – Ecuadorian optimal scenario

3.3.2.3 Final considerations on Ecuadorian isolated system

The optimal solution for additional VRES installations defined in 3.3.2.2, able to ensure a proper adequacy of the Ecuadorian power system, includes 1,750 MW of PV, 2,050 MW of wind power plants and storage of about 280 MW. To ensure that the good adequacy is maintained also in dry conditions, an additional dispatchable 300 MW power plant has been included, which in the development plans might be represented by a CCGT or by some equivalent hydropower plants able to provide the required energy in the dry conditions.

No need for new additional thermal generation emerges for the coverage of the load increase from 2025 (target year for the planning by CELEC [3]) to 2030, a part from the need due to the dry conditions to face the high dependency on the hydro resource.

The simulations showed an already high level of coverage of the demand by means of hydroelectric power plants in many cases with limited regulation capacity. The reduced amount of remaining load to be covered with other resources than hydro becomes the limiting factor for further VRES penetration, as the introduction of additional generation would cause an increase in the risk of curtailments due to the overproduction situations, making the construction of new plants not convenient from the economic point of view, also because of the limited availability of wind and PV resources compared to other South American countries.

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

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 impact significantly the advantages and benefits that VRES can introduce in the system, as they modify the amount of load to be covered with generation different than hydro and the correspondent costs of the production. 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 also small changes in the assumptions.

3.3.3 Peru

In this Chapter the main results related to the isolated Peruvian power system are presented. First of all, the results of Reference scenario are illustrated. Then scenario with optimal economic amount of additional VRES is analysed and compared with the reference one.

3.3.3.1 Reference scenario

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

- A ***low adequacy***, with EENS due to lack of power or line overload higher than 12.6 GWh, about 1.5×10^{-4} of the total load.
- Expected ***generation by PV*** power plants around 660 GWh (2,300 EOH) without curtailments due to system constraints.
- Expected ***generation by wind*** power plants about 1,930 GWh (about 4,700 EOH) without curtailment.

The operation of the Peruvian system in the Reference scenario, isolated from the neighbouring countries has been simulated. The main results are presented in this paragraph.
From Table 28, it can be seen that the Peruvian power system has a low generation adequacy, and that the EENS reaches more than 12.6 GWh, mainly for lack of power, corresponding to about 1.5×10^{-4} of the total load. This is due to the fact that the increase of the load up to the 2030 level was not followed by the same increase of the generation capacity in the Reference scenario. All the available generation, even the expensive one fuelled with oil, is used in periods with high load, and the flexibility provided by the hydropower plants with storage is able to limit the situations with lack of generation.

Table 28 - Expected Energy Not Supplied – Peruvian Reference scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
PERU	10,351	2,303	0	12,654

EENS due to lack of power is generally distributed all over the country, while EENS due to line overload in this Reference scenario is concentrated mainly in specific nodes and areas. In particular, most of load curtailments are concentrated in the area close to Lima as the load has been increased to 2030 level while the transmission capacity has been kept at the committed one for 2024, used as basis for the Reference scenario, described in the Plan de Transmisión 2019 – 2028 by COES [4]. Some other limited curtailments are present in the area of Trujillo station and in the South of the country. Moreover, some nodes connected with weak schemes (not meshed) may suffer load curtailments if the load in some conditions is higher than the capability of the link, in particular in case of some unavailability. The solution of these cases and of the issues in the area of Lima is not in the scope of the present study, which is focused on the optimal VRES penetration and how improvements of the transmission system might allow higher exploitation of wind and sun. Bottlenecks of transmission system which limit the VRES production are analysed, while local constraints causing load curtailments will remain present in all the analysed scenario if the VRES have no impact on them.

Costs for generation are evaluated in about USD 1,715 million/year, and there is a very limited need of redispatching to solve overloads on the transmission system. It is worth recalling here that for Natural Gas it is assumed a subsidized cost equal to 4.35 USD/MBTU [1], which makes the thermal production from this source cheaper.

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

As regard PV generation (Table 29), the total production is around 660 GWh/year, and no PV production curtailments are required. The equivalent operating hour is around 2,300 h/year.

Table 29 - Total production of PV plants – Peruvian Reference scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
PERU	657	0	0	0	2,301

As regard wind generation (Table 30), the total production is a bit higher than 1,930 GWh/year with an equivalent operating hour approximately of 4,700 h/year. The flexible management of hydropower plants makes the curtailment of production not necessary.

Table 30 - Total production of Wind plants – Peruvian Reference scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
PERU	1,931	0	0	0	4,694

The following Figure 13 provides a visual summary of the operation of the Peruvian system in the identified scenario, highlighting the generation mix, the curtailed production and the amount of thermal energy to be redispatched to solve network congestions.

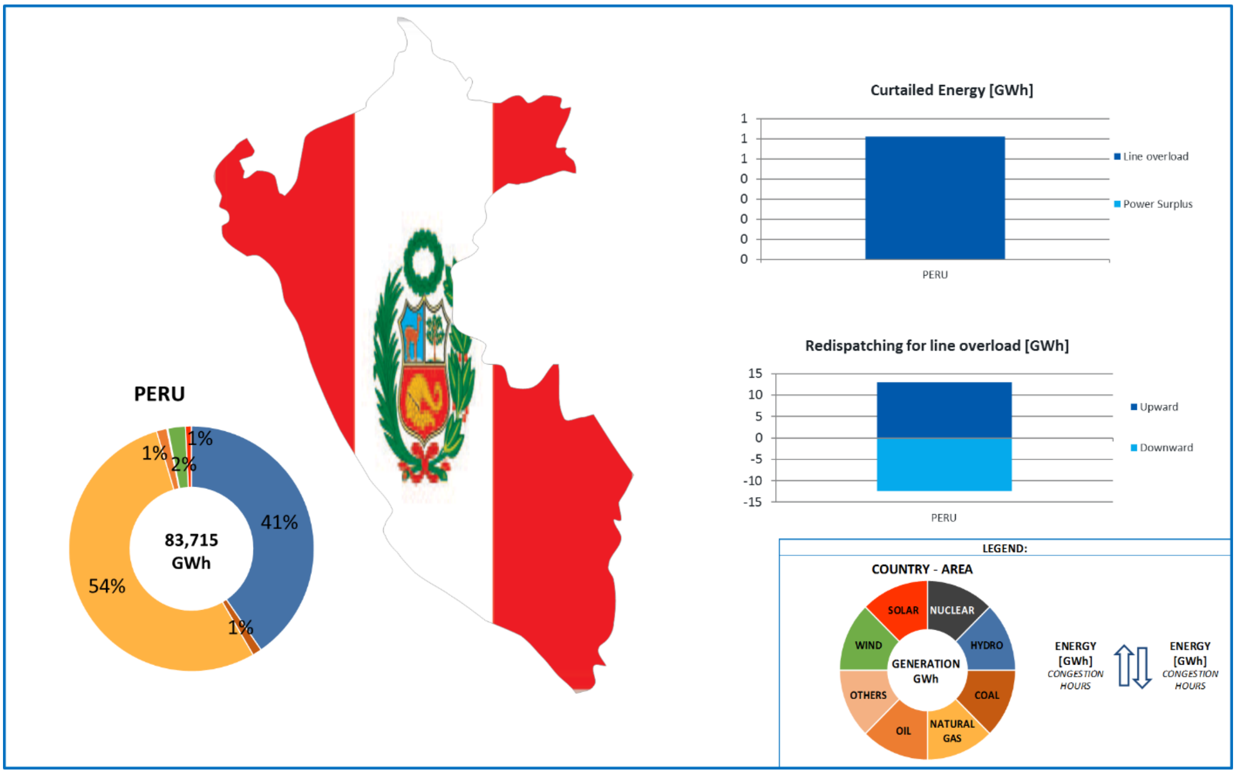

Figure 13 - Total production and energy exchanges – Peruvian Reference scenario

3.3.3.2 Scenario with optimal economic amount of additional VRES

The results of computational process depicted in Figure 8 shows that the **optimal amount of VRES** sums up to **2,750 MW PV** and **1,700 MW wind**, more than six times the amount in the Reference Scenario, plus 320 MW storage installed close to the new plants.

With this additional installed power, the Peruvian system reached the following:

- The ***EENS*** reduces to slightly more than 2 GWh, mainly due to network constraints already present in the Reference scenario, not related to the presence of VRES plants but to the high load increase. EENS due to Lack of Power goes nearly to 0 MWh.
- Expected ***generation by PV*** increases by more than 5.6 TWh, reaching a total amount equal to 6.3 TWh, maintaining 2,300 equivalent hours as no expected curtailments are present.
- The ***generation by wind*** increases by more than 5 TWh, totalling 7 TWh with the already existing plants. Curtailments remains negligible.
- The ***generation costs*** decrease by USD 590 million thanks to the VRES production which replaces expensive thermal generation mainly by liquid fuel and gas.
- 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.
- The total benefit for the system taking into account the costs for the installation of the new VRES plants is estimated in about USD 200 million.

At the end of the calculation of the optimal economic amount of additional VRES plants with respect to the Reference scenario, the resulting values are the ones listed in Table 31.

Table 31 - Additional and total VRES installed power in the Peruvian Scenario with optimal economic amount [MW]

AREA	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

There is no need to introduce additional thermal generation to ensure the system adequacy which can be obtained thanks to the new energy produced by the VRES plants and a different utilization of the hydro resource, which can be more concentrated in the periods when VRES plants show a lower production.

PV installed power becomes more than six times the one in the Reference scenario, reaching 2,750 MW, concentrated in the South area where the best resource is available.

Wind installed power increased by nearly 1,300 GW, distributed mainly along the coast and in the North. 320 MW of electrical storage area also included in the system to limit variations of VRES plants and shift part of the produced energy to different part of the day (for instance evening).

With this amount of additional VRES power the EENS reduces considerably to about 2 GWh, corresponding to 2.5×10^{-5} p.u. of the load. The greatest part is related to line overloads which however remain aligned with the value already present in the Reference scenario, meaning that VRES do not introduce additional problems, and that the EENS is mainly due to small problems more related to the load increase. In particular, the EENS in the area of Lima remains similar, while the additional production from VRES plants in the North contributes to solve issues in Trujillo area. In the South, energy flows are modified by the presence of the new plants, increasing the conditions with transfer from South to the central regions thanks to the PV and wind plants. Some EENS due to line overload remains caused by local congestions, in particular on the 220 kV lines in the area of Moquegua station[7].

Table 32 - Expected Energy Not Supplied - Peruvian optimal scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
PERU	14	2,021	0	2,035

Thanks to the additional production of VRES power plants, the generation costs of the thermal are strongly reduced (-USD 530 million). As usual in power systems with growing penetration of VRES, the need for redispatching increases but the relevant costs remain a small part of the total. No problems due to minimum production constraint are present.

[7] 220 kV improvements committed in PT2019 have been already considered.

Table 33 - Total production and fuel costs - Peruvian optimal scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
PERU	83,614	1,163	0	-561	561	20

Table 34 shows the new production of the PV power plants, with the total amount that becomes nearly ten times the one in the Reference scenario, up to 6.2 TWh (7.6% of the load). Some curtailments are present due to the overloading of transmission system, in particular due to the 220 kV lines form Moquegua to the central part of the country, but the curtailed energy (100 GWh) remains well below 2% of the PV production. Due to the presence of subsidies to Natural Gas which keep the cost of the primary resource lower than international references and consequently lower the cost of thermal generation, there is no strong convenience to improve the transmission network to increase exploitation of VRES as the advantages achievable reducing the curtailments would be not high enough to cover the investment in new infrastructure. If the subsidies were lower or null, bringing the cost of Natural gas closer or equal to the market price, the thermal generation would become more expensive and installation of VRES plants more advantageous. Transmission bottlenecks would have then a more significant impact that might be convenient to remove them with proper reinforcements.
Table 35 highlights the differences with respect to the Reference scenario. It is possible to note that due to the curtailment, there is a slight reduction of the average EOH.

Table 34 - Total production of PV plants - Peruvian optimal scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
PERU	6,332	0	-101	0	2,266

Table 35 - Difference of total production of PV plants between Peruvian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
PERU	5,675	0	-101	0	-35

As far as wind power plants are concerned, Table 36 and Table 37 report the main figures.
They produce 7 TWh (8.6% of the load), with an increase of more than 5 TWh with respect to the Reference scenario. There is no risk of curtailments and this means that there is also no need for network reinforcements to exploit this amount of wind plants.
The equivalent hours of the overall wind projects decrease, as the high amount of additional plants cannot be installed in the areas with the best resources, and areas with less potential have to be considered.

Table 36 - Total production of Wind plants - Peruvian optimal scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
PERU	6,998	0	0	0	4,116

Table 37 - Difference of total production of Wind plants between Peruvian optimal scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
PERU.	5,067	0	0	0	-578

Thanks to the excellent availability of resources and the assumed low installation costs, expected LCOE are around 30 USD/MWh for PV and 36 USD/MWh for wind.

Table 38 shows the main figures in terms of costs and benefits for the system which summarize the difference between the Reference scenario and the one with the optimal amount of VRES. It is possible to see that the advantages for the system are significant, mainly thanks to the replacement of the thermal generation by VRES: the investments needed to install new VRES plants and the relevant storage systems considered to reduce the variability of their production and improve their exploitation are significantly lower than the fuel cost saving obtained by the reduction of thermal generation.

Table 38 - Total benefit – Peruvian optimal scenario with respect to Reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	3,750	-335
NEW STORAGE	320	-18
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-10,730	532
RES CURTAILMENT	101	-
TOTAL EENS	-10.6	21
TOTAL BENEFIT	**-**	**200**

BENEFIT/MW VRES [kUSD/year]	**53**

If no subsidy were considered for Natural Gas, the benefits would become even higher, as the thermal generation replaced by VRES would be more expensive. This creates also the conditions for an increase of the optimal amount of VRES plants, as a higher advantage derives from the replacement of thermal generation and higher risk of curtailments would become economically acceptable.

The same considerations apply in case externalities were considered, which would correspond to an increase of the thermal generation costs depending on the relevant efficiency and polluting effects, similarly to what already applied in some countries, for instance in Colombia, with a specific carbon tax [5].
A more detailed assessment on the scenario without subsidies for NG is presented in chapter 3.3.3.3.

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

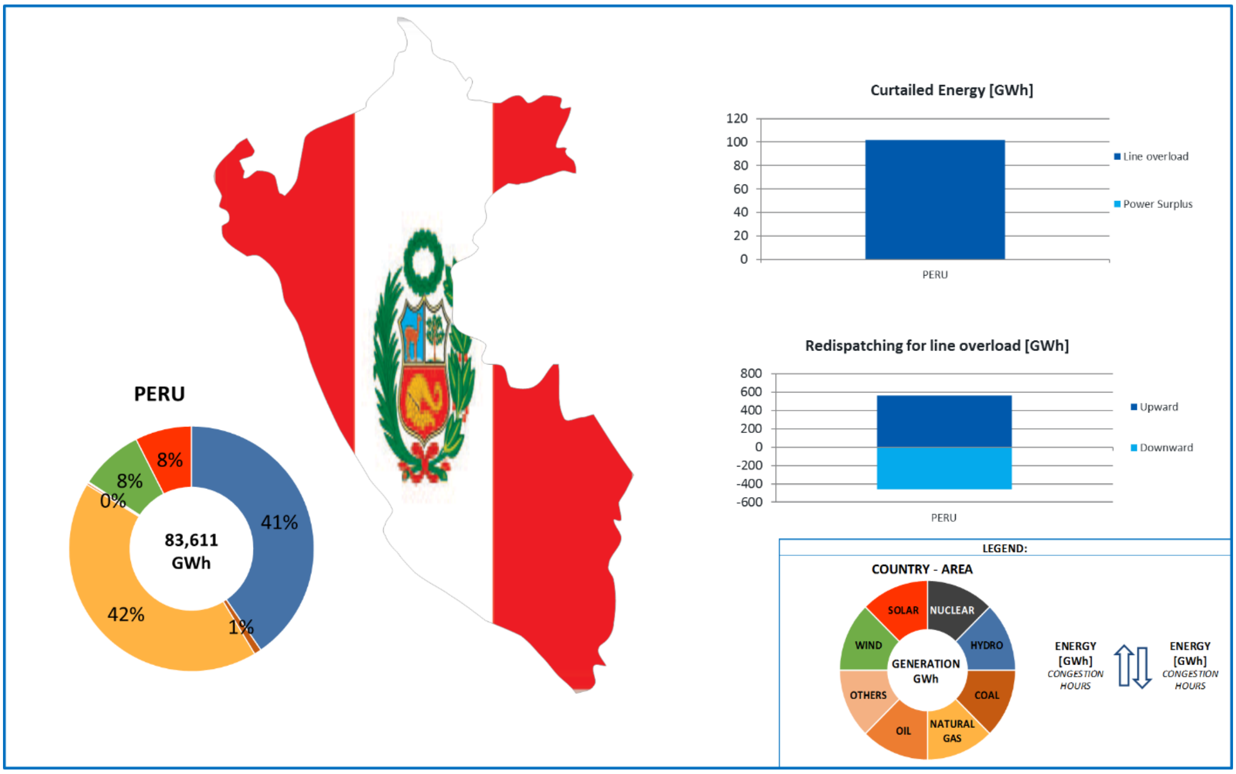

Figure 14 - Total production and energy exchanges – Peruvian optimal isolated scenario

3.3.3.3 Case with no subsidies to Natural Gas

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 consequently also the cost of energy produced using NG as primary source increased with the same proportion.
In this scenario, VRES plants become even more attractive as the merit order between VRES and NG generation changes with respect to the previous analysis because the cost of energy produced by NG becomes higher than VRES cost, which remains the same.
Considering the same amount of VRES plants which resulted to be the optimal value in presence of subsidies to NG (in total, 2,750 MW PV and 1,700 MW wind), the overall benefit resulting for the

Peruvian system becomes nearly the double (USD 389 million against the previous USD 200 million) as NG consumption replaced by VRES is more expensive. Comparing Table 39 with Table 38 it is possible to appreciate the increase of economic competitiveness in the thermal generation fleet.

