ENERGY TRANSITION PATHWAYS IN SOUTH AMERICA

The Enel Foundation is supporting an IRENA project that aims to provide an energy system transition pathway for South America that comprises a detailed technology perspective focused on renewable energy but also on energy efficiency synergies and other important technologies and sector linkages to 2050. This brief details the data collection and data analyses[1] performed for Argentina, Bolivia (Plurinational State of), Chile, Paraguay and Peru to populate IRENA's toolkit FlexTool, which performs power system flexibility assessments based on national capacity investment plans and forecasts.

DATA COLLECTION AND ANALYSIS FOR **ARGENTINA**

KEY SOURCES OF DATA

The main sources of historical data analysed for Argentina are:

- Compañía Administradora del Mercado Eléctrico Mayorista S.A. (CAMMESA)
- Argentine government, Ministerio de Economía, Secretaria de Energía

Concerning future system development, the key source is the *Planeamiento Energético* from the Ministerio de Economía, Secretaria de Energía - specifically the Efficient Scenario.

Other relevant sources for current and expected electricity grid development are:

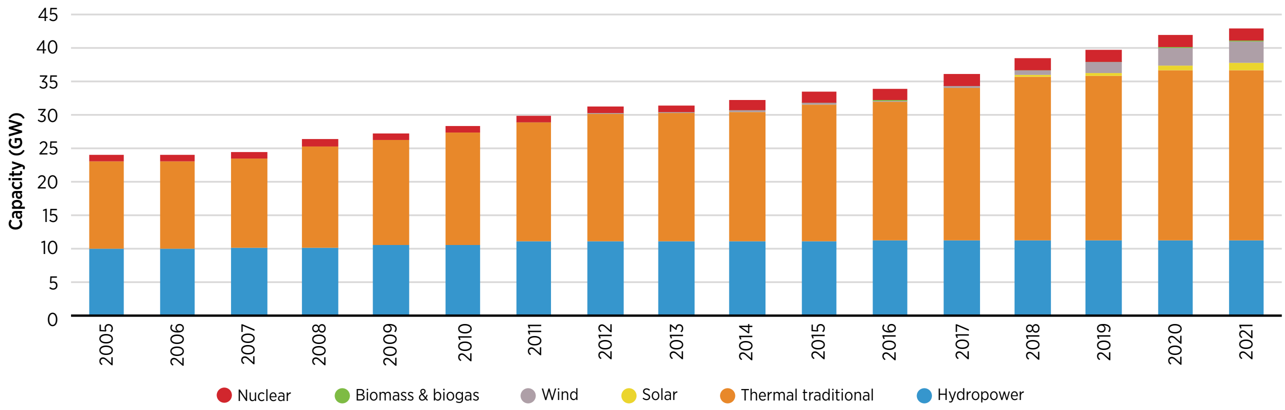
- El Consejo Federal de la Energía Eléctrica (CFEE)
- Compañía de Transporte de Energía Eléctrica en Alta Tensión (Transener)
- Research Series on VRES and grid interconnection in South America from Enel Foundation

HISTORICAL DATA

From 2005 to 2021 the total capacity installed in Argentina increased significantly (Figure 1). Nuclear capacity increased by 75% (from 1 gigawatts (GW) to around 1.8 GW); the total capacity from non-renewable traditional thermal power plants almost doubled (from 13 GW to 25 GW), with most capacity natural gas-fueled (22.3 GW in 2021, the rest being coal, with 0.5 GW and oil derivatives, with 2.6 GW). For renewables, wind and solar deployment began in 2011; in 2021, 3.3 GW of wind and 1.1 GW of solar were installed in the country, while biomass and biogas accounted for around 0.14 GW in 2021. Hydro remained fairly constant (rising from almost 10 GW to 11.3 GW); Table 1 shows the split of hydro capacity by type in 2021. Figure 2 shows the evolution of generation by source, illustrating the dominance of thermal generation, the variability of hydro, and the wind and solar presence in recent years.

1 *The preparation of this document benefited from technical advisory provided by CESI S.p.A., including data collection, assessment and analysis.*

Figure 1 Evolution of installed capacity in Argentina



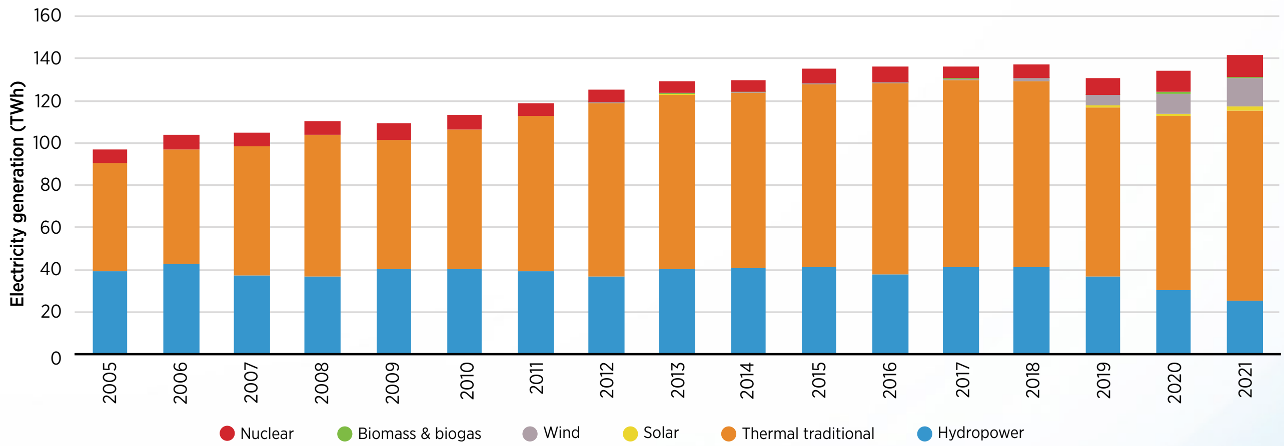
Based on: CAMMESA statistical data.
Note: GW = gigawatt

Table 1 Hydro power plants by type in Argentina in 2021

HYDRO	MEGAWATTS (MW)
Pumped storage	974
Reservoir	6 993
Run of River	3 379
TOTAL	**11 345**

Based on: CAMMESA statistical data.

Figure 2 Evolution of electricity generation by source in Argentina



Based on: CAMMESA statistical data.
Note: TWh = terawatt hour

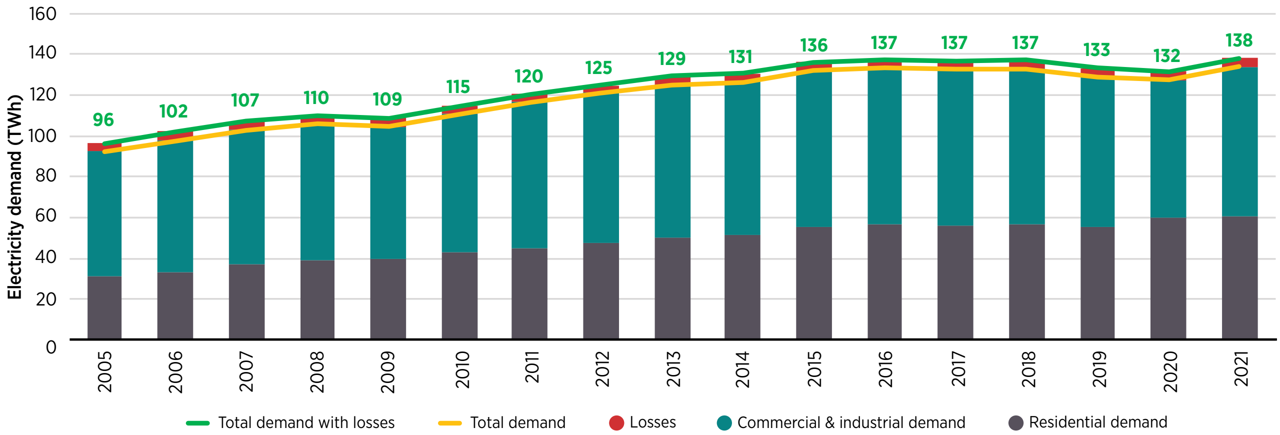
Categorised by fuel type, the traditional thermal power plants are then classified according to specific technology types[1], with different related technical specifications and costs.