Table 39 - Total benefit obtained with no NG subsidies in presence of 2,750 MW PV and 1,700 MW wind

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	3,750	-335
NEW STORAGE	320	-18
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-10,730	721
RES CURTAILMENT	101	-
TOTAL EENS	-10.6	21
TOTAL BENEFIT	**-**	**389**

BENEFIT/MW VRES [kUSD/year]	**104**

The higher economic convenience makes it advantageous to install more VRES plants eventually accepting higher curtailments, or even 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 penetration of wind plants (up to 3,500 MW), located in the North of the country and along the coasts, which do not stress the grid in only one area, but being more distributed do not cause excessive changes in the energy flows. On the contrary, it is not convenient to increase considerably the amount of PV plants defined in the previous analysis, as the limited transmission capacity in particular of the 220 kV network in the South in the area of Moquegua station, causes more than 20% of the production of the new plants to be curtailed. The optimal value for PV in this case reaches around 3,000 MW. 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.

In this condition the main critical bottlenecks limit the exploitation of VRES in the South of the country (in particular of PV plants in Tacna, Moquegua and Arequipa regions). The most critical lines are the 220 kV ones in the area of Moquegua station, which reach their limit when the high amount of power produced by VRES plants in the South has to be evacuated towards the centre. At the same time, the 500 kV lines, and in particular the new Montalvo-Yarabamba-Poroma one, are not always fully loaded, and the power flow remains at the 220 kV level where load and possibly also VRES generation are connected. Some investments would be useful to improve the power transfer from the 220 kV to the 500 kV level and ensure the best exploitation of the transmission capacity from South to centre, in some cases also increasing the reliability of the system. Moreover, interventions should be aimed at making the transmission system more flexible, able to accept VRES power injections in different nodes as the exact location of the future power plants is not known in advance, and the time required for the improvement of transmission network can be much longer than the one needed for the VRES plants development.

A smoother transfer of the power between the 220 kV and the 500 kV level with the effect to reduce the loading on critical lines can be obtained doubling the transformers present in the 500-220 kV stations (Montalvo 500 kV and Yarabamba). This solution, which might be challenging due to the very big dimensions of the existing equipment, would also reach the additional result to improve the reliability of the system thanks to the better fulfilment of the N-1 criterion, very important with increasing power production coming from the South. Another possible technical solution which allows to increase the loading of the 500 kV lines from South to North is to force the injection of the new PV power plants directly at the 500 kV level with special and dedicated connection schemes, applicable in particular in presence of big plants developed in close areas. The flexibility of the 500 kV transmission system can be obtained with solutions which allow to control the distribution of the power transferred northwards between the existing 500 kV lines[8], in order to ensure the maximum exploitation of the transmission capacity.

With the higher and more balanced loading of the 500 kV lines obtained by means of proper control systems, additional room for VRES production appears as bottlenecks can be resolved in an easier way, and their optimal amount increases up to 4,000 MW both for PV and wind.

In this condition, VRES would provide more than 24.5 TWh, covering nearly 30% of the load. Total curtailments are limited to about 600 GWh due to line overloads.

The benefits deriving from this additional production are quantified in about USD 35 million per year, which have to be compared with the cost of the additional equipment necessary for the optimal exploitation of the transmission grid.

3.3.3.4 Final considerations on Peruvian isolated system

Peru has very good availability of PV and wind resource, and these technologies can play a significant role in the future coverage of the demand at 2030 even against production from Natural Gas at subsidized price. Among the analysed ones, it is also the country with the lowest share of demand covered by hydropower plants and the highest amount of energy to be covered by technologies other than hydro. In addition, the presence of big hydropower plants with reservoirs and the availability of a good amount of thermal generation make the Peruvian system the one where less system constraints are expected.

Also thanks to the flexibility due to the hydropower plants, the introduction of PV and wind plants does not show criticalities in terms of system constraints, and can provide considerable benefits to the system, compared to other technologies. When the NG cost is lowered by subsidies, the optimal amount of VRES installed power reaches about 4.5 GW, covering more than 15% of the demand. In this case, the main factor limiting VRES penetration is the low cost of electricity produced by NG, which makes not advantageous the replacement with PV and wind plants.

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[8] For instance, the usage of a Phase Shifter Transformer (PST) on one line allows to control the power flowing along the line, and in consequence the loading of both the 500 kV circuits towards the centre of the country. More detailed analyses have to be performed to identify the best technical solution and the real limits which can be obtained, considering also the system behaviour after critical contingencies. The interaction of PST with the existing Series Capacitors, which in future in some cases are planned to be bypassed or regulated through a Thyristor Control (forming a TCSC, Thyristor Controlled Series Capacitor), with the existing generators and with the issues already present in the system, such as the Sub-Synchronous Resonance, must be better evaluated.

If subsidies for NG are not considered, the introduction of VRES results more attractive as they replace more expensive generation, and for this reason slightly higher curtailments might be acceptable. In this condition, if no improvements of the transmission network are considered, it turns out to be convenient to increase significantly the share of wind installed power, more distributed in the country, up to 3,500 MW, and to increase only partially the amount of PV, up to 3,000 MW. PV is in fact more subject to possible curtailments as it is concentrated only in the South of the country and especially 220 kV lines limit the evacuation of the power towards North.

With limited interventions on the transmission system, aimed at increasing the amount of power transported by the 500 kV lines and at allowing the control of the power flowing on them from South to North to ensure the best usage of the total transmission capacity, the amount of VRES plants can further increase. In this condition, the optimal values reach 4,000 MW both for wind and for PV plants, achieving an additional benefit for the system around USD 35 million per year. In order to assess the convenience of these interventions, this possible benefit has to be compared with the costs to install the additional devices necessary to strengthen the transmission system and increasing its flexibility.

Similarly, an economic convenience would be present in case the externalities such as CO_2 emissions or other pollutants were considered, similar to the carbon tax already applied in Colombia [5], actually increasing the thermal generation costs, especially for the less efficient technologies.

3.3.4 Interconnected countries

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

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

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

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

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

All the analysed countries are operated at 60 Hz, and the interconnections allow to maintain synchronism among them.

3.3.4.1 *Reference scenario for Colombian, Ecuadorian and Peruvian systems*

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

Table 40 - Total VRES installed capacity in Reference scenario for COL, ECU and PERU together [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

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

- ***EENS*** is around 1.4 GWh; it is about 0.6×10^{-5} of the total load, and mainly caused by transmission constraints in Peru not related to the presence of VRES plants.
- ***Overall generation costs*** are close to USD 2,320 million; of which USD 32 million due to presence of network congestions.
- Expected ***generation by PV*** power plants around 12,420 GWh (2,000 EOH) with a curtailment higher than 830 GWh, corresponding to 6.2% of the total PV production.
- Expected ***generation by wind*** power plants close to 22,400 GWh (about 3,750 EOH) with a curtailment of nearly 1,390 GWh, corresponding to 5.8% of the total wind production.

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

The detailed results of the simulations of the Colombian, Ecuadorean and Peruvian power systems together but not interconnected are reported below. The system configuration and the generation fleet are the ones resulting from the evaluation of the optimal amount of additional VRES carried out on the isolated countries (3.3.1.2, 3.3.2.2 and 3.3.3.2).
Results are aligned with the ones obtained with the simulations of single countries, but some small differences can appear due to different probabilistic simulations applied to the countries together. The new Reference scenario for the evaluation of the benefits resulting from the interconnection is then briefly presented.

The following table shows the EENS, expressed as MWh/year, split by area and reason. As in the isolated cases, there is no risk for Lack of Power in the countries, and the only issue is represented by transmission network bottlenecks in Peru which are due to load increase and not to the presence of additional VRES plants. In this table, the lack of interconnection mostly would correspond to situations with lack of power in the simulations of the single country, which now would be counted as interconnection problems because some power might be available in the other country if there were an interconnection available (in this Reference scenario, no power exchange is allowed between countries). Line overloads that are not solved after redispatching produce about 1,386 MWh/year of EENS, mainly concentrated in Peru.

Table 41 - Expected Energy Not Supplied – COL, ECU and PERU Reference scenario (NTC=0)

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	11	0	11
ECUADOR	0	91	0	91
PERU	0	1,284	1	1,285
TOTAL	**0**	**1,386**	**1**	**1,387**

Table 42 shows the total energy produced in each area and the related costs. These costs are only due to thermal power plants. In Reference scenario overall generation costs including redispatching are around USD 2,320 million/year in the whole system (Colombia, Ecuador and Peru).

Table 42 - Total production and fuel costs – COL, ECU and PERU Reference scenario (NTC=0)

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	98,579	560	657	-44	44	1
ECUADOR	49,039	574	1,487	-111	111	9
PERU	83,594	1,154	0	-631	631	24
TOTAL	**231,212**	**2,287**	**2,144**	**-786**	**786**	**34**

The following table shows PV generation before redispatching and PV curtailments after redispatching for each area of the system. Total production is around 12,550 GWh/year, already considering the reduction for overgeneration equal to 700 GWh/year (6% of total production). The energy curtailed to solve network congestions during redispatching is moderate, 133 GWh/year that is about 1% of total production.

Table 43 - Total production of PV plants – COL, ECU and PERU Reference scenario (NTC=0)

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	4,002	151	0	0	1,668
ECUADOR	2,225	549	-1	0	1,271
PERU	6,324	0	-132	0	2,252
TOTAL	**12,551**	**700**	**-133**	**0**	**1,800**

As regard wind generation, total production is around 22,410 GWh/year, as illustrated in Table 44, and the reduction for overgeneration is equal to 1,380 GWh/year (less than 6% of total production), concentrated in Ecuador and Colombia, as already seen in the analysis of the single countries. The energy curtailed after redispatching phase is negligible, only 11 GWh/year that is less than 0.05% of total production.

Table 44 - Total production of Wind plants – COL, ECU and PERU Reference scenario (NTC=0)

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	11,702	494	-11	0	4,330
ECUADOR	3,712	886	0	0	1,811
PERU	6,997	0	0	0	4,116
TOTAL	**22,411**	**1,380**	**-11**	**0**	**3,473**

The following Figure 15 provides a visual summary of the operation of the Colombian, Ecuadorian and Peruvian power systems together without power exchanges (as the simulation has been carried out without the possibility for the countries to exchange energy), highlighting the generation mix per countries, the energy exchanges, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

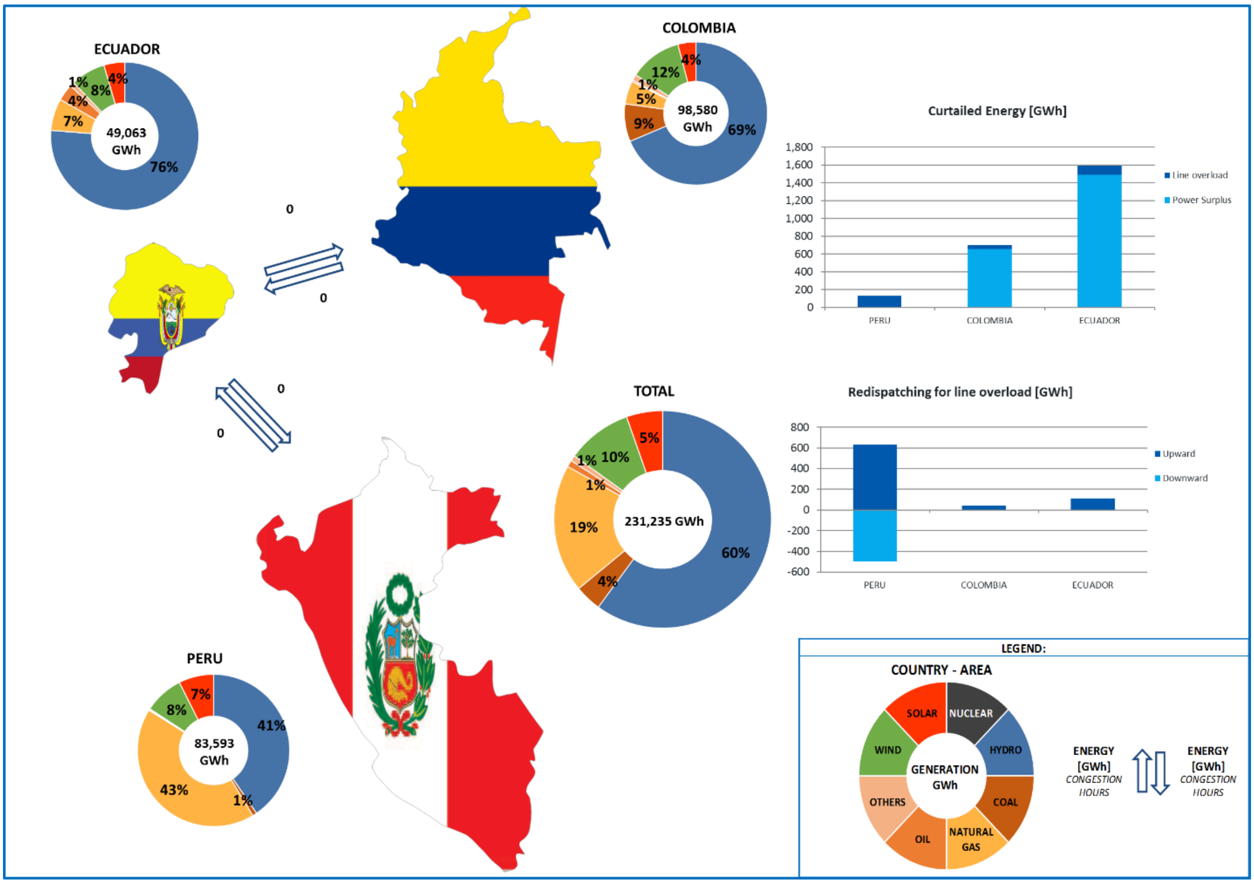

Figure 15 - Total production and energy exchanges – COL, ECU and PERU Reference scenario not interconnected (NTC=0)

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

3.3.4.2 *Colombia, Ecuador and Peru interconnected*

This case represents the Colombian, Ecuadorian and Peruvian power systems interconnected with the possibility to exchange energy (according the information collected in [1], the NTC between the countries are equal to 660 MW between Peru and Ecuador in both directions, 395 MW from Colombia to Ecuador and 535 MW from Ecuador to Colombia).

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

- A *reduction of the EENS* from more than 1.4 GWh to 0.95 GWh (-31%). The final EENS is less than 0.5×10^{-5} of the total load.
- *Overall generation costs* are reduced by 335 M$, thanks to the better exploitation of the cheap generators and of VRES (see next point).
- Expected *generation by PV* increases 635 GWh with respect to the Reference scenario thanks to lower curtailments, which in this case account for 200 GWh in total.
- Expected *generation by wind* increases 1.2 TWh with respect to the Reference scenario; total curtailments reduce to 184 GWh.
- *Energy exchanges* equal to:
    - 2.4 TWh from Colombia to Ecuador and 0.3 TWh from Ecuador to Colombia. The loading of interconnections in the two directions, evaluated as energy/NTC, is respectively 69% and 7% and it is worth noting that from Colombia to Ecuador the exchange limit is reached in 10% of time.
    - 1.1 TWh from Peru to Ecuador and 1.85 TWh from Ecuador to Peru. The loading of interconnections in the two directions is respectively 18% and 32%. From Ecuador to Peru the exchange limit is reached in 3% of time.
    - The presence of the interconnection provides *benefits for the whole system* evaluated in USD 335 million mainly due to the reduction of generation costs which is possible thanks to the possibility to better exploit the cheap resources such as the VRES (which are less curtailed), and coal and efficient NG plants.

The possibility to exchange power between the countries thanks to the presence of interconnections, which enables more generators to participate to the redispatching necessary to solve line overloads, allows reducing the EENS due to line overload down to about 950 MWh, corresponding to less than 0.5×10^{-5} p.u. of the total load of the system.

Table 45 - Expected Energy Not Supplied - COL, ECU and PERU interconnected scenario

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	12	0	12
ECUADOR	0	132	0	132
PERU	0	808	0	808
TOTAL	**0**	**952**	**0**	**952**

The interconnections also allow a more optimized utilization of the cheap energy resources, reducing the VRES curtailments and the usage of expensive generators with liquid fuels. Generation costs are thus strongly reduced (-USD 334 million) as it is shown in Table 46. The amount of redispatched energy is nearly double, but the cost does not increase so significantly. It is worth noting the strong reduction (nearly -90%) of required generation reduction due to overgeneration conditions.

Table 46 - Total production and fuel costs - COL, ECU and PERU interconnected scenario

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	101,462	589	150	-533	34	-9
ECUADOR	47,694	213	100	-148	407	25
PERU	82,543	1,140	0	-676	916	29
TOTAL	**231,699**	**1,942**	**250**	**-1,357**	**1,357**	**45**

Table 47 shows the new production of the PV power plants and Table 48 highlights the differences with respect to the Reference scenario: the number of equivalent hours increases by nearly 100 hours thanks to the lower curtailments for overgeneration and line overloads, which reduce respectively from 700 GWh to 79 GWh and from 133 GWh to 120 GWh.

Table 47 - Total production of PV plants - COL, ECU and PERU interconnected scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	4,116	37	0	0	1,715
ECUADOR	2,733	42	-2	0	1,561
PERU	6,324	0	-118	0	2,257
TOTAL	**13,173**	**79**	**-120**	**0**	**1,892**

Table 48 - Difference of total production of PV plants between interconnected scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	114	-114	0	0	47
ECUADOR	508	-507	-1	0	290
PERU	0	0	14	0	5
TOTAL	**622**	**-621**	**13**	**0**	**92**

In the same manner, Table 49 shows the new production of the wind power plants: thanks to the possibility to exchange power between the countries, the total curtailments due to overgeneration and transmission constraints are reduced from 1,391 GWh to 184 GWh with respect to the Reference scenario.
The average equivalent hours of the overall wind projects increase by nearly 200 hours as a result of reduction of curtailment.