For hydro power plants, hourly and monthly historical generation data, and key characteristics in terms of type/technology available from CAMMESA, have been combined to define a consistent profile for hydro inflows (in terms of energy) for both run-of-river and reservoir power plants, as well as to define the total (energy) storage capacity of the reservoirs.

Total electricity demand in Argentina (Figure 3) takes into account transmission losses as well as net electricity imports from Brazil, Chile, Paraguay and Uruguay.

1 *Combined cycle (CC), motor-generator (MG), gas turbine (GT), steam turbine (ST).*

Figure 3 Evolution of electricity demand in Argentina

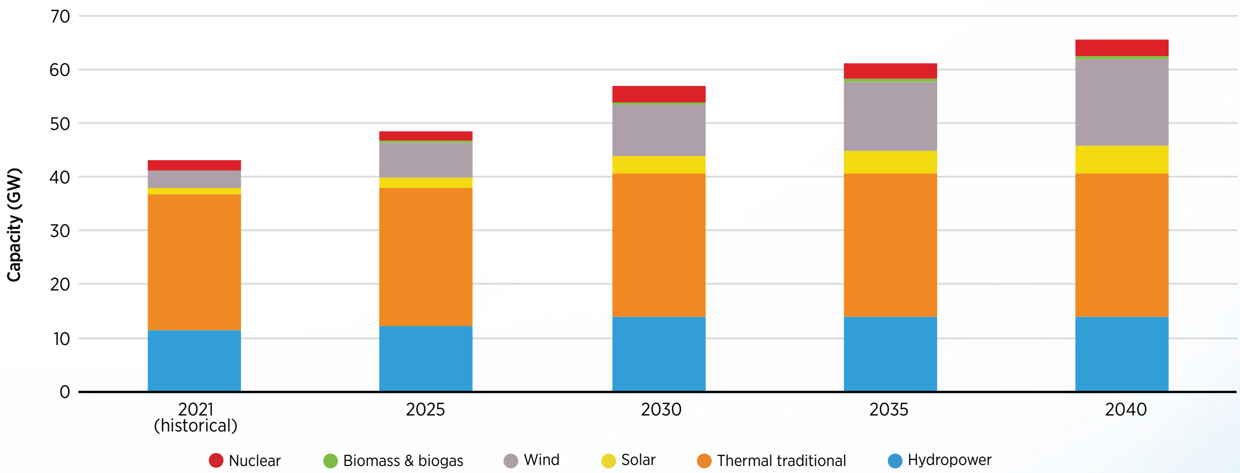


Based on: CAMMESA statistical data.
Note: TWh = terawatt hour

SCENARIO DATA

The *Planeamiento Energético* defines a complete power system scenario to 2030, while for the period from 2030 to 2040, some specific conservative assumptions are defined (Figure 4). Total traditional thermal capacity will slightly increase from 2021 to 2030 and is then assumed to remain at that level until 2040; hydro generation will see the commissioning of new plants for 2.5 GW in the 2030 horizon, while no new capacity is expected in the longer term; for nuclear, commissioning of an additional 1.2 GW is expected through 2030. Meanwhile, solar and wind installed capacity is expected to significantly increase (+200%) from 2021 to 2030 and is assumed to continue rising at the same pace thereafter.

Figure 4 Forecast data on installed capacity in Argentina (2021: historical data)



Based on: CAMMESA statistical data and planeamiento energético (energy planning) from the Ministerio de Economía.
Note: GW = gigawatt

The total demand (Table 2) is expected to significantly increase up to 2030 (2.1% compound annual growth rate) and is then assumed to keep on growing at the same rate up to 2040.

Table 2 Electricity demand in Argetina

YEAR	TOTAL DEMAND (TWH)
2021	138.2
2025	149.8
2030	165.9
2035	183.8
2040	203.5

Based on: CAMMESA statistical data and planeamiento energético (energy planning) from the Ministerio de Economía.

OTHER SPECIFIC ASSUMPTIONS

The hourly generation profiles for PV and wind in p.u. have been elaborated on the basis of IRENA data. For solar PV the profiles with the highest producibility (PV class I) - and for wind, an average between wind onshore class II and III - are taken into consideration to provide for the calculation of total generation in 2021. Biomass and biogas profiles have been assumed flat (constant in MW per hour, each hour of the year).

For primary frequency regulation requirements, the optimal percentage of primary reserve regulation determined by CAMMESA is equal to 3% of the dispatched capacity of the generation units qualified to perform it (hydro power plants - excluding pumped storage - and traditional thermal power plants). This 3% is therefore applied to all the existing traditional thermal and hydro power generation plants. The required reserve for secondary frequency regulation is 2.1% of the dispatched capacity of the generation units enabled to perform it, which is specific to hydro power plants with reservoirs, amounting for c. 78% of the total capacity of this specific technology available in Argentina.

For fuel costs, the scenario document provides information on natural gas and oil-based fuels, yet no data is reported for coal, which is assumed to have the same price as in 2021. Based on historical data, it was also possible to include the cost of transport to the power plant in the total fuel cost (Table 2). After 2030, the same prices are maintained.

Table 3 Fuel costs in Argentina: Historical and scenario

USD/MWh	FUEL + TRANSPORT - 2021	FUEL + TRANSPORT - 2030
Natural gas	20.7	36.1
Fuel oil	28.7	47
Diesel oil	33.8	53.1
Coal	38	57.2
2040	41.2	60.1

Based on: CAMMESA statistical data and planeamiento energético (energy planning) from the Ministerio de Economía.

Finally, regarding transmission capacity, the Enel Foundation “Research Series on VRES and grid interconnection in South America” is the key source of data and information on the internal grid and interconnections. For the internal grid, the country can be divided into three main areas, with limited transmission capacity in between them (North East and Center – NEC; North West – NWE; Patagonia – PAT), together with some foreseen developments based on Transener data and the *Planeamiento Energético*. In terms of international links, Argentina is connected with Brazil (600 MW available in 2021; 3 000 MW from 2030 onward), Uruguay (500 MW available in 2021, 2 000 MW from 2030 onward), Chile (200 MW available in 2021, 850 MW from 2030 onward), Paraguay (no capacity data for this interconnection) and Bolivia (120 MW available from 2025).

CONCLUSIONS

Official national sources provide detailed descriptions of the current power system of the country, while the official scenario from the Government provides a good overview up to 2030, with some data gaps for certain variables. The electricity generation mix in Argentina is mainly based on natural gas-fueled and hydro power plants, with some solar and wind, and one nuclear power plant. In the future, the role of solar and wind will increase; but, as electricity demand is projected to increase at a significant annual rate, natural gas generation will remain very relevant and a new nuclear power plant will be commissioned, as will some new hydro capacity.

DATA COLLECTION AND ANALYSIS FOR **BOLIVIA**

KEY SOURCES OF DATA

The main sources of historical data analysed for Bolivia are:

- Comité Nacional de Despacho de Carga (CNDC)
- Autoridad de Fiscalización de Electricidad y Tecnología Nuclear (AETN)
- Empresa Nacional de Electricidad (ENDE)

The Empresa Nacional de Electricidad (ENDE) is also considered for the information regarding existing power plants and future developments in generation and transmission systems.

Other data for current and expected electricity grid development have been obtained from CESI internal references and elaborations.

HISTORICAL DATA

The power system of Bolivia is divided into the Sistema Interconectado Nacional (SIN) [National Interconnected System]; Sistemas Aislados (SA) [Isolated Systems]; and some Autoproductores [self-producers] that are kept separate from the SIN in the official statistics of the country. Until late 2022, when a line between Bolivia and Argentina was completed, no interconnections with other countries existed.

The current analysis focuses mainly on the SIN (Figure 1), which represents the bulk of the Bolivian power system.

Table 1 Installed capacity in the SIN and SA, including self-producers

TECHNOLOGY	INSTALLED CAPACITY (SIN), MW	INSTALLED CAPACITY (SA+SELF), MW
Hydropower	758	1
Thermal traditional	2 644	279
Wind	129	0
Solar	166	6
Biomass	25	128
TOTAL	**3 722**	**414**

From 2006 to 2021, total power plant capacity installed in the SIN tripled, increasing from 1 205 MW to 3 722 MW. Thermal plants account for the highest share of power across the entire timeframe, which rose from 708 MW in 2006 to 2 644 MW in 2021. Table 2 shows the breakdown by type and technology in 2021. Hydro has an important role, with 758 MW (498 MW in 2006) divided into run-of-river plants and reservoir plants in Table 3. In recent years, renewables have begun to play an increasing role in installed power generation in the country; the first 25 MW of biomass power was installed in 2007 and remained constant up to 2021. For wind energy, the first installations date back to 2013 (27 MW), with capacity rising to 129 MW in 2021. The first solar plant was installed in 2017 and total capacity reached 166 MW in 2021.

Table 2 Thermal traditional power plants per type and fuel in Bolivia in 2021

THERMAL TRADITIONAL	2021 (MW)
Natural gas – gas turbine	1 027.4
Natural gas – combined cycle gas turbine	1 577.3
Diesel – motor generator	38.4
TOTAL	**2 643.6**

Based on: CNDC and AETN data.

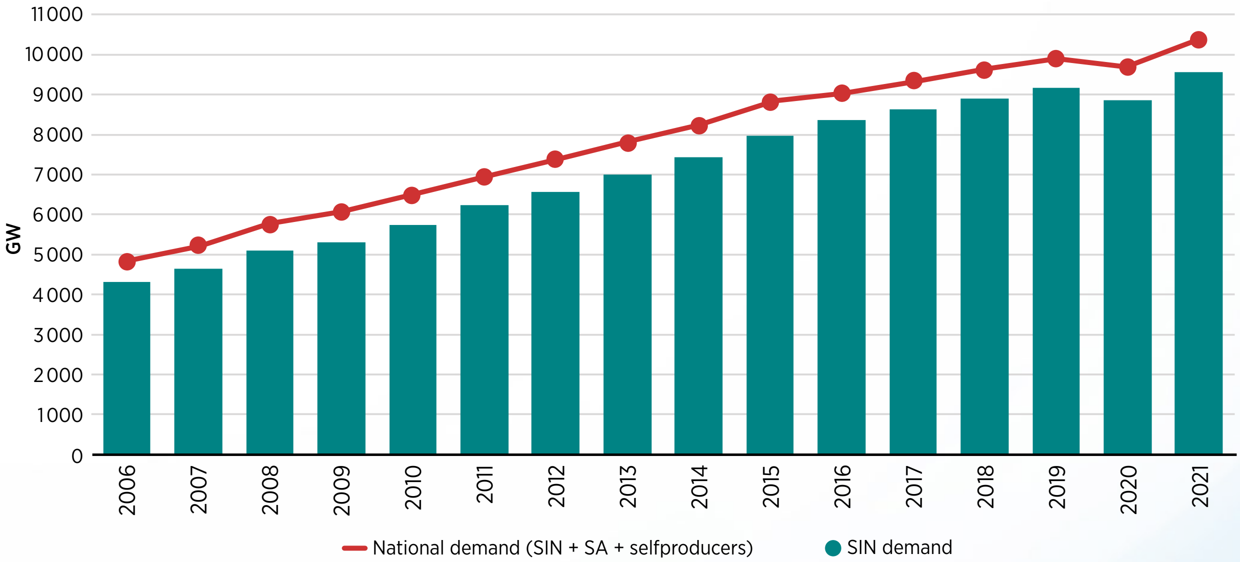
Table 3 Hydro power plants per type in Bolivia in 2021

HYDROPOWER	2021 (MW)
Reservoir	532
Run of River	226
TOTAL	**758**

Based on: CNDC and AETN data.

The total electricity demand of the country (Figure 2) considers the sum of the total net generation of all national generators and net electricity imports (null up to 2021).

Figure 1 Evolution of electricity demand in Bolivia



Source: CESI elaboration on CNDC data.

CNDC also published a historical hourly profile of "total demand" - which, based on the available data for 2021, corresponds to the total gross generation of the SIN. This 2021 profile has been scaled down to match the total net generation and applied both to the historical and scenario inputs for the IRENA FlexTool.

SCENARIO DATA

Owing to a lack of information, the data on the scenario are based on CESI internal references, elaborations and knowledge of the Bolivian power system.

According to the CNDC "Memoria Anual 2021", the gradual integration of the SA into the SIN has been considered.

CESI elaborations take into account the hydro potential of the country, proposing a generation capacity evolution that foresees the commissioning of several new hydro power plants between 2030 and 2040 (table 4) that are already under study.

Table 4 Total installed capacity (MW) from solar PV, wind and biomass in 2021, and in the scenario, in Bolivia (SIN)

YEAR	HYDRO RUN OF RIVER	HYDRO RESERVOIR
2021	532	226
2025	532	226
2030	737	425
2035	737	1565
2040	797	1966

For other renewables (Table 5), CESI elaborations remain quite conservative in terms of solar PV and wind development in the country. Regarding biomass, CESI foresees a total of 75 MW (at the 2040 horizon) of capacity added in the future.

Table 5 Total installed capacity (MW) from solar PV, wind and biomass in 2021, and in the scenario, in Bolivia (SIN)

YEAR	SOLAR	WIND	BIOMASS
2021	166	129	25
2025	193	172	44
2030	219	215	63
2035	245	258	82
2040	272	301	100

Regarding thermal power plants, a steady capacity compared to 2021 is foreseen, with increases coming only from the partial integration of the SA plants. Moreover, an increase in the efficiency of the existing plants has been considered in the long term.

Table 6 Total thermal installed capacity (MW) in 2021, and in the scenario, in Bolivia (SIN)

YEAR	GT	CCGT	MG
2021	1027	1577	39
2025	1027	1577	39
2030	1049	1577	64
2035	1070	1577	90
2040	1070	1577	90

According to government announcements, as well as CESI internal references, Bolivia has significant potential to export electricity to Argentina and Brazil; but since such potential interconnections are yet to be included in the government's plans - and there is very limited information available about them - they are not included in the reference scenario. If the interconnections with other countries were established, they would provide opportunities to better exploit the hydro potential of the country.

Electricity demand in the scenario is based on the CNDC "Memoria Anual 2021", which provides a forecast up to 2032 and includes gradual integration of isolated systems in the SIN. For the period 2032-2040, the same growth rate (4%) is assumed, and total demand in 2040 reaches 20 259 GWh. Table 7 reports the resultant demand trend from 2021 to 2040.

Table 7 Electricity demand in the scenarios for Bolivia

YEAR	TOTAL DEMAND (GWH)
2021	9 557
2025	11 195
2030	13 642
2035	16 625
2040	20 259

Based on: CNDC data.

OTHER SPECIFIC ASSUMPTIONS

For each of the renewable energy plants, a different approach has been used to assess the hourly profile:

- **Solar and wind:** assessment of the hourly profile through an open-source tool, using the plant location as input.
- **Biomass:** The hourly generation curves for biomass power plants are based on the monthly generation per power plant data from CNDC.
- **Hydro RoR:** Combining all the available information it was possible to define a consistent profile for hydro inflows. The hourly inflow profile for 2021 is based on the hourly generation profiles of some run -of-river hydro power plants, adjusted to consider the total monthly generation profile.
- **Hydro reservoir:** For reservoir power plants, the hourly inflow profile is based on average monthly values considering the 2021 data.

For the hydro profiles, a flow rate analysis has been performed to identify the years with the driest seasons and those with significant variances in order to provide additional scenarios to the FlexTool.

Regarding the reserves, the spinning reserve margin is applied individually to the effective capacity of each generating unit. The latest documentation available related to the amount of spinning reserve is calculated to 2017.

The final outcomes may be summarised as follows:

- The spinning reserve for the period November 2017 to October 2018 shall be 7%, 8% and 10%, for the High, Medium and Low blocks of demand, respectively.
- Hydro units must have a primary reserve of 4% and thermal units of 6%.
- For the scenario, the requirements for the spinning reserve are increased by 0.5%.

Bolivia is a natural gas producer and has a fossil fuel subsidy system resulting in low electricity prices compared to other countries. Regarding scenario prices, the reference scenario as elaborated by CESI adopts a conservative hypothesis of prices in line with current values (2022). All the prices are listed in Table 8.

CONCLUSIONS

Official national sources provide a good description of the current power system of the country. For the projections, internal elaborations, references and knowledge from CESI were required to compensate for the lack of data. The electricity generation mix of Bolivia is mainly based on natural gas-fueled thermal power plants and hydro power plants, with some solar, wind and biomass in recent years. In the future, the role of hydro will increase; eventually the SA will be integrated in the SIN, leading to an increase in demand. Generation expansion planning in Bolivia will be influenced by its envisaged role as an exporter to Argentina and Brazil.