Table 49 - Total production of Wind plants - COL, ECU and PERU interconnected scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	12,085	110	-16	0	4,470
ECUADOR	4,539	58	0	0	2,214
PERU	6,997	0	0	0	4,116
TOTAL	**23,621**	**168**	**-16**	**0**	**3,660**

Table 50 - Difference of total production of Wind plants between interconnected scenario and the Reference one

DIFFERENCE RESPECT TO THE REFERENCE SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	383	-384	-5	0	140
ECUADOR	827	-828	0	0	403
PERU	0	0	0	0	0
TOTAL	**1,210**	**-1,212**	**-5**	**0**	**187**

Finally, Table 51 shows the main figures which summarize the difference between the Reference scenario and the interconnected one. It is possible to see that the advantages for the system in terms of reduction of generation costs are significant (USD 334 million), thanks to the reduction of VRES curtailments (which allows to exploit in the system more than 1.8 TWh of free energy produced by PV and wind, replacing thermal) and a generally better optimization of the generation fleet of the whole system. The benefits due to EENS reduction are negligible, as the system had already a good adequacy even without the interconnections.

VRES curtailments reduce significantly by more than 80%. As already explained in other previous paragraphs, this value might be even further reduced during real operation of the system with a better short-term planning of the resources. To this aim, it is necessary to ensure a good coordination among all the different energy sources, which might become more complex with an increased amount of VRES power plants.

Table 51 - Main results with Colombia, Ecuador and Peru interconnected [MW]

	Isolated countries	Interconnected scenario	Difference
EENS [GWh]	1,387	952	-435
Total generation costs [MUSD/year]	2,321	1,987	-334
PV production [TWh]	12.4	13.1	0.7
Wind production [TWh]	22.4	23.6	1.2
RES Curtailments [GWh]	2,226	383	-1,843
Total benefit [MUSD/year]	335		

The resulting conditions and energy exchanges corresponding to the interconnected case are depicted in Figure 16.

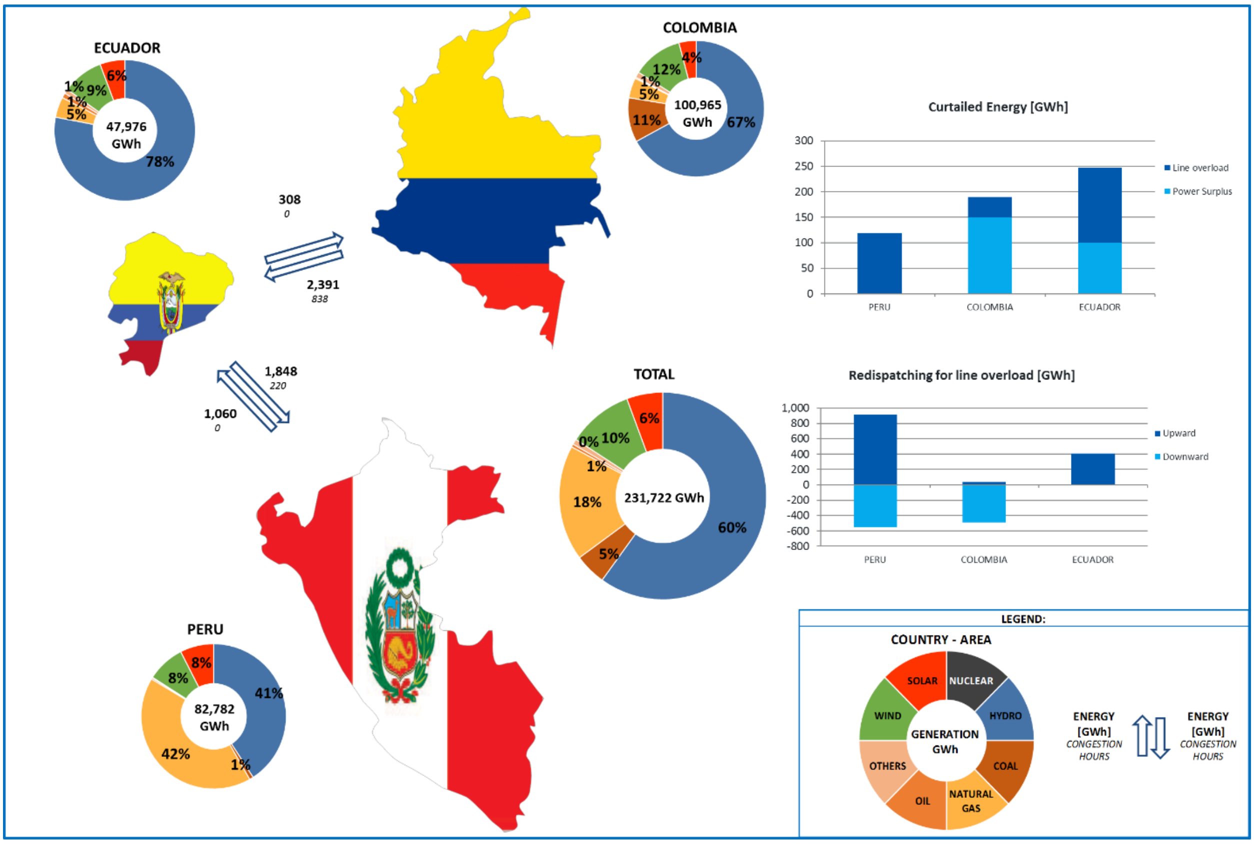

Figure 16 - Total production and energy exchanges – Colombia, Ecuador and Peru interconnected systems

3.3.4.3 Configuration with additional VRES installed power in Colombia and Peru

The presence of the interconnections between the countries improves the operation of the systems, because the generation resources can be shared better when necessary, further reducing the EENS and exploiting the cheap generation in a better way. In this condition, two opposite effects affect the possibility to increase VRES penetration:

- on one hand, PV and wind power plants are less curtailed, and their production increases, making the energy produced by these plants even cheaper than before. This fact has a positive impact on the economic advantage VRES bring in the system, and would push for further deployment of these plants in the countries;
- on the other hand, interconnections enable a more effective exploitation of cheap thermal generation[9], reducing the overall generation costs and making VRES competing against cheaper resources. This fact would have a negative impact on the advantages that VRES introduce on the system as they would replace more economical generation.

The actual economic advantage deriving from additional VRES installations depends on which effect has the strongest influence. In order to evaluate more in detail the operation of the system in these conditions, a new scenario is analysed: new investments in PV and wind plants are assumed in the countries with highest VRES resources considering the operation in the interconnected system, and the convenience is assessed on the basis of the comparison between the benefits introduced in the systems and the considered investments.

As it can be seen in previous analysis, solar and wind resources in Ecuador are lacking and for this reason, in an interconnected scenario in which energy exchanges between countries are not constrained, investments in Ecuador provide much lower advantages and it results to be not convenient overinvest in this country.

In the simulated scenario, additional VRES are considered (600 MW of PV and 450 MW of wind, with 90 MW of additional storage), distributed in the countries as detailed in Table 52.The installation of these new plants corresponds to an overall investment equal to about USD 110 million.

Table 52 – Additional VRES installed power considered in the interconnected scenario

Country	Additional PV [MW]	Additional Wind [MW]	Additional Storage [MW]
COLOMBIA	250	250	40
ECUADOR	-	-	-
PERU	350	200	50
TOTAL	**600**	**450**	**90**

In this new scenario, the network results a bit more loaded due to the presence of the additional VRES installed power, and for this reason some limited increase of EENS due to line overload appears (as reported in Table 53), which however does not represent a critical condition.

[9] 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.

Table 53 - Expected Energy Not Supplied - Additional VRES installed power in COL and PERU

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	21	0	21
ECUADOR	0	140	0	140
PERU	0	913	0	913
TOTAL	**0**	**1,074**	**0**	**1,074**

Thanks to the additional VRES capacity, the thermal generation costs reduce, even with an increase of the redispatching needs, as it is shown in Table 54.

The cost reduction is however substantially aligned with the amount of money invested for the new plants, and this indicates that the two opposite effects described above have a similar impact on the VRES convenience, suggesting that in the flexible interconnected scenario the economic advantages are close to the optimal values even in case of some variations of the VRES installed power. With the assumption that no externalities are considered, the optimal VRES installed power calculated for the isolated systems and assumed in chapter 3.3.4.2 can be considered an optimal solution also when the countries are interconnected.

On the other hand, in case externalities were taken into account and the cost of the thermal generation increased to consider effects on GHG emissions and pollution -as it happens for instance in Colombia with the introduction of a carbon tax-, the benefits introduced by VRES would also increase, and for this reason optimal amount of VRES installed power might shift towards higher values.

Table 54 - Total production and fuel costs - Additional VRES installed power in COL and PERU

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	101,619	537	321	-511	69	-7
ECUADOR	47,569	201	126	-163	403	25
PERU	82,606	1,080	0	-840	1,043	36
TOTAL	**231,794**	**1,818**	**447**	**-1,514**	**1,515**	**54**

Table 55 shows the new production of the PV power plants in all the countries of the system: thanks to the additional capacity, the net production increase by 1 TWh, but also the curtailments increase by about 220 GWh (both for OG and line overloads), which corresponds to almost 20% of the possible production of the new added plants. The increased risk of curtailments is also part of the reason of the not strong convenience of the additional investments, as it represents a disadvantage for the new power plants which cannot be exploited adequately. Also in this case, if externalities for thermal generation were considered, the risk of VRES curtailments would become more acceptable from an economic point of view, and the optimal installed capacity might further increase.

Table 55 - Total production of PV plants - Additional VRES in the interconnected scenario

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	4,513	75	0	0	1,880
ECUADOR	2,722	52	-3	0	1,554
PERU	7,129	0	-288	0	2,488
TOTAL	**14,364**	**127**	**-291**	**0**	**2,040**

Table 56 shows the new production of the wind power plants in all the countries of the system: thanks to the additional capacity, the production increases by about 1.7 TWh/year, but also the curtailment increase almost 200 GWh/year, which corresponds to more than 10% of the production of the new plants.

Table 56 - Total production of Wind plants - Additional VRES in the interconnected scenario

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	13,080	244	-57	0	4,415
ECUADOR	4,525	73	0	0	2,207
PERU	7,784	0	-2	0	4,096
TOTAL	**25,389**	**317**	**-59**	**0**	**10,718**

3.3.4.4 Final considerations on Colombia, Ecuador and Peru interconnected system

The operation of the interconnected system brings significant advantages in terms of generation costs reduction and adequacy increase with respect to the results obtained considering the three power systems isolated. All the cheap energy sources, even the not dispatchable ones, are better exploited reducing their curtailments, and the demand is also better supplied thanks to the availability of a wider generation fleet which can be used even if located in other countries. In particular, curtailments of PV and wind power plants, which in the isolated case were present mainly due to overgeneration conditions, reduce by more than 80% and 1.8 TWh of free energy can be injected in the system. Also EENS, that was already at a good level, further reduces thanks to the possible support between the countries.

The operation of the interconnected system is simulated allowing energy exchanges between countries every time there is an economic advantage, i.e. every time in a country is available generation cheaper than in another and the interconnections between them are not congested: in this way, the cheapest generation is dispatched in the whole system through the interconnections, and the simulations show the maximum benefit which can be obtained with the exploitation of the interconnections. It is worth recalling here that in the real operation, the energy exchanges between the countries are subject to bilateral agreements between the governments and require also a proper regulatory framework. In

order to exploit at best the possible advantages due to the interconnections, a strong and flexible cooperation and coordination between the countries is required. If this is not possible or allowed to a limited extent, for instance because the definition of energy exchange programs between countries can be defined and fixed only many days in advance with reduced flexibility during real time operation, the advantages which can be achieved will also be limited.
The assumed NTCs between the countries correspond to adequate values, as only in a limited part of the year the power flows on the interconnections reach the relevant limits. This means that the considered NTCs do not represent a critical constraint for the best exploitation of the generation fleet, and there would be limited advantage in increasing them.

The presence of the interconnections creates the technical conditions for an increase of the VRES installed power, as the system becomes more flexible and the occurrence of overgeneration conditions, which were the main limiting factor in Colombia and Ecuador, is strongly reduced. Nonetheless, the analysis of the system with an increased value of installed VRES power in the countries with highest potential shows that the net benefit for the system deriving from additional investments in PV and wind power plants is almost null, as they would replace cheaper generation with respect to the operational conditions in the isolated countries. In this case, the fuel cost savings for the system reduce, as generation is cheaper, and remain well aligned with the investment costs needed for the new VRES plants: under the assumption that no externalities are considered for thermal generation, the optimal VRES installed power defined for the isolated countries is confirmed as the optimal solution also for the interconnected system.
However, if externalities or other additional costs were considered for the thermal plants to assess the impact of pollution and emissions (as it happens in Colombia [5] and is planned in other countries with the introduction of a carbon tax or other carbon pricing mechanisms), thermal generation costs would increase and advantages due to the presence of VRES would also become higher. In this case, the additional VRES plants replace more expensive thermal generation and it might turn out that also the optimal VRES installed power shifts towards higher values.

3.4 Sensitivities of final optimal configuration Colombia, Ecuador and Peru interconnected system

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

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

The scope of the sensitivity analysis is the assessment of the expected behaviour of the system (including the optimal amount of VRES plants calculated in an "average year") in case some changes take place with respect to the average conditions. Depending on the variations (for instance higher or lower availability of hydro resource or of other generation), the VRES plants will suffer higher or lower curtailments, and security of supply also is affected, as well as generation costs. It is important to assess whether there are risks in some particular condition which should be addressed properly defining proper solutions, such as the installation of further generation to ensure adequate security of supply.

3.4.1 Dry hydrological conditions

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

- The EENS increases to 3 GWh, equal to nearly 1.3×10^{-5} of the total load, remaining at an acceptable level in this critical condition. The EENS mainly increases in the Peruvian area.
- Overall generation costs increase up to more than USD 1,700 million, more than 85% higher with respect to the optimal scenario, due to the need to use expensive thermal generation to compensate the lower energy production by hydro.

The optimal amount of VRES calculated in the previous Chapters has been defined considering an average production of the hydroelectric power plants, which is the correct approach when the profitability of the VRES plants is considered along their lifetime, equal to at least 20 years.
However, it is necessary to ensure that in different hydrological conditions, such as dry periods, the system has enough generation available to supply the load, avoiding a dramatic deterioration of the adequacy, which would cause a high EENS value. In these conditions, there must be other generation resources, even expensive ones, to be used to cover the demand. In case the simulation shows critical results, some countermeasures, based on thermal generation or other technologies, should be considered in the power system planning.
In order to define a "dry hydrological condition", an analysis has been carried out on the available historical data. The typical dry year has been defined looking at the average conditions of years which present an availability of the hydro resource around about the 10^{th} percentile of the series. The different behaviour which takes place in the countries has been taken into account in the creation of the scenario. Based on the available data, the dry year has been modelled with a reduction of about 25% of the energy available from hydropower plants in Colombia, 20% in Ecuador and 15% in Peru.

As expected, the simulation of the scenario with lower availability of hydro resource shows an increase of the EENS, up to 3 GWh, even this does not affect the adequacy of the system: EENS is about $1.3x10^{-5}$ of the total load, which is acceptable in this critical condition. Table 57 reports the detailed results of EENS, and it can be noticed that it is mainly caused by lines overloads in Peru where the network is less adequate (the model includes 2024 committed projects, plus some reinforcements that have been included in the reference scenario as necessary for the supply of the load in normal conditions).
The generation fleet resulting in the optimal scenario, characterized by the high increase of VRES plants, is adequate to ensure the load coverage also when there is a significant reduction of the availability of the hydro resource. The increase of EENS due to lines overload is due to a major use of thermal minor plant situated in more remote areas of the grid.

Table 57 - Expected Energy Not Supplied in dry condition for interconnected system

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	65	0	65
ECUADOR	0	366	0	366
PERU	0	2,626	0	2,626
TOTAL	**0**	**3,057**	**0**	**3,057**

The produced energy by PV and Wind power plants increases due to the reduction of curtailments for overgeneration. As reported in the following tables, PV and wind plants are not curtailed anymore for overgeneration but in redispatching phase some higher limitations are required for PV in Peru to solve overload situations which are caused by a different usage of the thermal generation.

Table 58 - Total production of PV plants in dry condition for interconnected system

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	4,153	0	0	0	1,730
ECUADOR	2,774	1	0	0	1,585
PERU	6,324	0	-242	0	2,212
TOTAL	**13,251**	**1**	**-242**	**0**	**1,885**

Table 59 - Difference of total production of PV plants between optimal scenario and dry conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	37	-37	0	0	15
ECUADOR	41	-41	2	0	24
PERU	0	0	-124	0	-45
TOTAL	**78**	**-78**	**-122**	**0**	**-6**

Table 60 - Total production of wind plants in dry conditions

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	12,195	0	-18	0	4,510
ECUADOR	4,597	1	0	0	2,242
PERU	6,997	0	0	0	4,116
TOTAL	**23,789**	**1**	**-18**	**0**	**3,685**

Table 61 - Difference of total production of wind plants between optimal scenario and dry conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	110	-110	-2	0	40
ECUADOR	58	-57	0	0	28
PERU	0	0	0	0	0
TOTAL	168	-167	-2	0	68

In order to supply the load compensating the lower energy by hydroelectric power plants, the thermal generation increases its production and the relevant costs reach USD 3,585 million, more than 85% higher with respect to the optimal scenario.

Table 62 summarizes the main economic figures describing the operation of the system in this dry year scenario with respect to the optimal one with average hydrological conditions: there is a significant increase of the costs (USD 1,724 million) due to the higher thermal generation obtained also with expensive plants, and the cost associated to EENS.