Table 8 Fuel costs in Bolivia, historical and scenario

YEAR	NATURAL GAS PRICS		DIESEL PRICE	
	USD / MMBTU	USD / MWh	USD / l	USD / MWh
2022	1.22	4.15	0.50	50.2
2025	1.22	4.15	0.50	50.2
2030	1.22	4.15	0.50	50.2
2035	1.22	4.15	0.50	50.2
2040	1.22	4.15	0.50	50.2

Based on: CNDC statistical data.

DATA COLLECTION AND ANALYSIS FOR **CHILE**

KEY SOURCES OF DATA

The main sources of historical data analysed for Chile are:

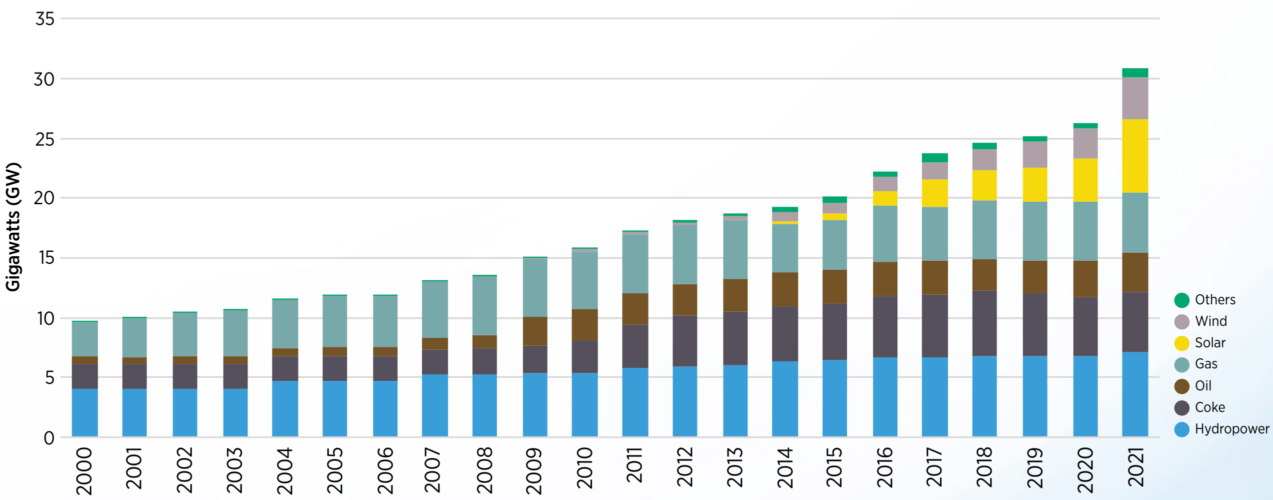
- Coordinador Eléctrico Nacional (CEN)
- Comisión Nacional de Energía (CNE)
- Ministerio de Energía (MINEM)
- Energía Abierta BETA

Concerning the development of the system in the future there are two main sources: PELP (Planificación Energética de Largo Plazo) released by MINEM and the transmission system planning released by Coordinador Eléctrico Nacional (CEN).

HISTORICAL DATA

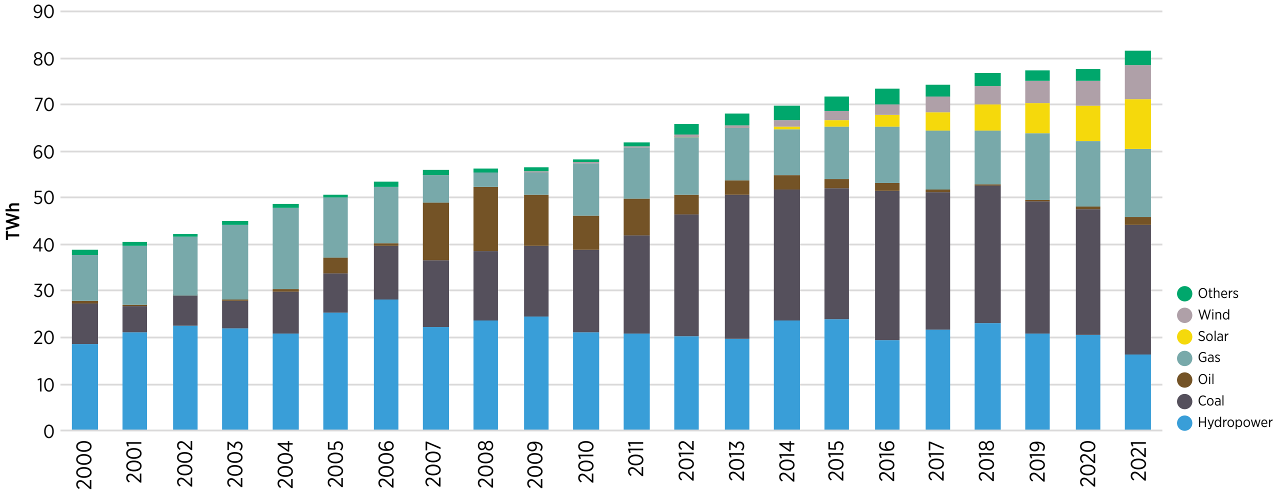
From 2000 to 2021 the total capacity installed in Chile tripled, and all energy sources increased substantially. Starting from the 2010s, investments in solar and wind resources have also been made, and today renewable capacity makes up around 56% of the total installed capacity (Figure 1). In terms of energy quantities, coke still makes up more than one third of total electricity generation, and overall non-renewable thermal generation represents more than half of the total. Hydro also has a very prominent share (20% in 2021), but its weight has been decreasing due to the increase in generation from other sources (Figure 2).

Figure 1 Evolution of installed capacity in Chile



Based on: CEN statistical data.
Note: Others = geothermal, biomass, co-generation.

Figure 2 Evolution of electricity generation by source in Chile



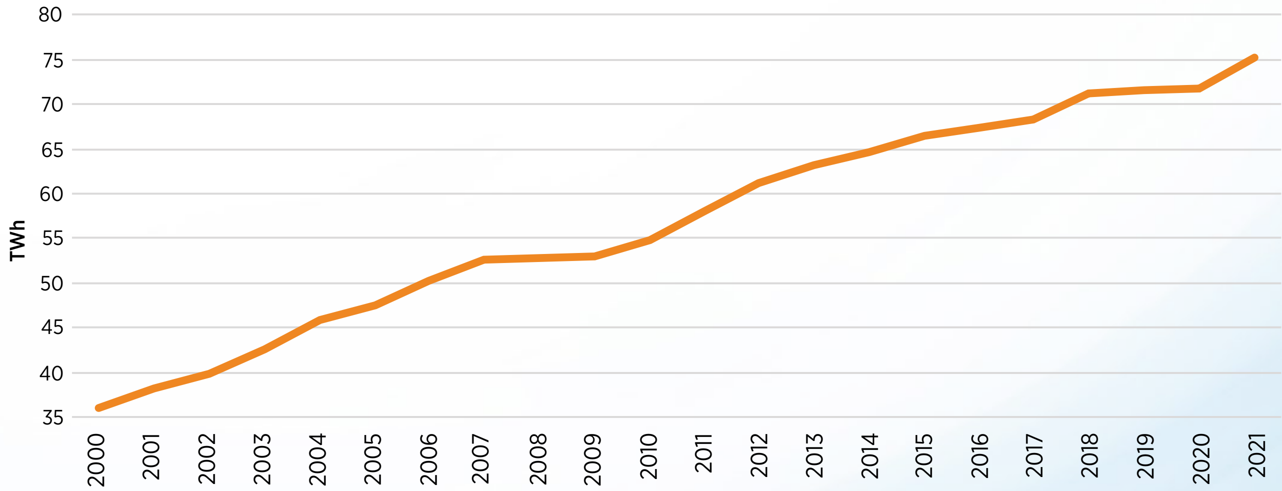
Based on: CEN statistical data.

The power plants per fuel are then classified according to specific technology types[1], with different related technical specifications and costs.

For hydro power plants only the ones that can control the generation with a high degree of flexibility were classified as "reservoir". The inflows for these power plants are based on the available historical data on a monthly basis. For "run-of-river" power plants the generation profile is based on the latest historical hourly available data and total annual energy inflow on the average generation of the last 10 years.

The electricity demand, based on sold energy data, also reported a very strong increase from 2000 to 2021 (Figure 3). These values refer to the net demand, while the demand for FlexTool also includes the losses and is in line with the total generation.