Table 62 - Total benefit of the sensitivity case dry hydrological conditions

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	25,840	-1,720
RES CURTAILMENT	-121	-
TOTAL EENS	2.1	-4
TOTAL BENEFIT	**-**	**-1,724**

In Figure 17 it is possible to observe that in the considered dry conditions there is a strong import of energy in Ecuador, due to its dependence from hydro power generation, and also Colombia reduces its net balance by 1 TWh, exporting to Ecuador 1 TWh instead of 2 TWh.

Peru strongly increases its production as the generation fleet is characterized by less hydro penetration and the presence of more plants fuelled with natural gas, so in dry condition it can export thermal energy.

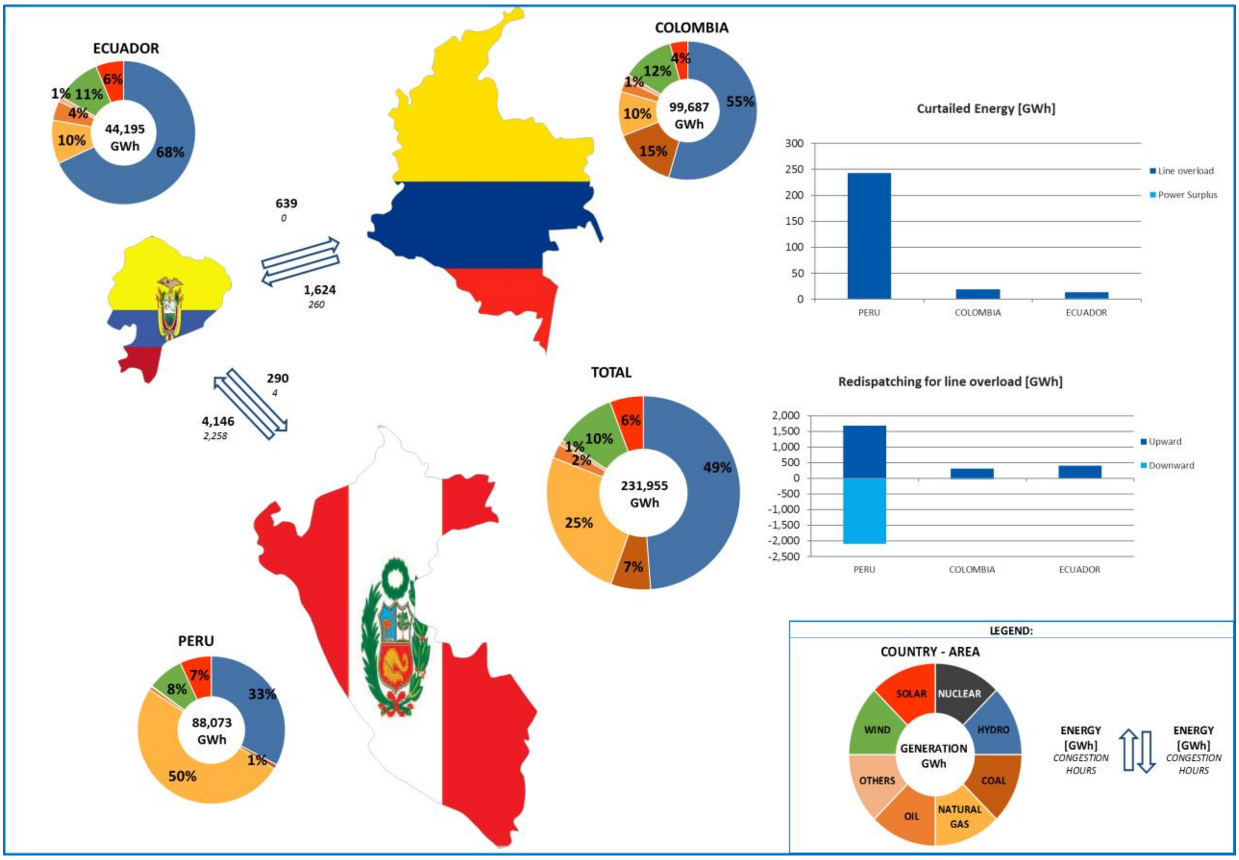

Figure 17 - Total production and energy exchanges – interconnected system with dry hydrological conditions

3.4.2 Wet hydrological conditions

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

- The *EENS* is about 1.1 GWh (less than 5×10^{-6} of the total load).
- Overall *generation costs* decrease to about 1,265 M$ (-36% respect to the optimal scenario) because of the higher availability of additional "free" generation by hydropower plants.
- Expected *generation by PV* and wind decreases due to more frequent and significant overgeneration conditions. PV must be curtailed nearly by 770 GWh more than in average hydrological conditions, while wind risks to be curtailed by almost 2 TWh more (the total curtailments reach respectively more than 7% and 9% of the total possible production).

The operation of the system in case of wet hydrological conditions is also to be analysed, because it can lead to greater curtailments of VRES and hydropower production due to more frequent and significant overproduction conditions due to the additional availability of hydro resource. This should not affect the adequacy of the system in terms of EENS, but a huge VRES curtailment might mean that the installed VRES generation is too high and that some plants might become not profitable at their full potential along the lifetime because during the wet year have to be curtailed in a significant way. This fact might have an impact on the economic viability of the projects, constituting a possible risk for the investment.

However, it is important to underline that the wet scenario should take place only a couple of times during the project lifetime, and for this reason in general should have a limited impact on the overall profitability. Nonetheless, it is important to verify how much the production of VRES plants is affected during wet years in order to have a clearer indication of the possible risks which the investment might face.
As done for the definition of the typical dry year explained in the previous paragraph, the "typical wet year" has been defined based on historical data series of hydro resource in the considered countries. Colombian plants have been assigned an increase of the available energy equal to about 20 %, while in Ecuador the increase has been set to 15 % and in Peru to 25 %.

The simulation of the scenario with wet hydrological conditions shows that the EENS is very limited in the system (1.1 GWh, equal to about $5x10^{-6}$ of the total load). The total EENS is due to lines overload and is slightly greater with respect to the reference scenario because of the big amount of imposed power in network than generate more grid congestions and makes the overall system less flexible in some operational conditions. Table 63 shows the EENS, expressed as MWh/year, split by country and cause.

Table 63 - Expected Energy Not Supplied in the wet scenario for COL, PER and ECU interconnected

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	209	0	209
ECUADOR	0	263	0	263
PERU	0	640	0	640
TOTAL	**0**	**1,112**	**0**	**1,112**

Thanks to the additional availability of hydro resource, there is an increment of hydropower production that causes a reduction of the thermal generation with the relevant costs. This benefit is estimated in USD 722 million, -36% respect to the optimal scenario with average hydrological conditions.

On the other hand, the higher production by hydropower plants makes more frequent the conditions in which the overgeneration constraint in the system is reached, requiring some curtailment of the new power plants. For this reason, PV and wind power plants decrease their production respectively by nearly 770 GWh and by 1,950 GWh with respect to the final optimal scenario with average hydrological conditions.
It can be noticed that in Peru the curtailment of PV and wind and the variation between conditions is very low with respect to Colombia and Ecuador, this because Peru has a lower hydro penetration with respect to the other countries and for this reason is less sensitive to hydrological conditions.
Curtailed energy corresponds respectively to more than 7% of the overall PV possible production and 9% of the wind. These values represent a possible risk of reduced revenues which might affect the profitability of investment in VRES plants. Despite the quite high value resulting in this wet scenario, it is expected that the overall impact on the project is limited, as this wet scenario corresponds to a very limited amount of the project lifetime.
On the other hand, as already commented, the actual curtailments of VRES power plants might result lower than the calculated amount in case a proper short-term and real-time coordination between thermal, hydro and VRES plants is put in place, managed by the system operator.

Table 64 - Total production of PV plants in wet conditions

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	3,671	482	0	0	1,530
ECUADOR	2,332	443	-7	0	1,329
PERU	6,324	0	-37	0	2,286
TOTAL	**12,327**	**925**	**-44**	**0**	**1,780**

Table 65 - Difference of total production of PV plants between optimal scenario and wet conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	-445	445	0	0	-185
ECUADOR	-401	401	-5	0	-232
PERU	0	0	81	0	29
TOTAL	**-846**	**846**	**76**	**0**	**-105**

Table 66 - Total production of wind plants in wet conditions

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	10,664	1,532	-4	0	3,948
ECUADOR	3,997	601	0	0	1,950
PERU	6,997	0	0	0	4,116
TOTAL	**21,658**	**2,133**	**-4**	**0**	**3,357**

Table 67 - Difference of total production of wind plants between optimal scenario and wet conditions

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	-1,421	1,422	12	0	-522
ECUADOR	-542	543	0	0	-264
PERU	0	0	0	0	0
TOTAL	**-1,963**	**1,965**	**12**	**0**	**-328**

Table 68 summarizes the main figures relevant to the operation of the power system during wet years with respect to the scenario with average hydrological condition. The availability of more hydro resource in wet conditions provides a benefit for the whole power system equal to 722 M$.

Table 68 - Total benefit of the sensitivity case wet hydrological conditions

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-16,300	722
RES CURTAILMENT	2,738	-
TOTAL EENS	0.2	0
TOTAL BENEFIT	**-**	**722**

Figure 18 shows that in the wet conditions, all the countries increase the share of demand supplied using hydro resource, and Colombia and Ecuador increase the energy exported towards Peru that has lower penetration of hydro power plants.

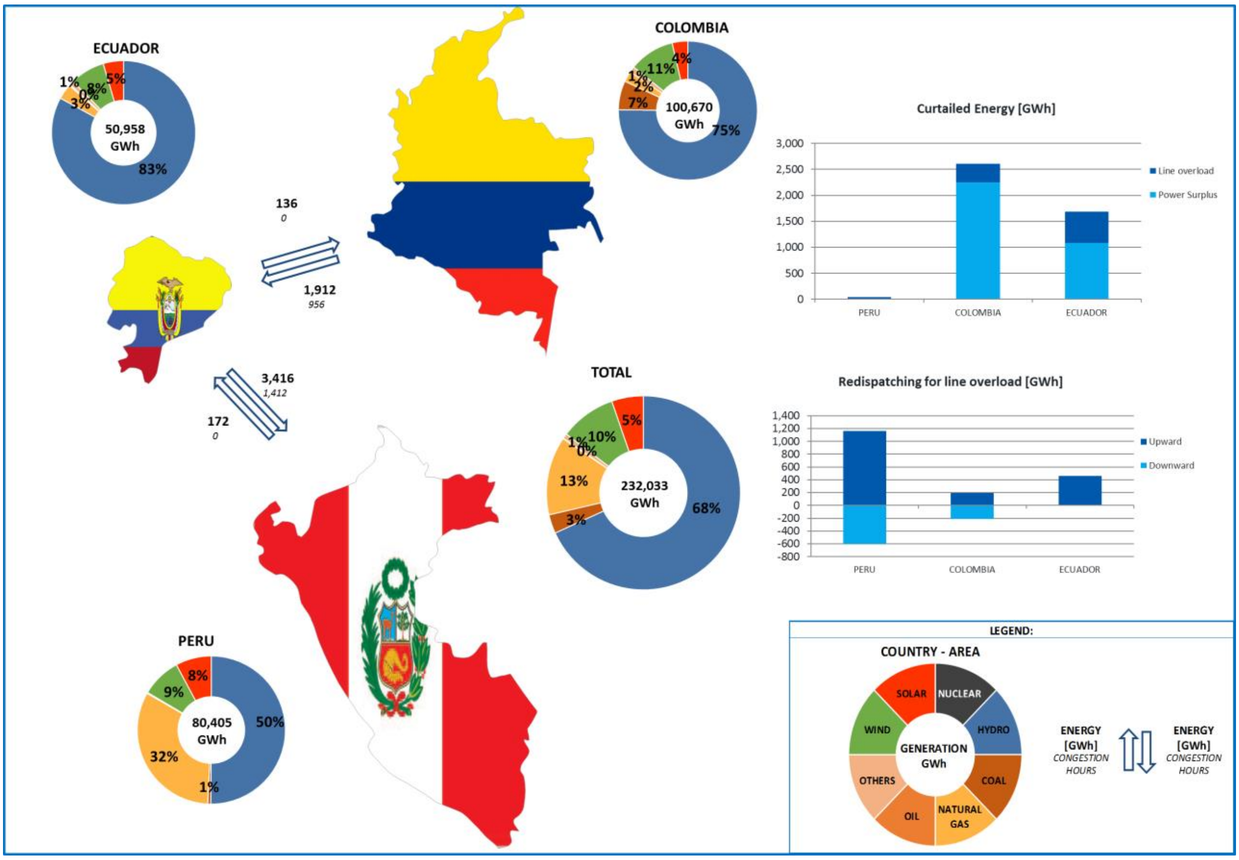

Figure 18 - Total production and energy exchanges – interconnected system with wet hydrological conditions

3.4.3 *Avoided investments in new thermal generation*

In the interconnected scenario, VRES generation can be better exploited and replace more effectively thermal generation. A possible benefit for the system might therefore derive from the possibility to avoid investments in new thermal plants. In order to assess possible advantages, a sensitivity case is considered with the same amount of VRES defined in the optimal scenario and a variation of the thermal generation fleet in which the following new power plants or upgrades are not considered:

Country	Power Plant	Power in reference scenario [MW]	Notes
COLOMBIA	Tasajero III	180	Not considered
ECUADOR	New dispatchable plant needed for adequacy	300	Not considered
PERU	Nepi Puerto Bravo	1,024 1,024	Switch to NG and upgrade to CCGT not considered Power reduced to 710-720MW with oil

- The *EENS* does not change significantly and is about 840 MWh, equal to $3.5x10^{-6}$ of the total load
- Overall *generation costs* increase a lot, almost USD 730 million (+37% respect to the optimal scenario) because of the reduction of cheap thermal generation[10]. This strong cost increase highlights that if the absence of the listed thermal generators had been assumed also in the Reference scenario, there would have been additional room for VRES optimization, as the advantages deriving from VRES plants would have been more consistent.
- Expected *generation by PV and wind* decreases in a not significant way because of slightly more frequent overgeneration conditions due to lower flexibility of the system and different usage of available generation fleet with relevant operational constraints on minimum power.

In an interconnected scenario, VRES generation can replace thermal generation. In order to evaluate this possibility, it is considered a scenario with the same amount of VRES defined in the optimal scenario with variation of the thermal generation fleet. In particular, it is analysed the absence of the following planned power plants:

- In Colombia: the coal power plant Tasajero III (180 MW)
- In Ecuador: the added dispatchable power plant included to ensure adequacy (300 MW)

Moreover, in Peru it is not considered the conversion of the Nepi and the Puerto Bravo power plants form OCGT with liquid fuel to CCGT with Natural Gas, which also included about 300 MW power upgrade for each plant.

In total, the reduction of the cheap thermal power is about 1,100 MW, plus the switch back to liquid fuel of about 1,400 MW from Natural Gas in Peru.

[10] In case externalities were considered for thermal generation applying for instance the carbon tax already introduced in Colombia or other carbon pricing mechanisms, the variation of generation costs might be different, because also efficiency and effects on environment have to be considered. However, in general the benefits would be higher as the thermal generation costs would increase.

The results show that the reduction of the thermal installed power does not affect the adequacy of the system in terms of EENS that is 840 MWh, about $3.5x10^{-6}$ of the total load. In Table 69 it is possible to notice that the total amount EENS is due to lines overload, so the generation fleet remains adequate. The EENS slightly changes with respect to the one in the reference scenario because of the absence of some big plants and the usage of a greater number of little plants located in more remote areas of the grid modifying the loading of the transmission network.

Table 69 - Expected Energy Not Supplied - avoided investments in new thermal generation in the interconnected system

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	11	0	11
ECUADOR	0	122	0	122
PERU	0	707	0	707
EENS TOTAL	0	840	0	840

The absence of cheap thermal generation produces a significant increase of thermal generation costs due to the usage of less efficient and economic plants. The effect is of increase of total generation costs about USD 730 million.

Table 70 - Total production and fuel costs - avoided investments in new thermal generation in the interconnected system

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	101,534	724	275	-359	36	-6
ECUADOR	47,701	302	128	-190	274	19
PERU	82,372	1,650	0	-337	576	26
TOTAL	**231,607**	**2,675**	**403**	**-886**	**886**	**39**

The reduction of the overall installed power decreases the flexibility of the system and requires also a different usage of the hydro resource and of the remaining thermal generators, with different operational constraints on minimum power and minimum start-stop periods. The simulation of the expected behaviour of the system shows a possible slight increase of risk of overgeneration conditions, which implies some additional curtailment of the VRES power plants, limited to few thousandths. These small impacts on the VRES generation might be minimized during real operation with a proper coordination of the different generators and technologies, which allows to reduce the occurrence of overgeneration conditions.

Table 71 - Difference of total production of PV plants between optimal scenario and without new thermal generation

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	-28	28	0	0	-12
ECUADOR	-11	10	-1	0	-7
PERU	0	0	15	0	5
TOTAL	**-39**	**38**	**14**	**0**	**-4**

Table 72 - Difference of total production of wind plants between optimal scenario and without new thermal generation

DIFFERENCE RESPECT TO THE OPTIMAL SCENARIO					
WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	ΔGWh/year	Reduction Min.Tec.Gen. ΔGWh/year	ΔGWh/year DP < 0	ΔGWh/year DP > 0	Δh/year
COLOMBIA	-98	98	1	0	-36
ECUADOR	-17	18	0	0	-8
PERU	0	0	-1	0	-1
TOTAL	**-115**	**116**	**0**	**0**	**-17**

Table 73 summarizes the main figures relevant to the operation of the power system in the analysed condition with respect to the reference scenario. As already mentioned, the operation of the system with a lower amount of cheap thermal generation causes an increase of the cost equal to USD 728 million, that should be compared to the avoided costs for the new or upgraded plants.