Figure 3 Evolution of the total electricity sold in Chile



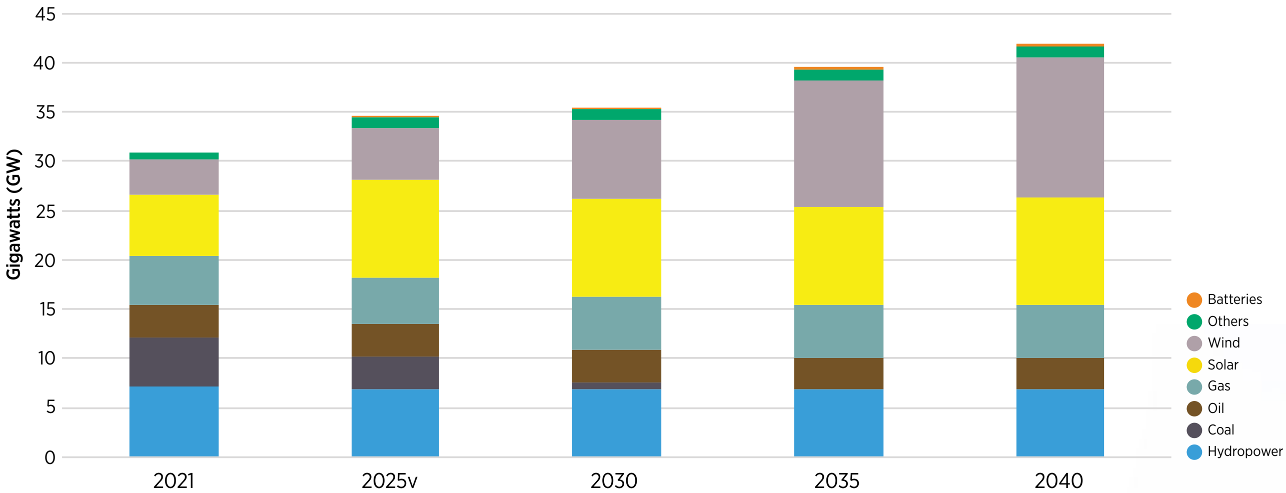
Based on: CEN statistical data

[1] *Hydro (run of river, reservoir), natural gas (CC, GT, MG), coke (TV coke), oil (GT, MG, ST), other thermal (biomass MG, biomass ST, petcoke ST, biogas MG, cogeneration ST), wind, solar (PV, CSP), geothermal, batteries.*

SCENARIO DATA

Based on the available scenario data, for the target years of the analysis (2025, 2030, 2035, 2040), a progressive and complete phase-out of the coke power plants was assumed. In the meantime, the solar and wind installed capacity is expected to significantly increase, while other sources will remain quite stable over time (Figure 4).[2]

Figure 4 Forecast data on installed capacity in Chile (2021: historical data)



Based on: CEN data from Informe de resultados escenarios de generación 2021 (Report on results for generation scenarios 2021).

Total national electricity generation is expected to see a significant increase of 45% between 2021 and 2040, equal to a 2.0% compound annual growth rate (Table 1).

Table 1 Forecast data on total generation in Chile (2021: historical data)

YEAR	TOTAL GENERATION - TWH
2021	81.5
2025	93.8
2030	101.4
2035	108.6
2040	118.3

Based on: CEN data from “Proyección de Demanda del SEN, periodo 2021-2041”.

OTHER SPECIFIC ASSUMPTIONS

The hourly generation profile of renewables, PV and wind hourly curves (per unit [p.u.]) have been elaborated on the basis of IRENA data. For solar PV the profiles with the highest producibility (PV class I) and for wind the profiles of the second class of plants (Wind class II) are taken into consideration. For 2021 real data are used for both wind and solar. Biomass, biogas, cogeneration and geothermal hourly curves have been obtained, starting from the 2021 actual generation data.

[2] For the power system scenario, we considered the more conservative estimates provided by CEN (Transmission System Operator) instead of the PELP pathway of the Ministry of Energy and Mines.

For the load frequency control, both the requirements for primary and secondary reserves have been considered and modeled at hourly level, according to the methodology published by CEN. The methodology considers the reference incident (disconnection of a 400 MW generation unit) for primary, and the uncertainties applied to load, PV and wind for secondary.

For fuel costs the PELP documents provide detailed information about the current and scenario prices (Table 2), while CEN documents provide data on the investment costs (USD/kW), variable non-fuel costs (USD/MWh) and fixed costs (% of investment costs) per technology.

Table 2 Fuel costs in Chile, historical and scenario, USD/MWh

YEAR	FUEL OIL	DIESEL	NGL	COAL
2021	20.7	36.1	23.9	6.5
2025	28.7	47	27	6
2030	33.8	53.1	28.8	5.8
2035	38	57.2	29.8	5.9
2040	41.2	60.1	29.8	6.1

Based on: CESI elaboration on MINEM data from "Informe preliminare of PELP – 2023 – 2027".

Finally, for interconnections, the retrieved data show that: between Chile and Argentina there is one 600 MW existing line, and one new future line of 1000 MW is planned; while between Chile and Peru[3] there are two future asynchronous lines of up to 200 MW and 1000 MW (per unit [p.u.]), respectively. Currently the energy flows between Chile and Argentina are almost null, and no scenario data is available for expected international flows.

CONCLUSIONS

The official national sources for Chile provide all the necessary data for a comprehensive description of the power system of the country and its expected evolution according to the Government. Today, Chile has a fairly diverse electricity generation mix, but although renewables are increasing quickly, they are not keeping pace with demand growth, so fossil generation remains highly relevant. According to the scenario data, renewable capacity will increase substantially on the 2040 horizon; on the other hand, thermal generation (from natural gas and oil) will remain relevant due to projected demand growth but will be progressively decommissioned.

[3] *Which are operated at different nominal frequencies.*

DATA COLLECTION AND ANALYSIS FOR **PARAGUAY**

KEY SOURCES OF DATA

The main sources of historical data analysed for Paraguay are:

- Administración Nacional de Electricidad
- Viceministerio de Minas y Energía - MOPC, Paraguay

Other countries' databases have been used to obtain useful data about the bi-national power plants that are shared with Brazil and Argentina.

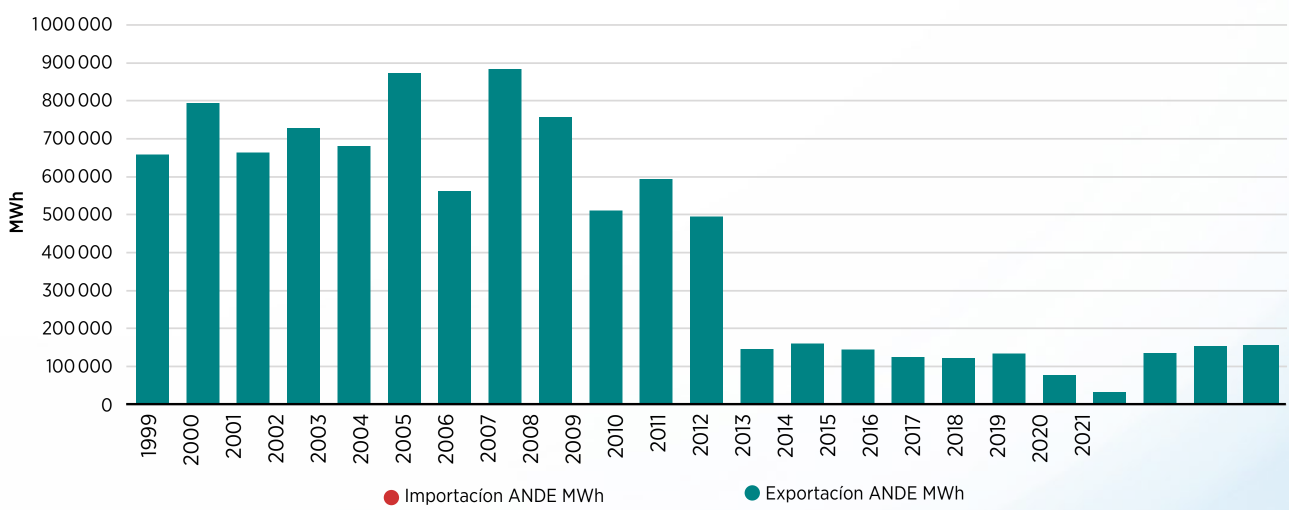
Other data for current and expected electricity grid developments have been obtained from CESI internal references and elaborations.