Table 73 - Total benefit of the sensitivity case without new thermal generation

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	70	-728
RES CURTAILMENT	140	-
TOTAL EENS	-0.1	0
TOTAL BENEFIT	**-**	**-728**

On one hand, the evaluation of this scenario allows to conclude that, from a technical point of view, the additional 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. Looking at this condition, it would be therefore possible to avoid some investment in new thermal power plant planned for the adequacy of the system. On the other hand, from an economic point of view, the absence of some thermal plants causes a strong increase of the generation costs and might also create the conditions for a further convenience of other VRES plants as they would replace more expensive generation and therefore would provide higher benefits. A more detailed economic evaluation would be necessary also for the excluded thermal plants to check whether the investment would be convenient from the economic point of view in a scenario with increased VRES generation.

Figure 19 shows the energy exchanges between Colombia, Ecuador Peru.

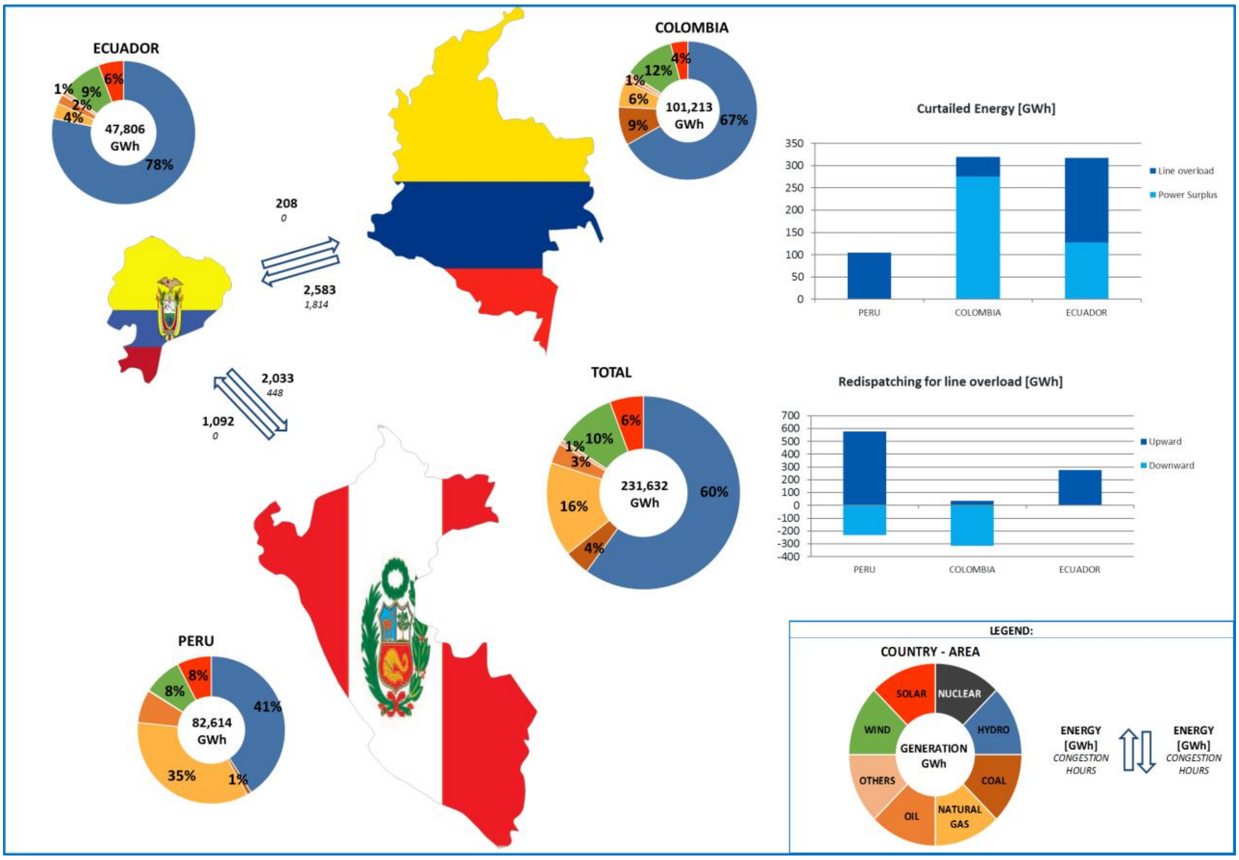

Figure 19 - Total production and energy exchanges – no investments in new thermal generation in interconnected systems

4 VARIANTS

Two Variants have been investigated in order to evaluate the behaviour of the system in case some major changes take place with respect to the assumptions at the basis of the Base Case discussed in the previous chapter.

4.1 First Variant: Accelerated decarbonization in a strong economic development

In the first Variant a higher demand growth together with an important change in the generation fleet, due to a transition to a carbon-free condition, has been examined. The main aspects that characterize this scenario with respect to the final optimal configuration described in paragraph 3.3.4.2 are described in the following.

Electric demand

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

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

The annual energy consumption is deemed to become 5% higher than the final optimal scenario in Colombia, and 12 % in Ecuador and Peru. The increase of the load is assumed to be mainly due to a stronger economic growth and partially to the impact of the e-mobility, concentrated in the biggest cities.

According to the values defined in [1], the additional demand due to e-mobility is estimated in 0.97 TWh in Colombia (more than 1 % of the total load), about 0.12 TWh in Ecuador (less than 0.4% of the total load) and 0.3 TWh in Peru (less than 0.3 % of the total load). This demand due to e-mobility is considered to be concentrated in the urban areas of the main cities during the night hours (between 8pm and 6am). The rest of the demand increase (the part caused by a general higher economic growth of the countries) is applied in a flat way in all the regions.

The energy increase is summed up in the following table.

Table 74 - First Variant - Energy Increase

COUNTRY	Energy increase due to e-mobility [GWh]	Energy increase due to population and economic growth [GWh]
COLOMBIA	970	3,870
ECUADOR	120	5,570
PERU	300	9,490

Generation

For the definition of the generation fleet for this first Variant, the power plants present in the final optimal interconnected scenario are taken into account, shutting down the coal plants and enhancing the transition towards a “carbon-free” generation, applied to minimize GHG emission. The coal power

plants have been removed and tentatively replaced by equivalent VRES power plants to substitute all of them keeping a suitable level of generation adequacy.
The amount of coal plants to be replaced is about 2,000 MW in Colombia and about 140 MW in Peru.

Electric storage systems

All the systems have already a good flexibility provided by the presence of hydropower plants with big reservoirs. This allows an optimized usage of the hydro resource and the focus on peak coverage and reduction of OG conditions.
As far as the VRES are concerned, as done in the previous analysis, additional batteries are introduced related to the installation of new power plants, allowing them to provide services to the system, but above all, reducing the uncertainty of their production forecasts.

4.1.1 Reference scenario for Variant 1

The ***Reference scenario for Variant 1*** is defined starting from the scenario with the optimal economic amount of additional VRES with the interconnected countries (paragraph 3.3.4.2).
The ***total amount of VRES*** installed power is indeed:

Table 75 - Total VRES installed power in the reference scenario for Variant 1 [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**

The ***demand is increased of 5% in Colombia and 12% in Ecuador and Peru*** taking into account also the ***high electric vehicles penetration*** (increased load during the night in main cities).
Coal plants present in the Colombian and Peruvian power systems have been ***switched off,*** in order to have a "coal-free" system.
The simulation of this scenario, which becomes the reference for the comparison of results of other simulations, brings to the following results:

- ***EENS*** is around 2.2 TWh, it is less than $1x10^{-5}$ of the total load. In the considered conditions, the power system maintains an acceptable level of adequacy.
- ***Overall generation costs*** are about USD 4,170 million; this mean that the average costs are double respect to the final optimal scenario. This increase is due to both increased load and higher cost of generation used respect to the coal.
- Expected ***generation by PV*** power plants is more than 13 TWh (higher than the PV production in the final optimal scenario). The reduction of PV curtailments becomes nearly null thanks to the higher load.
- Expected ***generation by wind*** power plants is close to 24 TWh. The curtailments are limited to less than 50 GWh, thanks to the higher load.

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

The following Table 76 shows the EENS, expressed as MWh/year. As expected, the higher load and the lower availability of generation cause an increase of the EENS compared to the final optimal scenario but the system maintains an acceptable level of adequacy.
EENS due to lack of interconnection[11] increases because with a higher load and without the coal power plants there are more conditions in which the generation available in the system or in a specific country is not sufficient to cover the power peak. The EENS due to line overload increases since the system is generally more loaded due to the demand growth.

[11] "Lack of Interconnection" differs from "Lack of Power" because it is triggered when some power would be available in other countries, but it is not possible to import it in the area with not enough generation due to interconnection constraints.

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

Table 76 - Expected Energy Not Supplied - Reference scenario for Variant 1

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	191	3	194
ECUADOR	0	391	0	391
PERU	0	1,057	523	1,580
EENS TOTAL	**0**	**1,639**	**526**	**2,165**

Table 77 shows the total energy produced in each country and the related costs. In this reference scenario of the first variant overall system costs are USD 4,168 million/year in the whole system (Colombia, Ecuador and Peru), double with respect to the final optimal scenario. This is due to the higher load and to the replacement of the coal plants with the more expensive thermal ones.

Table 77 - Total production and fuel costs – Reference scenario for Variant 1

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	103,037	1,458	16	-179	412	32
ECUADOR	52,707	812	11	-218	210	25
PERU	97,489	1,830	0	-693	467	11
TOTAL	**253,233**	**4,100**	**27**	**-1,090**	**1,089**	**68**

The following table shows PV generation and curtailments for each country of the system. Total production is nearly 13,250 GWh/year. The curtailed energy, which in the scenario with standard load was about 200 GWh, drops down to 7 GWh. This is because with a higher load, more generators are in service and also less constrained to the minimum when the PV production is high, providing more flexibility to the overall system.

Table 78 - Total production of PV plants – Reference scenario for Variant 1

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	4,149	3	0	0	1,729
ECUADOR	2,771	4	0	0	1,583
PERU	6,324	0	0	0	2,300
TOTAL PHOTOV. GENER.	**13,244**	**7**	**0**	**0**	**1,919**

The wind production is reported in Table 79. The annual wind production reaches nearly 23,800 GWh/year and still there are conditions with risk of curtailments up to about 38 GWh/year (almost one fifth with respect to the optimal economic scenario).

Table 79 - Total production of Wind plants – Reference scenario for Variant 1

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	12,183	13	-18	0	4,506
ECUADOR	4,591	7	0	0	2,240
PERU	6,997	0	0	0	4,116
TOTAL WIND GENER.	**23,771**	**20**	**-18**	**0**	**3,683**

The following Figure 20 provides a visual summary of the operation of the Colombia, Ecuador and Peru system in the reference scenario for Variant 1, highlighting the generation mix per areas, the energy exchanges between areas, the curtailed VRES production and the amount of thermal energy to be redispatched to solve network congestions.

Given the higher load, the high generation costs and the lower curtailments suffered by VRES, it is expected that in this Variant 1 there is room for additional VRES installed power, at least in the countries with highest resources.

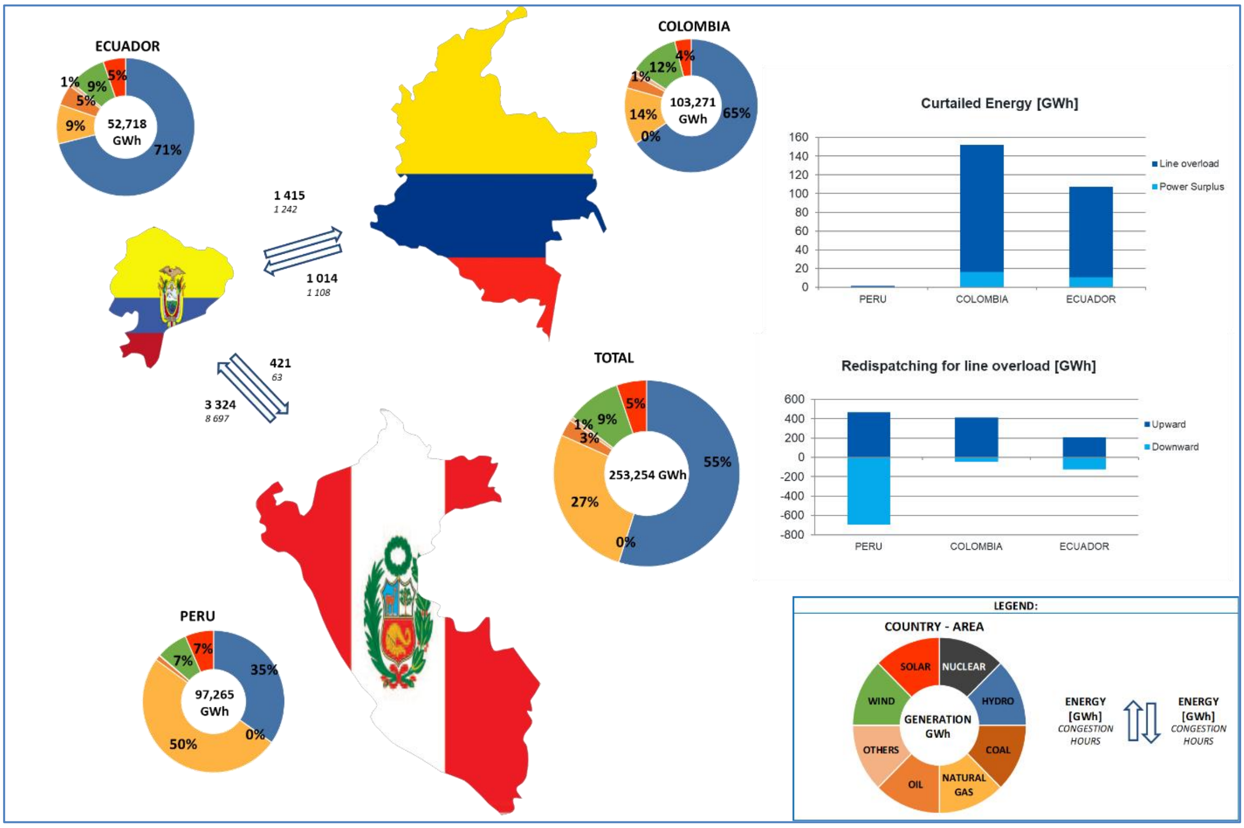

Figure 20 - Total production and energy exchanges – Reference scenario for Variant 1

4.1.2 Scenario V1: additional VRES

A new optimal configuration with ***additional VRES power plants*** has been evaluated: 5,000 MW of PV power plants and 2,000 MW of wind power plants are added because the higher load in Variant 1 requires more generation and makes profitable the introduction of these new VRES. Moreover 620 MW of storage system has been considered.
The amount of additional VRES has been calculated and divided between the countries and areas considering the load increase, the lack of generation due to the switch-off of the coal plants and system constraints highlighted in previous analyses.
The Table 80 sums up the additional VRES installed in this scenario. The highest share of new plants is in Colombia and Peru.

Table 80 - Additional 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 simulation of this scenario, leads to the following results:

- ***EENS*** is around 7.7 GWh; it is about $3x10^{-5}$ of the total load. Some network constraints appear, that should be reinforced in a scenario of faster load increase.
- ***Overall generation costs*** are close to USD 3,055 million; the thermal costs decrease by USD 1,113 million thanks to the higher VRES generation.
- Expected ***generation by PV*** power plants is about 23 TWh, about 9.4 TWh more than the one in the reference scenario. The production curtailments are about 770 GWh.
- Expected ***generation by wind*** power plants is almost 31.7 TWh, nearly 8 TWh more than the one in the reference scenario. The production curtailments are about 950 GWh.

Almost all the load increase can be supplied by the additional VRES introduced in the system.

Table 81 shows the EENS, expressed as MWh/year, split by country. The results show that with respect to the reference scenario the considered additional VRES generation cause an increase of the values of EENS in particular in Peru. This EENS is due to lines overload, so the generation fleet is quite adequate, but in a scenario of augmented load some grid reinforcements have to be considered. With the increase of EENS the system reduces its adequacy (EENS is about $3x10^{-5}$ of the total load), and some network reinforcement would be necessary. They would be required in a scenario of higher load growth.

Table 81 - Expected Energy Not Supplied - scenario V1

EENS [MWh/Year]	Lack of Power	Line overload	Lack of interconnection	TOTAL
COLOMBIA	0	780	20	800
ECUADOR	0	745	0	745
PERU	0	6,176	43	6,219
EENS TOTAL	**0**	**7,701**	**63**	**7,764**

Table 82 shows the total energy produced in each area and the related costs. Respect to the reference scenario there is a reduction of USD 1,113 million thanks to the higher VRES generation which replaces expensive thermal generation. The impact of needed redispatching becomes significant, as the transmission network is much more loaded than before.

Table 82 - Total production and fuel costs – scenario V1

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	104,936	947	848	-797	882	56
ECUADOR	50,551	557	21	-210	655	70
PERU	98,198	1,396	0	-1,884	1,355	28
TOTAL	**253,685**	**2,901**	**869**	**-2,891**	**2,892**	**154**

In the Table 83 and Table 84 the PV and wind production are reported. Compared to the reference scenario for this Variant, there is a significant increase, about +71% and +32% respectively. Also the curtailments increase considerably, but still the VRES remain profitable because they replace more expensive generation with respect to the reference scenario. PV can increase more than wind as it is a more distributed generation and it is also very convenient in Peru which is the country with less OG issues (in Peru, the main limiting factor is the presence of some transmission constraints which impact the overall generation with a 4% reduction).