HISTORICAL DATA

Today, the interconnected power system of Paraguay comprises six regions and three main lines (Figure 1).

The country has interconnections with Brazil and Argentina, of 7 000 MW (ITAIPU) and 1 680 MW (YACYRETA, EDEFOR and EMSA), respectively. The interconnections allow Paraguay to export energy to these countries, given that its imports was minimal from 1999 to 2008 and ceased entirely thereafter (up to 2021). An overview of export flows is shown in Figure 2.

Figure 1 Annual import and export of Paraguay with Argentina and Brazil



In terms of total installed capacity, almost all energy production in Paraguay is provided by hydro plants. In December 2021, the government disconnected the last thermal power plant making Paraguay the only country with 100% clean and renewable electricity generation.

Table 1 Evolution of installed capacity by source/technology in Paraguay

YEAR	THERMAL TRADITIONAL	YACYRETÁ (HYDRO)	ITAIPU (HYDRO)	ACARAY (HYDRO)
2012	6	1600	7 000	210
2013	54	1600	7 000	210
2014	54	1600	7 000	210
2015	54	1600	7 000	210
2016	40	1600	7 000	210
2017	40	1600	7 000	210
2018	40	1600	7 000	210
2019	23	1600	7 000	210
2020	23	1600	7 000	210
2021	23	1600	7 000	210

Based on: ANDE data.

Following the three hydro plants have been studied and their data analysed to obtain a correct model for the FlexTool:

- **Itaipu:** Binational hydro power plant shared between Brazil and Paraguay, located on the Paranà river; assumed as a run-of-river plant. Hourly profile calculated through CESI elaboration on ONS hourly data.
- **Yacyreta:** Binational hydro power plant shared between Argentina and Paraguay located on the Paranà river; assumed as a run-of-river plant. Hourly profile obtained from CESI elaboration from Paranà river data and comparison with Itaipu profile.
- **Acaray:** Hydro reservoir power plant located on the Acaray river and owned by ANDE. Its monthly profile, available from VMME, is used in the FlexTool model.

The monthly production data for 2021 of the three power plants are summarised in Table 2:

Table 2 Monthly hydro plant production per power plant for 2021

MONTH	MONTHLY PROFILES OF HYDRO PLANTS PER FOR 2021		
	ITAIPU	YACYRETÁ	ACARAY
	MWh	MWh	MWh
January	1 264 731	339 539	150 014
February	1 421 215	123 290	68 818
March	1 540 971	180 459	41 981
April	1 257 390	133 987	43 175
May	1 111 543	114 737	81 387
June	1 122 229	138 711	35 397
July	1 167 023	143 461	22 737
August	1 227 876	145 940	16 022
September	1 207 127	292 558	20 921
October	1 138 513	333 041	58 639
November	1 516 866	157 076	43 943
December	1 820 246	210 908	40 020

As part of the modeling of binational entities to correctly simulate the trading of energy from one country to another, a study of the treaties that regulate the management of plants was required. The trading of energy between the countries concerned - both in the case of Itaipu and Yacyreta - is as follows:

1. Both countries are entitled to 50% of the plant's production.
2. The power of the plant is assigned to both countries through a contract. Both countries pay for the contracted power obtained under treaty arrangements.
3. If a the contracted power of a country exceeds 50% of the total, remuneration on the surplus is due to the other country; this is fixed by agreement.

Regarding the FlexTool model for the Base scenario of the Binational Hydro plants, the average contracted power for 2021 (1 635 MW for Itaipu and 455 MW for Yacyreta) has been considered as the capacity.

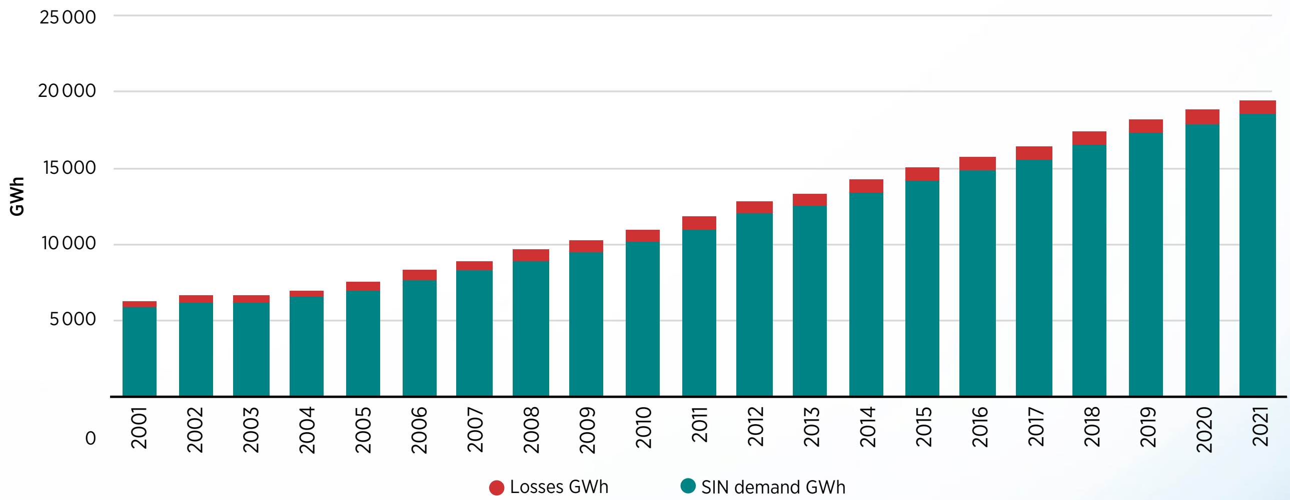
The conditions for contracted power acquisition and for remuneration for the surplus in 2021 are detailed in Table 3.

Table 3 Cost and remuneration prices for energy trading in Binational entities

TREATY CONDITIONS FOR 2021	ITAIPU	YACYRETA
Contracted Power	22.6 USD/kW	22.6 USD/MWh
Remuneration for the surplus	11.7 USD/MWh	3.0 USD/MWh

The total electricity demand of the country (Figure 3) considers the sum of the total net generation of all national generators and net electricity imports (zero as of 2021).

Figure 2 Evolution of the electricity demand in Paraguay



Based on: ANDE data.

The article, "Distribution level electric current consumption and meteorological data set of the east region of Paraguay", provides a dataset with hourly load profiles from 2017 to 2020 related to 55 feeders distributed in 14 substations in the Alto Paranà region. The profile for 2019 has been scaled to match total net generation and applied both to the historical and scenario inputs for the FlexTool.

SCENARIO DATA

The scenario data are based on the "Plan Maestro de Generacion 2021-2040" published by ANDE, which provides two scenarios for the evolution of the Paraguayan energy system:

1. A scenario based only on the projects planned by ANDE to evolve the energy generation system
2. A scenario that considers also the future installation of the two binational hydro plants of Itati- Itatora and Corpus Christi

Considering the lack of information regarding the Binational projects, which lie beyond ANDE's authority, the FlexTool model has been based on the first scenario, based on which an increase in total cumulative installed capacity in 2040 is estimated at 9 711 MW (hydro power plants), 1 600 MW (solar power plants) and 1 776 MW (battery banks). Table 4 provides a breakdown by type and technology of the installed power, together with some additional data.