Table 83 - Total production of PV plants – scenario V1

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	8,256	295	0	0	1,685
ECUADOR	2,767	7	-1	0	1,581
PERU	12,074	0	-465	0	2,211
TOTAL PHOTOV. GENER.	**23,097**	**302**	**-466**	**0**	**1,902**

Table 84 - Total production of Wind plants – scenario V1

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	16,163	553	-372	0	4,268
ECUADOR	4,584	14	0	0	2,236
PERU	10,931	0	-9	0	4,045
TOTAL WIND GENER.	**31,678**	**567**	**-381**	**0**	**3,704**

Considering the costs and benefits, this scenario presents an overall benefit for the whole power system equal to USD 458 million, due to the replacement of expensive generation with economic VRES energy.

Table 85 - Total benefit of the scenario V1 respect to the reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	7,000	-609
NEW STORAGE	620	-35
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-16,149	1,113
RES CURTAILMENT	1,671	-
TOTAL EENS	5.6	-11
TOTAL BENEFIT	-	**458**

It is important to underline that in this scenario VRES are curtailed more than in the Base Case (Chapter 3.3.4.3). In general, VRES curtailments, which in this optimal V1 scenario reach 1.7 TWh, are economically more acceptable as the thermal generation that is replaced by VRES in the periods in which there are no constraints is more expensive, and this provides more benefits to the system. Moreover, if externalities were taken into account for fossil fuel production, VRES would become even more advantageous, and even higher curtailments would become economically viable.

The following Figure 21 provides a visual summary of the operation of the Colombian, Ecuadorean and Peruvian power system in the optimal scenario V1, compared to the reference scenario of this Variant 1. It is possible to note how Peru now exports about 3 TWh towards Ecuador thanks to its high VRES penetration. Also Colombia export towards Ecuador about 1.1 TWh thanks to the good wind and PV resources.

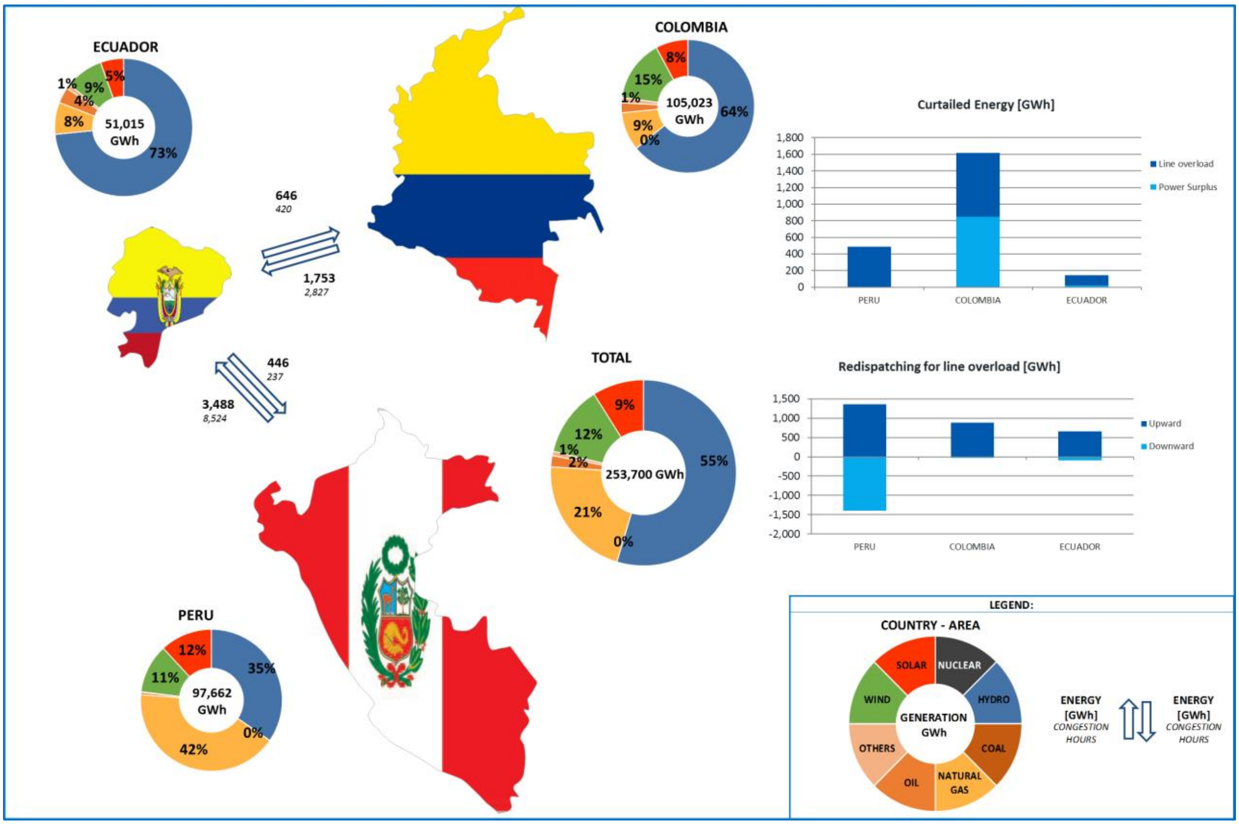

Figure 21 - Total production and energy exchanges – scenario V1a

4.2 Second Variant: enhanced energy efficiency

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

Demand

In this Variant 2 a scenario with lower demand is analysed. The main drivers which can contribute to a demand lower than the one considered in the previous analyses is a possible lower economic growth of the country and improvement of energy efficiency. According to what defined in [1], the load is reduced by 10% in Colombia, 15% in Ecuador and 15% in Peru. The demand reduction, caused by a general impact of energy efficiency, is distributed proportionally in all the regions.
The changes of the demand considered in this Variant 2 are summarized in the following Table 86.

Table 86 - Second Variant - Energy reduction

COUNTRY	Energy reduction [GWh]	Energy reduction [%]
COLOMBIA	-9.7	-10%
ECUADOR	-7.1	-15%
PERU	-12.2	-15%

Generation

The generation fleet assumed in the Variant 2 is the same as the one considered in the base case reference scenario of the each single country (respectively described in chapters 3.3.1.1, 3.3.2.1 and 3.3.3.1), but the 300 MW CCGT power plant added in Ecuador for adequacy in dry condition. In particular, the amount of VRES installed power is listed in Table 87:

Table 87 - Second Variant - Installed PV and Wind power in the starting condition [MW]

COUNTRY	PV	Wind
COLOMBIA	1,080	1,300
ECUADOR	80	120
PERU	280	410
TOTAL	**1,440**	**1,830**

4.2.1 Reference scenario for Variant 2

Reference scenario for Variant 2 is defined by the interconnected scenario with lower demand and with a generation fleet equal to the one considered in the reference scenario of each single country. The ***demand is reduced*** by 10% in Colombia, 15% in Ecuador and 15% in Peru, simulating a possible lower economic growth and the impact of energy efficiency on the power system.

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

- ***Good adequacy of the whole power system***, with value of EENS lower than 1.7×10^{-6} of the total load. This is because the considered generation fleet, sized on the higher load, is adequate to cover the lower load demand.
- ***Overall generation costs*** are about USD 1,680 million, which include the costs due to redispatching to solve overloads equal to USD 6 million.
- Expected ***generation by PV*** power plants up to 2.6 TWh. The PV curtailments are negligible.
- Expected ***generation by wind*** power plants is almost 8.2 TWh. The wind curtailments are negligible.

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

Table 88 shows the total energy produced in each country and the related costs. Generation costs are around USD 1,680 million/year in the whole system (Colombia, Ecuador and Peru). It is interesting to note that even with a limited amount of VRES, in the countries with higher share of hydropower plants there are already overgeneration conditions, even if not critical.

Table 88 - Total production and fuel costs – Reference scenario for Variant 2

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	92,081	485	9	-235	0	-5
ECUADOR	39,996	133	1	-18	90	5
PERU	69,449	1,055	0	-11	173	6
TOTAL	**201,526**	**1,673**	**10**	**-264**	**263**	**6**

The following table shows PV generation and curtailments for each country of the system. Total production is greater than 2.6 TWh/year. The curtailed energy is negligible, about 4 GWh/year, but as mentioned above, it is important to underline that some OG conditions are already present with a lower amount of installed power.

Table 89 - Total production of PV plants – Reference scenario for Variant 2

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	1,851	4	0	0	
ECUADOR	127	0	0	0	
PERU	657	0	0	0	
TOTAL PHOTOV. GENER.	**2,635**	**4**	**0**	**0**	

The wind production is reported in Table 90. The annual wind production reaches almost 8.2 TWh/year and the amount of curtailed energy is negligible, about 1 GWh/year.

Table 90 - Total production of Wind plants – Reference scenario for Variant 2

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	5,874	0	0	0	
ECUADOR	362	1	0	0	
PERU	1,931	0	0	0	
TOTAL WIND GENER.	**8,167**	**1**	**0**	**0**	

The following Figure 22 provides a visual summary of the operation of the Colombian, Ecuadorean and Peruvian power system in the reference scenario for Variant 2. It clearly appears how Ecuador has a strong demand coverage by Hydro power plants, which would make difficult the introduction of other generation sources.

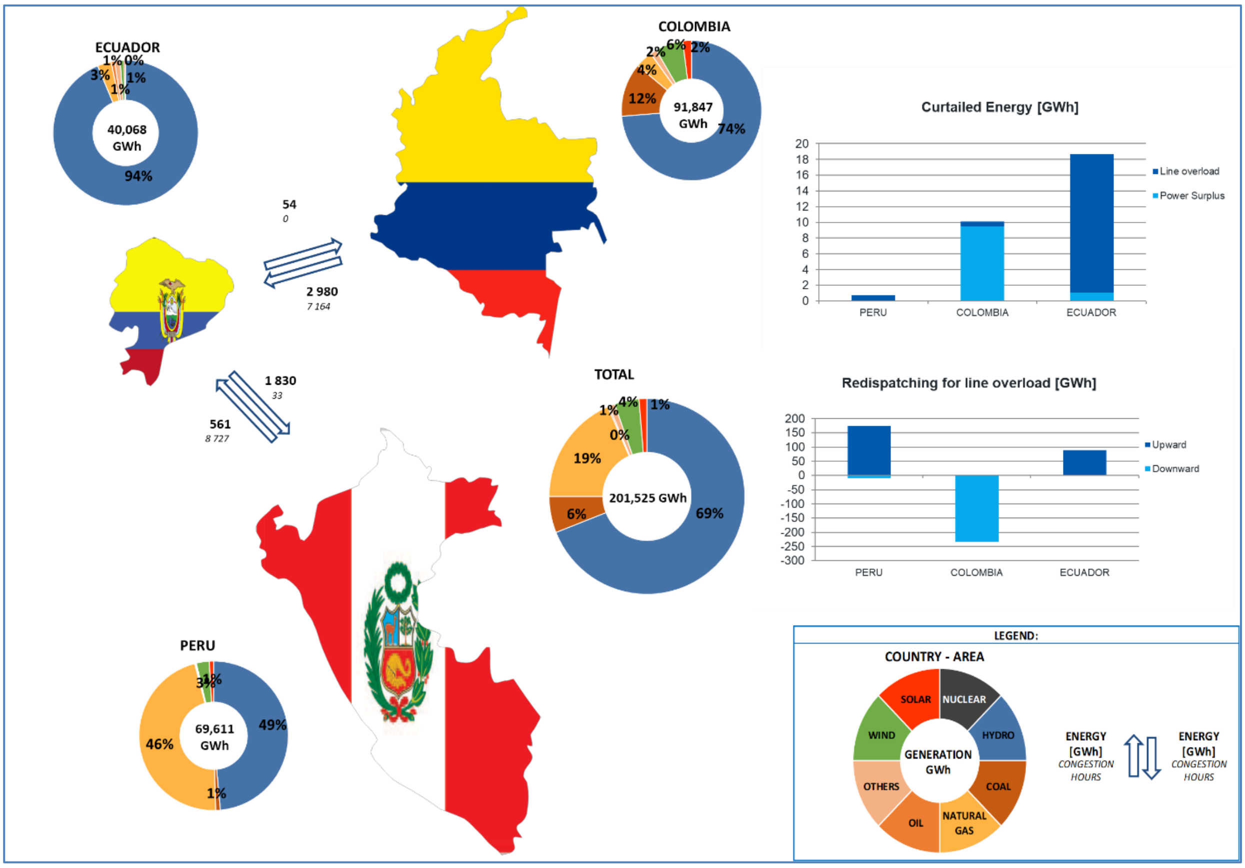

Figure 22 - Total production and energy exchanges – Reference scenario for Variant 2

4.2.2 Scenario V2: additional VRES

The optimal amount of ***VRES power plants*** has been calculated: 4,000 MW of PV power plants and 3,400 MW of wind power plants (together with 600 MW of storage system) divided as listed in Table 91.

Table 91 - VRES installed power in Variant 2 [MW]

COUNTRY	Added PV power plants [MW]	Total PV power plants [MW]	Added wind power plants [MW]	Total wind power plants [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**

The simulation of this scenario leads to the following results:

- ***Optimal adequacy of the whole power system***, the EENS remains around $1.5x10^{-6}$ of the total load.
- ***Overall generation costs*** are close to USD 1,265 million; the thermal costs decrease by USD 415 million with respect to the reference scenario thanks to the added VRES generation.
- Expected ***generation by PV*** power plants is close to 8,300 GWh. The production curtailments are about 40 GWh.
- Expected ***generation by wind*** power plants is close to 14,350 GWh. The production curtailments are about 70 GWh.

At the end of the optimization process aimed at defining the amount of VRES which is convenient to install in the system in the reduced load Variant, it turns out that this quantity is limited to 4,000 MW of PV and 3,400 MW of wind distributed in all the countries of the system. Peru has a lower penetration of hydro energy and so has a higher residual load with respect Colombia and in particular Ecuador, and for this reason is convenient install a greater amount of VRES. The installation of this VRES generation does not affect the security of supply in the system and EENS around $1.5x10^{-6}$ of the total load.
Table 92 shows the total energy produced in each area and the related costs. Respect to the reference scenario there is a reduction of about USD 415 million due to the presence of VRES generation.

Table 92 - Total production and fuel costs – scenario V2

ALL GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING			VARIATION AFTER REDISPATCHING		
AREA	GWh/year	M$/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	M$/year
COLOMBIA	92,113	415	91	-252	2	-6
ECUADOR	40,209	115	10	-28	96	6
PERU	69,290	727	0	-62	245	7
TOTAL	**201,612**	**1,257**	**101**	**-342**	**343**	**7**

In the Table 93 and Table 94 there is a significant increase of PV and wind productions with respect to the reference scenario due to the higher installed power. Some curtailments due to overgeneration conditions appear, equal to about 24 GWh/year for PV and 71 GWh/year for wind.

Table 93 - Total production of PV plants – scenario V2

PHOTOVOLTAIC GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	2,227	21	0	0	1,713
ECUADOR	314	3	0	0	1,570
PERU	5,761	0	-16	0	2,298
TOTAL PHOTOV. GENER.	**8,302**	**24**	**-16**	**0**	**2,072**

Table 94 - Total production of Wind plants – scenario V2

WIND GENERATORS	PRODUCTIONS & FUEL COSTS BEFORE REDISPATCHING		VARIATION AFTER REDISPATCHING		EOH
AREA	GWh/year	Reduction Min.Tec.Gen. GWh/year	GWh/year DP < 0	GWh/year DP > 0	h/year
COLOMBIA	7,614	65	0	0	4,479
ECUADOR	532	6	0	0	2,660
PERU	6,216	0	0	0	4,144
TOTAL WIND GENER.	**14,362**	**71**	**0**	**0**	**4,224**

Considering the costs and benefits, this scenario presents limited benefits for the whole power system equal to USD 8 million with respect to the reference scenario, as summarized in Table 95.

Table 95 - Total benefit of the scenario V2 respect to the reference scenario

	ELECTRICAL SYSTEM	ECONOMIC BENEFITS
	MW	MUSD/year
ADDITIONAL VRES	4,130	-391
NEW STORAGE	350	-16
	GWh/year	MUSD/year
TOTAL THERMAL GENERATION	-11,749	415
RES CURTAILMENT	106	-
TOTAL EENS	0.0	0
TOTAL BENEFIT	**-**	**8**

The amount of VRES plants in this Variant 2 is limited with respect to the optimal quantity resulting in the Base Case (Chapter 3.3.4.3) because the demand has been lowered in the whole system about 29 TWh while the generation fleet has been kept the same, with the same hydro resource. This results

in a higher availability of generation, and in particular cheap one by hydroelectric power plants, which reduces the need of further plants and limits the convenience install new VRES.
From the summary of the benefits, it is possible to calculate that the average cost of thermal energy replaced by VRES is around 35 USD/MWh, which represent a challenging value to compete with also for VRES in countries with good availability of resources. This makes the optimal values also subject to possible variations, as a slight change in the generation costs or in CAPEX/OPEX might modify them significantly. It is worth recalling here that costs 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. This scenario is highly probable in the future, as some countries are already introducing or planning carbon pricing mechanisms to be applied to thermal generation to reduce their environmental impact [5].

However, it is important to highlight that in the optimal configuration of Variant 2, almost 7.5 GW of PV and wind plants are present in the system, which represent a value much higher than today situation.
Moreover, it is possible that some non-VRES power plants (thermal, hydro, biomass…) considered in the generation fleet foreseen at 2030 will not be developed because not profitable in a scenario of lower demand growth (as they would operate for a lower number of hours) or because might incur difficulties during authorization process. In this case, VRES plants can become again a preferable solution to replace traditional generation, or to reduce environmental issues which for instance might affect big hydroelectric power plants. Flexibility and modularity of the VRES plants also constitute positive characteristics in this context because they allow the development and construction of generation facilities of different sizes which can better fit the needs of different areas. Furthermore, it is worth mentioning that also the shorter time required for the realization of VRES plants with respect to other technologies might become an advantage for PV and wind, because it allows to define more flexible generation development plans which can be adjusted depending on the demand growth in the areas and the development of the transmission grid. Moreover, the development of the generation fleet, even in a scenario with lower increase of the load, should remain balanced with a mix of technologies and sources that will allow the operational conditions to meet the energy load, modulation for intermittence and peak of demand.
In a context with high uncertainties relevant to the evolution of the demand in the next years, the flexibility and the shorter installation time of VRES plant, together with competitive LCOE, can be key factors which might foster the VRES penetration even in low demand growth scenario.

Figure 23 provides a visual summary of the operation of the Colombian, Ecuadorean and Peruvian power system in the scenario V2. Peru becomes an importer because of lower hydro penetration with respect to Colombia and in particular Ecuador that reaches 93% of energy produced by hydro power plants.

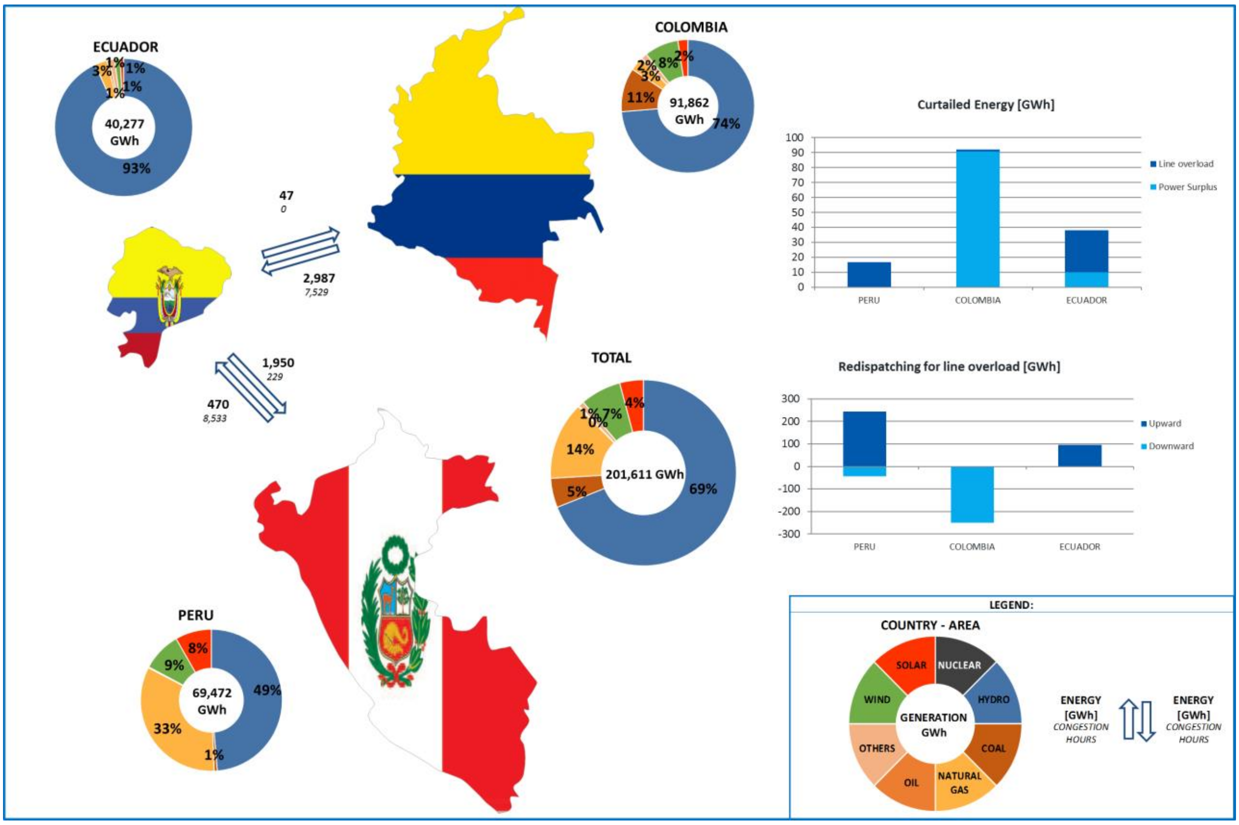

Figure 23 - Total production and energy exchanges – Scenario V2

4.3 Conclusions on Variants

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

In the Variant with higher load, it results to be economically viable to cover half of the variation of the demand (resulting from the load increase and from the absence of the energy generated by coal power plants) with VRES production. The 11,000 MW of PV power plants and 8,450 MW of wind power plants are introduced in the systems (in total, they correspond to more than 50% of the peak load), which allow the overall VRES plants to cover almost 22% of the demand in the system. However, the risk of load curtailments is a bit higher than before (EENS is about $3x10^{-5}$ of the total load) due to higher loading of the transmission network. Benefits introduced by VRES are significant (more than USD 450 million), but further deployment of VRES is limited by the increasing risk of curtailments which reach 1.7 TWh.

In the Variant with lower load, there is a significant excess of generation in the reference case, as the generation fleet is kept the same as in the optimal scenario. In this condition, the amount of VRES to be installed is limited (7,400 MW), as VRES generation would compete mainly against cheap thermal energy, and might result not convenient. The benefits provided to the system are also limited. If externalities were considered, the cost of thermal energy would increase, to include the impact on environment. In this case, the benefits deriving from the introduction of additional VRES plants would become higher, and a stronger penetration would turn out to be optimal.

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

5 LOAD FLOW ANALYSES IN SELECTED SNAPSHOTS

At the end of the activity during which the operation of the system has been analysed with a probabilistic approach, simulating thousands different operating conditions which might actually happen during a year, some Load Flow calculations have been performed[12], to describe some deterministic snapshots representative of particular situations.
This analysis is aimed at highlighting some possible critical conditions which might require special countermeasures during the real time operation, and at identifying power exchanges between countries in these situations, looking at the way how countries support each other.
For this reason, four conditions have been selected among the thousands analysed in the probabilistic simulations by GRARE, characterized by:

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

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

5.1 High load and high VRES production

In this paragraph a situation with high load and high renewable production is presented: in particular, in the selected case the total load of the system is about 28.4 GW and the VRES generation is nearly 6.8 GW, divided in the different countries according to Table 96. In this condition, hydro power plants supply more than 55% of the load.

Table 96 - Load and VRES production in high load and high VRES production snapshot

COUNTRY	Load [MW]	PV production [MW]	Wind production [MW]
COLOMBIA	12,090	1,200	1,540
ECUADOR	6,130	920	380
PERU	10,180	1,960	790
TOTAL	**28,400**	**4,080**	**2,710**

Figure 24 shows the power production of each country and the power exchanges between them, resulting from the Load Flow calculations. In the Table 97 the power exchanges are summarized.

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

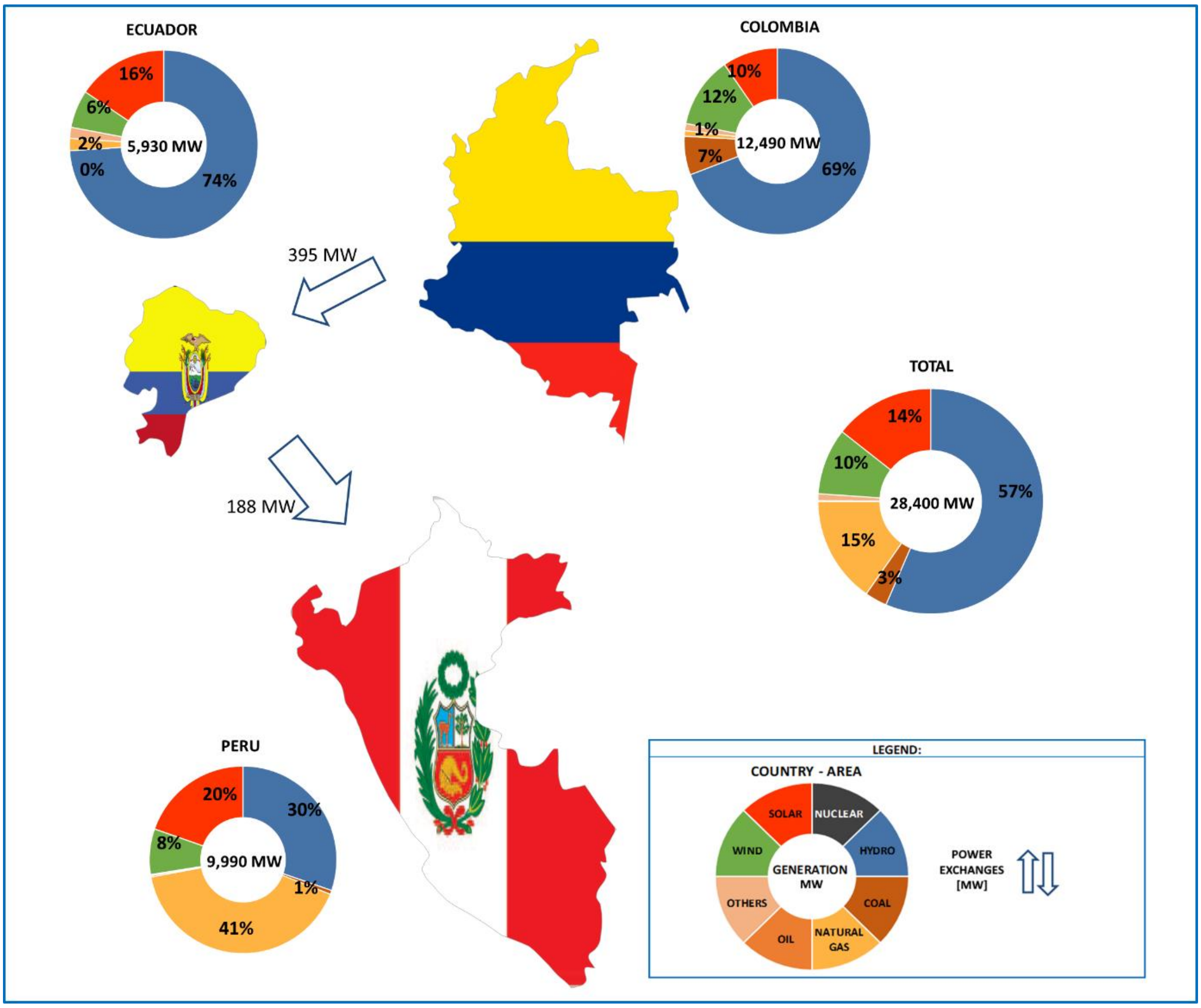

Figure 24 - Static Analysis - Power production and power exchanges with high load and high VRES production

As expected, no line is overloaded in sound network condition, as the active power dispatching is obtained by the GRARE optimization which already considered the network constraints.
The power exchanges between areas are reported also in the following Table 97.
It is worth underlining that between Colombia and Ecuador the NTC value (equal to 395 MW) is reached.

Table 97 - Power exchanges between countries in high load and high VRES production snapshot

From	To	[MW]
Colombia	Ecuador	395
Ecuador	Peru	188

5.2 High load and low VRES production

In this paragraph, the result of the Load Flow calculation performed on a situation with high load and low VRES production is presented. The value of load is a bit higher than 29 GW and the renewable production is around 1 GW, distributed among technologies and countries according the values reported in Table 98. In this situation, hydro power plants supply more than 70% of the demand in the system.

Table 98 - Load and VRES production in high load and low VRES production snapshot

COUNTRY	Load [MW]	PV production [MW]	Wind production [MW]
COLOMBIA	12,140	170	150
ECUADOR	6,360	0	190
PERU	10,570	0	540
TOTAL	**29,070**	**170**	**880**

Figure 25 shows the power production of each country and the power exchanges between them, resulting from the Load Flow calculations. Power exchanges are reported also in Table 99. It is interesting to note that the direction of the flows has changed with respect to the previous case, because in cases in which the VRES production is limited, thermal generation by coal power plants and subsidized natural gas in Peru increase their importance.

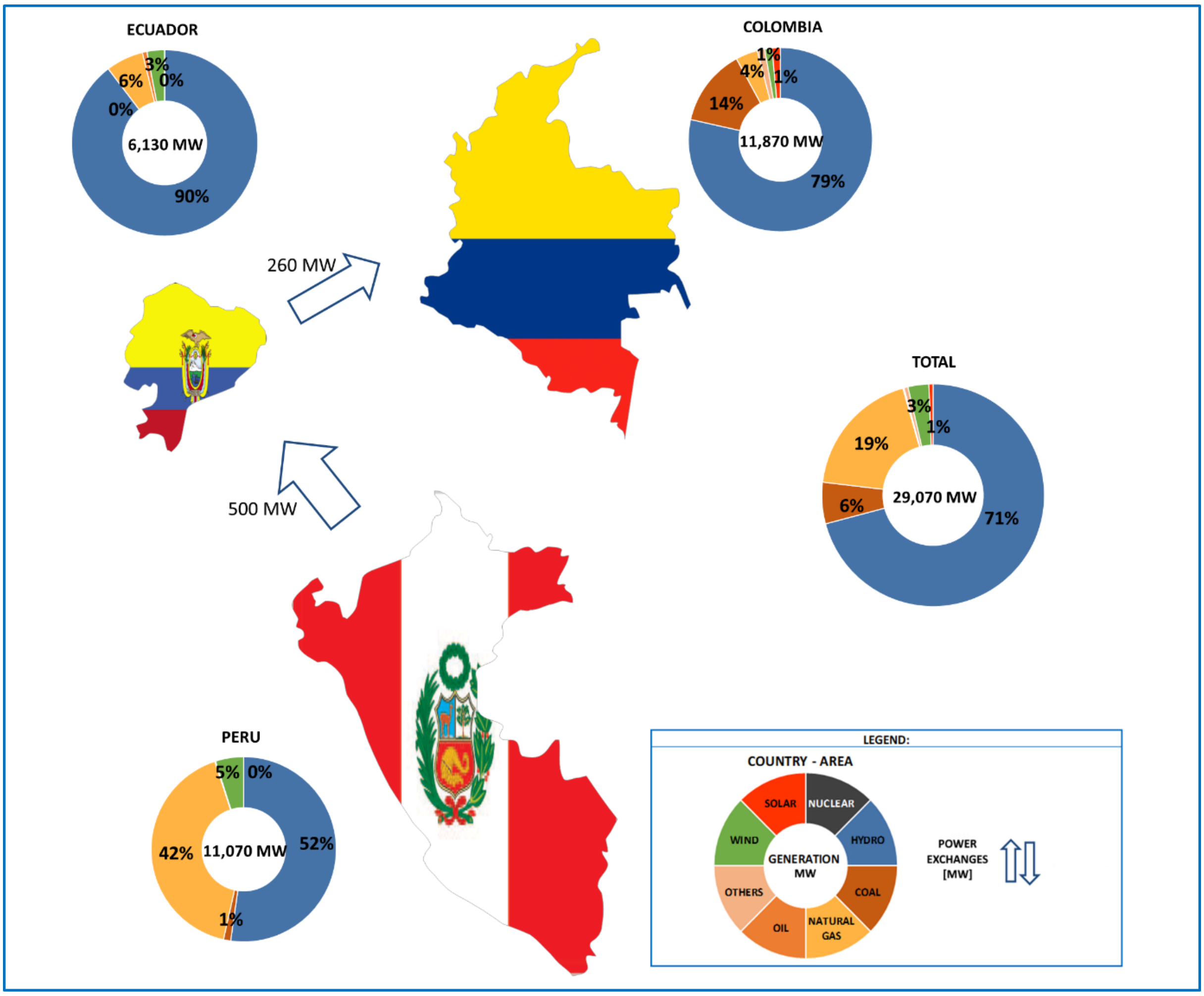

Figure 25 - Static Analysis - Power production and power exchanges with high load and low VRES production

Table 99 - Power exchanges between countries in high load and low VRES production snapshot

From	To	[MW]
Ecuador	Colombia	260
Peru	Ecuador	500

5.3 Low load and high VRES production

As a third case, the system was analysed with low load and high VRES production: in particular the selected condition is characterized by a load around 22 GW and the value of renewable production is 7 GW, covering nearly one third of the demand. Hydropower production supplies about 45% of the load. The distribution of the load and VRES production is listed in Table 100.

Table 100 - Load and VRES production in low load and high VRES production snapshot

COUNTRY	Load [MW]	PV production [MW]	Wind production [MW]
COLOMBIA	8,180	690	2,620
ECUADOR	4,900	1,020	390
PERU	8,890	1,800	530
TOTAL	**21,970**	**3,510**	**3,540**

Figure 26 shows the power production of each country and the power exchanges between them, also summarized in Table 101, resulting from the Load Flow calculations.

It is interesting to note that Ecuador imports power both from Colombia and Peru, limiting the production of hydropower plants because in low load conditions it is convenient to use energy produced by coal and natural gas plants in other countries and keep hydro resource available for conditions with higher demand and expected higher costs.

Moreover, the power exchange between Colombia and Ecuador reaches the NTC value equal to 395 MW.