Table 4 Power plants installed in the scenario

TECHNOLOGY	NUMBER OF PLANTS	INFO ON THE SINGLE PLANT
PVH **Hybrid-photovoltaic off grid plants**	8	PV panels 685 kWp, Inverter 125 kW, Battery bank 2 520 kWh
PCH **Small hydro plant**	19	-
CH **Run-of-river hydroelectric power station**	2	-
PV **Photovoltaic Plant**	3	PV panels 100 000 kWp Battery bank 44 000 kWh
Batt **Battery bank with Li-Ion batteries**	12	100 MW-400 MWh

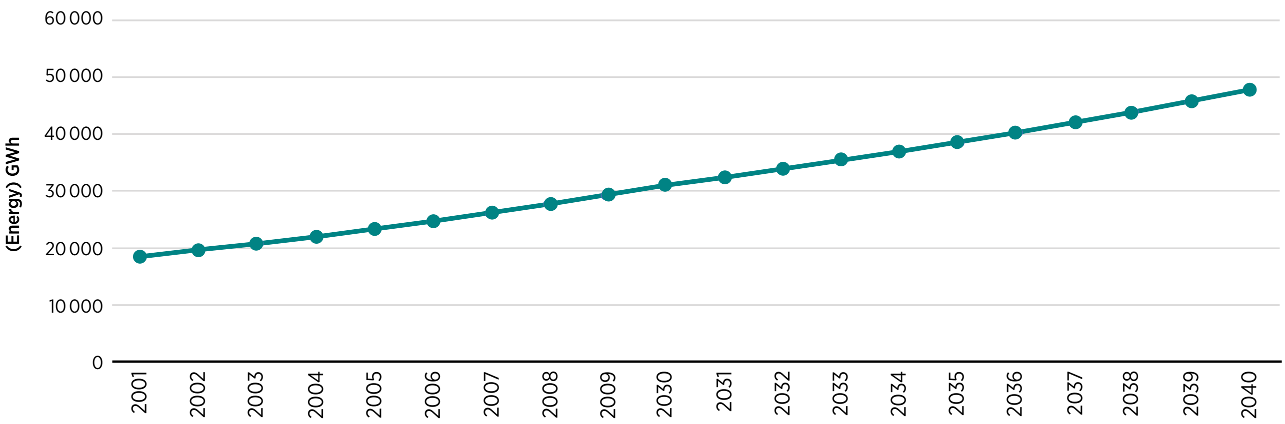
Source: "Plan Maestro de Generacion 2021-2040" ANDE.

Some hypotheses regarding the new plants in the FlexTool model:

- PVH plants have not been included since they will be installed in off-grid systems, isolated from the SIN, without clear information on their future interconnection. Their capacity is, in any case, smaller than the other plants and hence negligible.
- Two different units have been created to include the total PV power and the total battery power installed; the latter includes both the power installed in the battery banks and installed as storage in the PV plants.
- Small Hydro plants (PCH) and Hydro plants (CH) have been aggregated in two separate additional units.

Finally, the evolution of demand has been calculated considering the same profile obtained for the Base scenario, increasing the demand to an annual growth rate of 5.9% in 2021-2030 and 4.4% in 2031-2040, in accordance with the "Plan Maestro".

Figure 3 Demand projection to 2040



Based on: ANDE data.

OTHER SPECIFIC ASSUMPTIONS

For each of the renewable energy plants a different approach has been used to assess the hourly profile for the scenario:

- **Solar:** assessment of the hourly profile through an open-source tool, using the plant location as input.
- **New hydro RoR:** The hourly inflow profiles for the plants in the FlexTool are constant and equal to the average energy output.
- **Old hydro RoR:** To create a baseline profile that is rescaled according to the scenarios, the average flow rates and production data for the years 2015-2021 have been used. An installed power equal to 50% of the total power has been considered for the binational entities.
- **Small hydro power plants:** Following an analysis of the precipitation trends in the area of installation of the plants, the hourly inflow profile of the plants located in the temperate area has been considered constant and equal to the average power output that has been programmed. Regarding the plants located in tropical areas, a monthly profile proportional to the precipitation trend has been considered, rescaled to obtain the average power output of the plant.
- **Hydro reservoir:** For reservoir power plants the hourly inflow profile is based on average monthly values considering the 2015-2021 data.

For the hydro profiles, a flow rate analysis has been performed to identify the years with the driest seasons and those with significant variation to provide additional scenarios for the FlexTool.

The "Plan Maestro de Generación" defines the concept of "reserve margin", which is considered the main technical criterion for a satisfactory generation plan. Given the lack of data on the distribution of the reserve between the plants, as a first approximation, the latter has been supposed as equally distributed between the existing plants, which conribute to the reserve by providing 10% of their available capacity. This approximation has been applied also to the scenario.

CONCLUSIONS

The official national sources provide a good description of the current power system of the country, while for the expected evolution, some internal elaborations, references and knowledge from CESI were required to compensate for the lack of data. The electricity generation mix of Paraguay is based on hydro power plants. In future, the role of hydro will increase alongside the introduction of PV power and battery banks to increase the flexibility of the system, satisfy the increasing demand, and meet the requests for exports to Argentina and Brazil.

DATA COLLECTION AND ANALYSIS FOR **PERU**

KEY SOURCES OF DATA

The main sources of historical data analysed for Peru are:

- Peru government, Ministerio de Energìa y Minas, MINEM
- Comité de Operación Económica del Sistema, COES
- Organismo Supervisor de la Inversión en Energía y Minería, OSINERGIMIN, for technical and regulatory aspects

Concerning the development of the system in the future, the key source is the Comité de Operación Económica del Sistema (COES), which publishes every two years a transmission expansion plan - the goal of which is to establish interventions on the SEIN grid for the following 10 years. In accordance with the aproach defined by IRENA, the average demand scenario with renewable-focused generation was selected.

HISTORICAL DATA

Today, the power system of Peru is divided into the Sistema Eléctrico Interconectado Nacional (SEIN) [National Interconnected System] and the Sistemas Aislados (SA) [Isolated Systems], which are not connected to the national grid and are classified into:

- Sistema Aislado Mayor (major isolated systems): yearly maximum power > 3 MW
- Sistema Aislado Menor (minor isolated systems): yearly maximum power ≤ 3 MW

The generators for the SEIN and SA can be subdivided into those that sell energy on the energy market and those that generate for self-consumption.

The operation and planning of the SEIN is supervised by COES, whose compulsory members (Integrantes Obligatorios) are all SEIN Agents that meet conditions for installed power/transmission length/contracted demand, while the operation of the isolated systems is supervised by OSINERGIMIN.

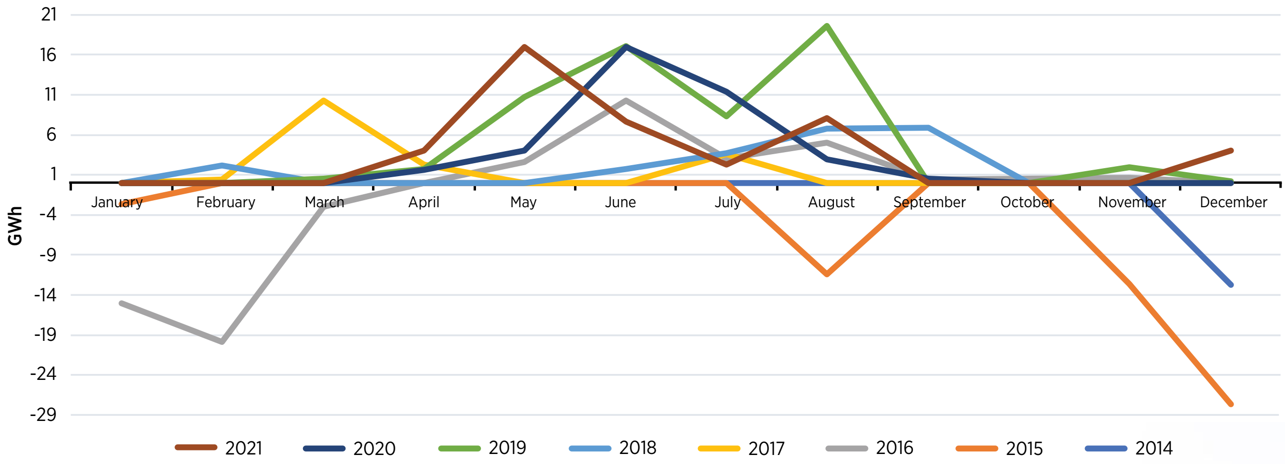
Table 1 Main indicators for the Peruvian energy system

2021 SYSTEM		INSTALLED CAPACITY [MW]	ENERGY PRODUCTION [GWH]
SEIN		**13 865**	**55 539**
Energy market	COES	13 279	54 018
	Not COES	341	1 034
Self-consumption	Not COES	244	487
Aislados		**1 476**	**1 858**
Energy market		241	486
Self-consumption		1 235	1 372
Total Nacional		**15 340**	**57 397**

As illustrated in Table 1, the COES system represents more than 95% of the total SEIN energy production and installed capacity. For this reason, the parameters of the FlexTool model are limited to the COES system, data for which is available with a greater level of detail.

Regarding the interconnections with other countries, Peru is connected to Ecuador, with a transfer capacity of 160 MW. The energy flows in 2014-2021 between the two countries are represented in Figure 1.

Figure 1 Monthly net imports from Ecuador to Peru



The evolution of the COES installed and effective capacity is reported in Tables 2 and 3.