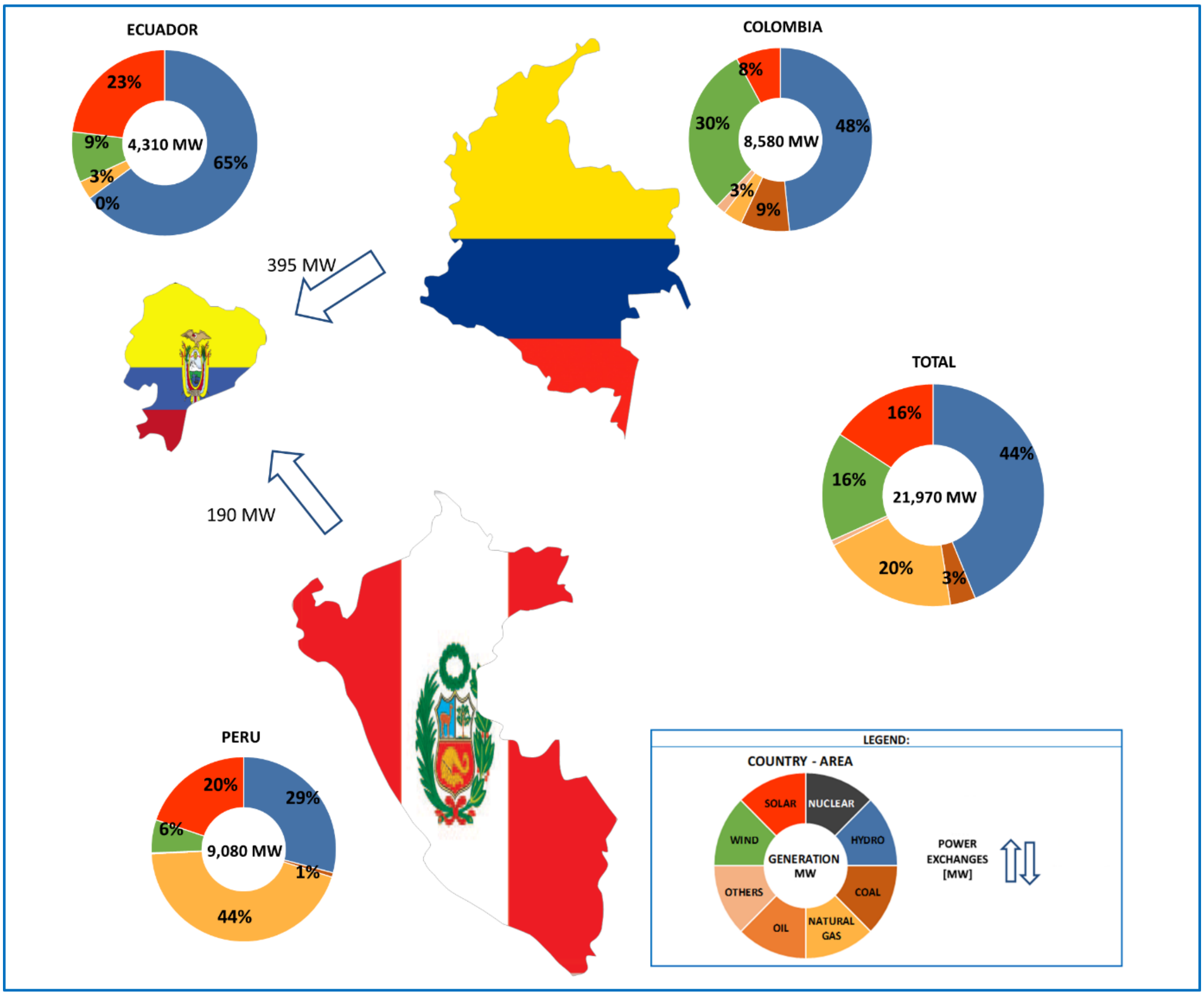

Figure 26 - Static Analysis - Power production and power exchanges with low load and high VRES production

Table 101 - Power exchanges between countries in low load and high VRES production snapshot

From	To	[MW]
Colombia	Ecuador	395
Peru	Ecuador	190

5.4 Low load and low VRES production

The last snapshot is characterized by low load and low renewable production: in particular the value of load is a bit higher than 22 GW and the value of renewable production is 1.3 GW, less than 6% of the demand. In this case, hydro power plants cover two thirds of the total load.

As it is possible to see in Table 102, which reports the distribution of load and VRES production in the countries, the selected condition corresponds to an operation of the system in the night, with no PV production.

Table 102 - Load and VRES production in low load and low VRES production snapshot

COUNTRY	Load [MW]	PV production [MW]	Wind production [MW]
COLOMBIA	9,440	0	590
ECUADOR	4,500	0	80
PERU	8,280	0	620
TOTAL	**22,220**	**0**	**1,290**

The power exchanges between the different countries in this condition are the ones reported in Figure 27 and Table 103.

With respect to the situation with low load and high VRES production, it is possible to note that the usage of thermal plants remains similar (the main difference is some higher coal generation in Colombia, while in Peru the high share of NG plants remains aligned). The lower generation by VRES, which pass from more than 30% to about 6% of the demand) is mainly compensated by a higher production by hydropower plants, increased from 44% to 67%.

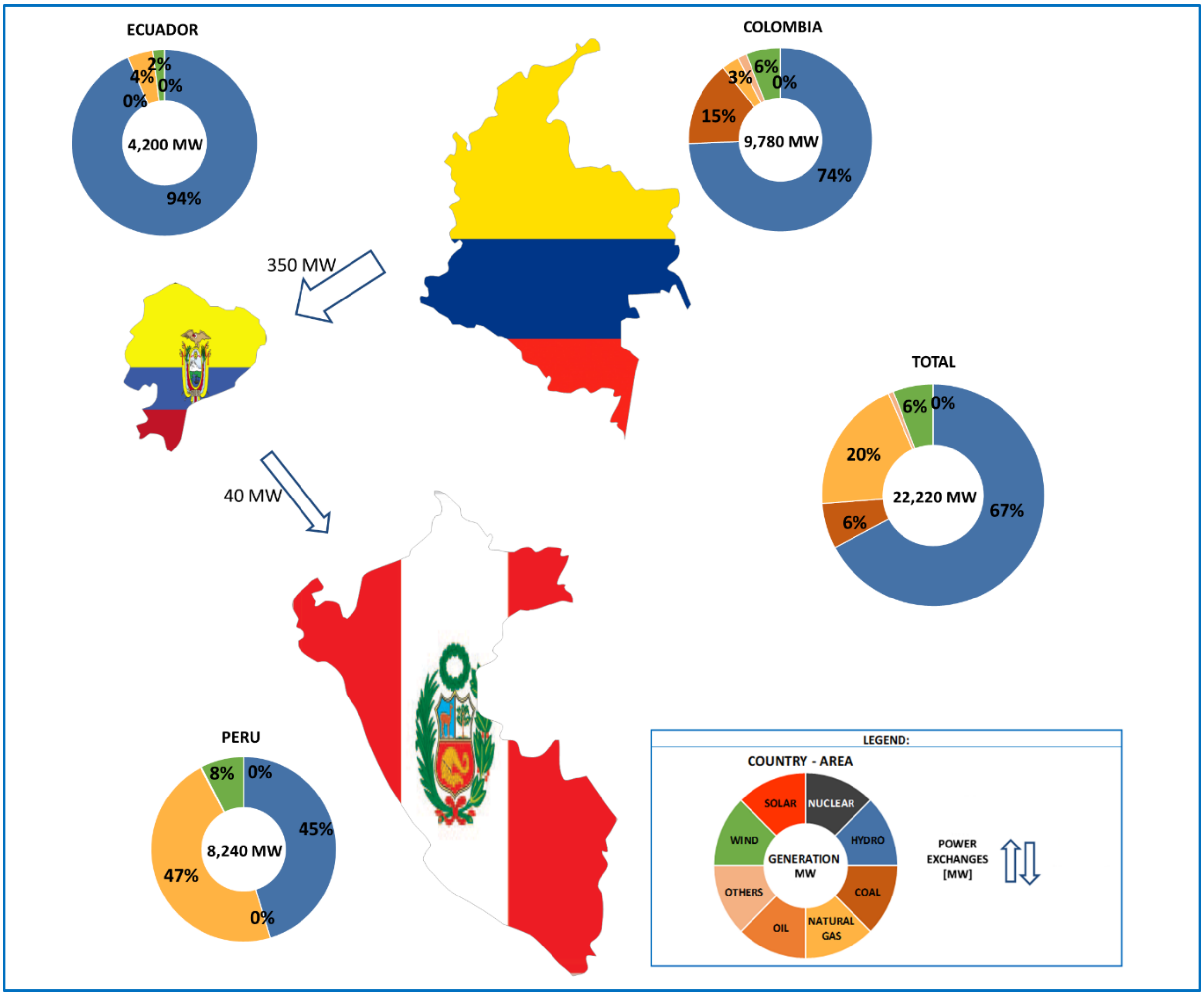

Figure 27 - Static Analysis - Power production and power exchanges with low load and low VRES production

Table 103 - Power exchanges between countries in low load and low VRES production snapshot

From	To	[MW]
Colombia	Ecuador	350
Ecuador	Peru	40

5.5 Conclusions on Load Flows analysis

Four snapshots have been presented with different levels of demand and VRES production.

Power exchanges between countries are strongly influenced by these factors and by the amount of energy produced by hydropower plants.

In line with the results obtained in the probabilistic analysis, the exchanges between Colombia and Ecuador take place mainly from the first to the second, and reach the NTC limit in conditions in which VRES production is high. In fact, thanks to the contribution of PV and wind plants, Colombia becomes often a net exporter due also to the high availability of hydropower resource and the presence of cheap coal plants.

The energy exchanges between Peru and Ecuador are more related to the value of the thermal load (that is the load that must be supplied by thermal power plans different form must-run units) in the system, as Peru is the country with the highest share of traditional power plants. In general, it is expected that when thermal load is high, as in the case with high load and low VRES generation, Peru exports more power to the North, but the actual exchange depends also on the usage of hydropower plants.

In other conditions, the flow between the two countries may vary with different levels in both directions, each time resulting from load level, VRES production and the optimal usage of hydro and thermal power plants.

6 CONCLUSIONS

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

The analysis carried out in the present study aimed at assessing the optimal amount of VRES plants which can be installed and operated in the year 2030 in Colombia, Ecuador and Peru (Base Case) considered in a first step as isolated systems and secondly evaluating the advantages which are present when the systems are interconnected thanks to the existing and planned electrical paths. With a conservative approach, no externalities are considered for thermal generation, and the assessment is based mainly on fuel costs. If additional costs were applied to take into account GHG emissions and pollutions (which can derive for instance from the introduction of carbon tax, as it happens in Colombia [5], or other carbon pricing mechanisms which are under study in different countries), the cost of thermal generation would increase, and consequently also the benefits achieved by replacing thermal production with VRES. In this condition, the optimal economic amount of VRES to be installed in the systems might reach higher values, as there would be convenience to have more VRES generation, also accepting higher curtailments.
In order to increase the penetration of PV and wind plants in the systems, some system operational constraints, such as reserve needs and inertia, have been loosened, assuming that new VRES technologies can actively support the system, sharing the burden usually assigned only to the plants traditionally classified as dispatchable. In particular, storage systems have been allocated to new installed VRES plants, aimed at mitigating the variability of their production, which negatively affects the operation of the electric power system, and providing required ancillary services.

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

- In Colombia, the installation of 2,400 MW of PV and 2,700 MW of wind power plants, plus storage systems for about 200 MW represents the optimal economic amount of VRES. These values are respectively about 1,300 MW and about 1,400 MW higher than the amount foreseen in the assumed reference scenario 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 introduce some minimum power constraints on the generation.
  Even with the flexibility ensured by hydropower plants with reservoirs, when the VRES installed power increases significantly some overgeneration conditions appear in the expected operation of the system, requiring the curtailment of new VRES generation and increasing the relevant LCOE. The calculated amount of curtailed energy (more than 600 GWh, corresponding to more than 7% of the production of the additional plants) still represent 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, the optimal solution consists in the installation of 1,750 MW PV and 2,050 MW wind, located in the south area with highest potential and then exploiting also regions with lower wind resource. An amount of 280 MW of storage has been also introduced, mainly used to reduce the overgeneration conditions, which are the main technical issue due to the particular generation mix in the Ecuadorian system, strongly dependent on hydropower plants. The VRES installed power is quite high notwithstanding the lower availability of solar and wind resource in this country with respect to the other analysed ones, and the main reason is related to the high costs of thermal generation, which mainly uses liquid fuel in power plants with low efficiency. Even if VRES in general have low equivalent hours, they are convenient against expensive thermal generation, and it is even convenient to accept high share of production curtailments (up to 20% of the energy generated by the additional power plants).

  PV and wind plants in this optimal configuration cover about 12% of the load, and VRES become the second source after hydro.

  Due to the strong dependency of the power system on hydro resource, it suffers low adequacy in dry hydrological conditions, when the energy available from hydro reduces by 20%. For this reason, a new dispatchable power plant has been introduced in the generation fleet, which ensures the availability of additional energy to cover the load. It has been modelled as a CCGT, but also an additional hydropower plant might be possible, provided that in dry conditions is able to ensure the required level of energy.
- 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 Reference scenario, the generation fleet and the transmission system correspond to the committed projects at 2024 while the load has been increased at the 2030 level. 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) and there is also the need for some limited network reinforcements necessary for the load supply.

  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 disappear 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, that means higher cost of electricity produced from that source, VRES become even more attractive, as they would replace more expensive generation, and the new optimal values would become 4 GW both for PV and wind. In this case some network reinforcements in the South area are necessary, aimed at reducing the congestions on 220 kV lines caused by PV and control the power flows on the 500 kV lines for an optimal evacuation of the produced power. If only limited reinforcements are put in place, it is convenient to install only 3 GW of PV.

Once the optimal solutions for each isolated country have been defined, the analysis has been focused on the operation of the interconnected system, assuming the NTCs defined in [1].

The possibility to exchange energy between the countries brings significant benefits (more than USD 300 million) to the system: the overgeneration conditions are strongly reduced and the curtailments of VRES plants decrease by 80%, mainly in Ecuador. This contributes, together with the better

optimization of the cheap generation fleet to lower thermal generation costs and to further improvement of already good system adequacy. To exploit the benefits during the real operation, 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.
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 the best. Improvements of the NTCs are expected to give no significant benefits as would improve the operation of the system only in the limited periods in which the exchanges are constrained.
It has been simulated the operation of the system with additional investments in VRES plants in Colombia and Peru, countries with the highest potentials. With the assumption that no externalities are considered for thermal power plants, it turns out that the introduction of additional VRES plants provides limited benefits to the system due to two opposite effects: in fact the interconnections allow a better exploitation of the resources (and this improves the room for VRES) but at the same time they make them competing against cheaper generation, made available also from other countries, thus reducing the economic advantage the VRES plants introduce in the system. In this case, the amount of VRES plants defined as optimal for the isolated countries results to be the optimal condition also for the interconnected systems.
However, it is worth recalling here that in the analysis no externalities or additional costs on thermal generation have been assumed and the assessment was based mainly on fuel costs. If some cost increase were applied to energy produced with fossil fuel (e.g. carbon tax or other mechanisms currently under analysis in some of the countries [5]), the economic advantages brought by the introduction of VRES would be higher, and the optimal installed power would probably move towards higher values.

The following Table 104 shows the final amount of installed PV and wind power in the different countries, and the corresponding production.
In this scenario, Colombia is a net exporter of about 2 TWh, while Ecuador and Peru have a more bidirectional energy exchange which varies along the different periods of the year depending on the typical hydrological conditions, and Peru is a net importer of about 800 GWh (almost 1% of the internal demand).

Table 104 - Total VRES installed capacity and production in final optimal scenario for COL, ECU, PER 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	4.1
ECUADOR	1,750	2,050	3,800	2.7	4.5	2.7
PERU	2,750	1,700	4,450	6.2	7.0	6.2
TOTAL	6,900	6,450	13,350	13.0	23.6	13.0

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 or changing the available generation fleet simulating the operation without some investments in new cheap plants.

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

As already mentioned, already during the analysis of the isolated country it was necessary to introduce an additional dispatchable generator in Ecuador to ensure a good adequacy in case of scarcity of hydro resource. In the dry scenario, all the countries maintain a good adequacy thanks to the availability of thermal generation which can replace missing hydro production. Generation costs increase dramatically due to the usage of more expensive plants necessary to avoid high EENS. In these conditions, overgeneration does not happen, and VRES plants are not curtailed anymore for this cause, but 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.

On the contrary, in the wet conditions there is plenty of hydro resource, which causes more frequent overgeneration conditions, with consequent risk of curtailments of VRES and hydro productions. Moreover, also the transmission system is more loaded, and the system becomes less flexible, as the reservoirs in some cases can be used less than before because more filled with the additional water.

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. The impact on the whole profitability of the plants is lower, as wet years happen only few times in the lifetime, but it is important to highlight this possible risk.

The last sensitivity was built based on the consideration that with the introduction of additional VRES plants, less thermal generation is necessary and some planned investments on new future plants and on upgrade of existing ones might be avoided. The thermal generation fleet has been then 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 keeping two big plants in south of Peru in the today configuration, with OCGT with liquid fuel and no switch to CCGT. The results showed still a good adequacy, meaning that in 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 detected, as cheap generators have been removed: this cost increase might create further room for additional VRES plants as they would replace more expensive generation than before, or might be also the reason for the decision to invest in the analysed plants, even if not technically needed, but just for economic reasons.

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

In the first one, the demand increases by 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 one for the system and introduce constraints in periods of high VRES availability.
The second Variant considers a lower demand as a result of slower economic growth and energy efficiency improvements, keeping the same generation fleet of the Base Case, as defined in the available development plans. Due to the reduction of the load and the availability of a significant generation fleet, the introduction of additional VRES plants results less attractive, as more than 2/3 of the total demand is already covered by production by hydro and VRES would replace very cheap thermal generation (mainly coal in Colombia and Natural Gas in Peru, kept low also because subsidized). The results show that a total amount of 4,000 MW PV and 3,400 MW wind is possible. The plants are distributed mainly in Peru (where the final values do not differ significantly from the results of the Base Case) and in Colombia, especially for wind. Ecuador remains with a limited amount of VRES, due to the lower availability of resource.
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 to be considered, thanks to their competitive LCOE and to flexibility, modularity and relative celerity in the execution of the projects with respect to other technologies.

As a summary, the analysis carried out in the present study on the interconnected system constituted by 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 are able to play a significant role in the load coverage at 2030, avoiding the need of new thermal generation and possibly avoiding some investments. Planned transmission systems in the different countries do not represent a critical bottleneck for the development of VRES. The availability of huge amount of hydro resource, has a significant influence on the optimal VRES amount especially in Colombia, 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, especially in low load conditions, because of the possible overgeneration conditions and because VRES production would compete with generation without fuel costs.

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