Table 2 Evolution of Installed and effective capacity in COES (MW)

POWER [MW]	TOTAL INSTALLED	TOTAL EFFECTIVE	HYDRO EFFECTIVE	THERMAL EFFECTIVE	SOLAR EFFECTIVE	WIND EFFECTIVE
2010	6 759	6 475	3 098	3 365	0	0
2011	6 842	6 496	3 110	3 335	0	0
2012	7 620	7 116	3 140	3 897	80	0
2013	9 002	7 813	3 171	4 562	80	0
2014	9 311	8 747	3 312	5 164	96	146
2015	10 109	9 686	3 850	5 522	96	146
2016	12 575	12 079	4 858	6 881	96	243
2017	12 624	12 118	4 822	6 797	96	243
2018	13 002	12 608	4 942	6 979	285	375
2019	13 123	12 715	5 068	6 909	285	375
2020	13 181	12 756	5 079	6 931	285	412
2021	13 279	12 802	5 190	6 918	282	412

Table 3 Historical evolution of COES energy generation (GWh)

ENERGY [GWh]	HYDRO	THERMAL	SOLAR	WIND	TOTAL COES
2010	18 964	13 462	0	0	32 426
2011	20 404	14 813	0	0	35 217
2012	20 849	16 413	60	0	37 321
2013	21 129	18 344	197	0	39 669
2014	21 003	20 337	199	256	41 796
2015	22 456	21 262	231	591	44 540
2016	23 010	24 021	242	1 054	48 326
2017	27 741	19 898	288	1 065	48 993
2018	29 358	19 220	745	1 494	50 817
2019	30 168	20 313	762	1 646	52 889
2020	29 318	17 288	778	1 803	49 187
2021	30 664	20 723	802	1 801	53 990

As can be seen from the data, most of the installed power is in the form of thermal and hydroelectric plants, with a minority of wind and solar. The thermal capacity installed is divided as follows:

- Combined Cycle – CC
    - Diesel oil (0 MW)
    - Natural gas (3 355 MW)
- Motor-Generator – MG
    - Biogas (13 MW)
    - Diesel oil (138 MW)
    - Natural gas (23 MW)
- Gas Turbine – GT
    - Diesel oil (2 322 MW)
    - Natural gas (1203MW)
- Steam Turbine - ST
    - Bagasse (96 MW)
    - Coal (135 MW)
    - Residual 500 (68 MW)

From the COES website, the demand profile (Figure 3) has been elaborated to obtain an hourly base profile for 2021.

Figure 2 Evolution of maximum COES demand, 1995-2021

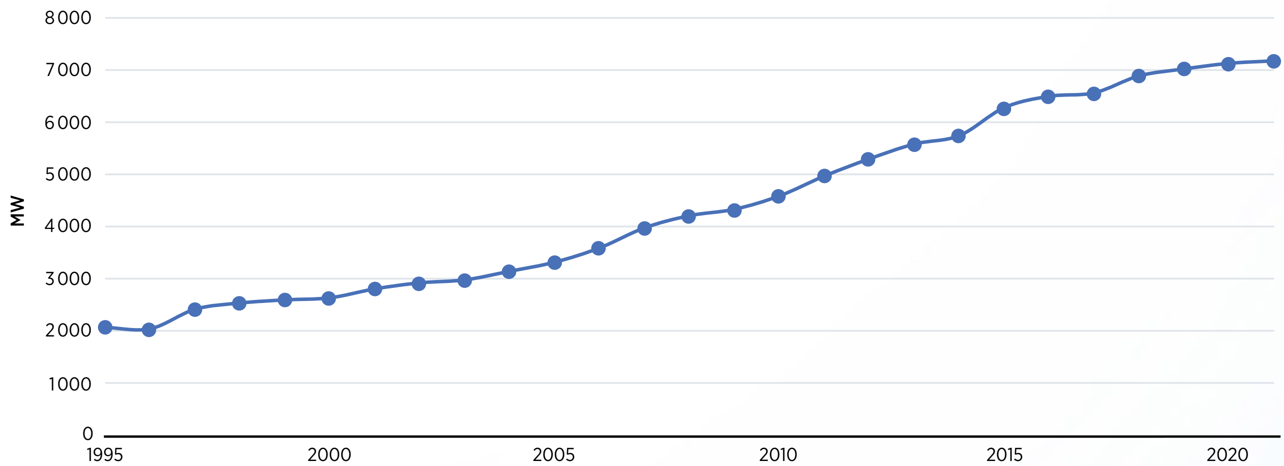
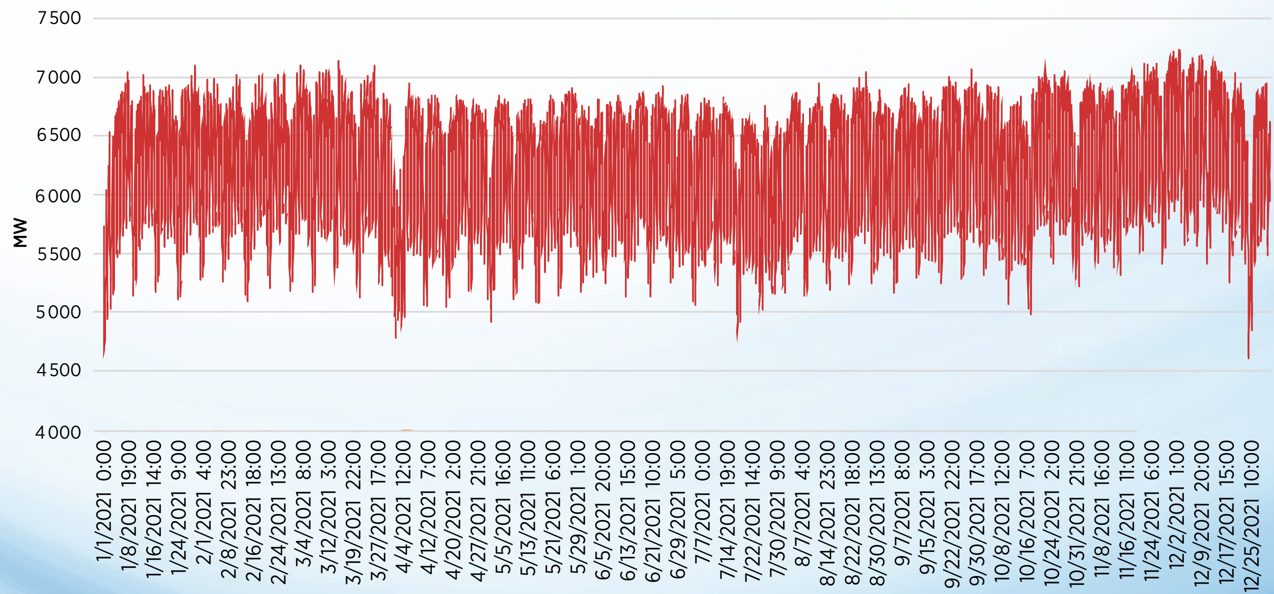


Figure 3 Hourly demand in the COES, 2021



SCENARIO DATA

The COES publishes a transmission expansion plan every two years, the goal of which is to establish the interventions on the SEIN grid for the following 10 years. The latest approved plan is the PLAN DE TRANSMISIÓN 2023-2032, which has been taken as a reference for the scenario data in the FlexTool model. The expansion plan reports several scenarios for load demand growth and generation expansion, with a target year of 2032, but also includes some analysis for 2037. IRENA suggested to select the average demand scenario with renewable-focused generation.

Considering the data available, the implementation of new transmission lines between Peru and Ecuador has been considered for the scenario.

Table 4 Peru-Ecuador interconnection capacity (MW)

INTERCONNECTION CAPACITY	ECUADOR TO PERU	PERU TO ECUADOR
2025	160	160
2030	600	650
2035	1 500	1 100
2040	1 500	1 100

The evolution of the installed capacity for the scenario is summarised below:

- The thermal plants' capacity decreases by 140 MW owing to the retirement of the coal thermal power plant of Ilo2, ENGIE ENERGIA PERU S.A (member of COES).
- The two hydropower plants of San Gabàn (209.3 MW) and Chilia (180 MW) will be members of COES and will be of reservoir type; they will be commissioned in 2023 and 2032, respectively.
- A total of five solar plants and nine wind plants will be commissioned between 2023 and 2032.

The evolution of the effective installed capacity is summarised in Table 5.

Table 5 Effective capacity of power plants, scenario years (MW)

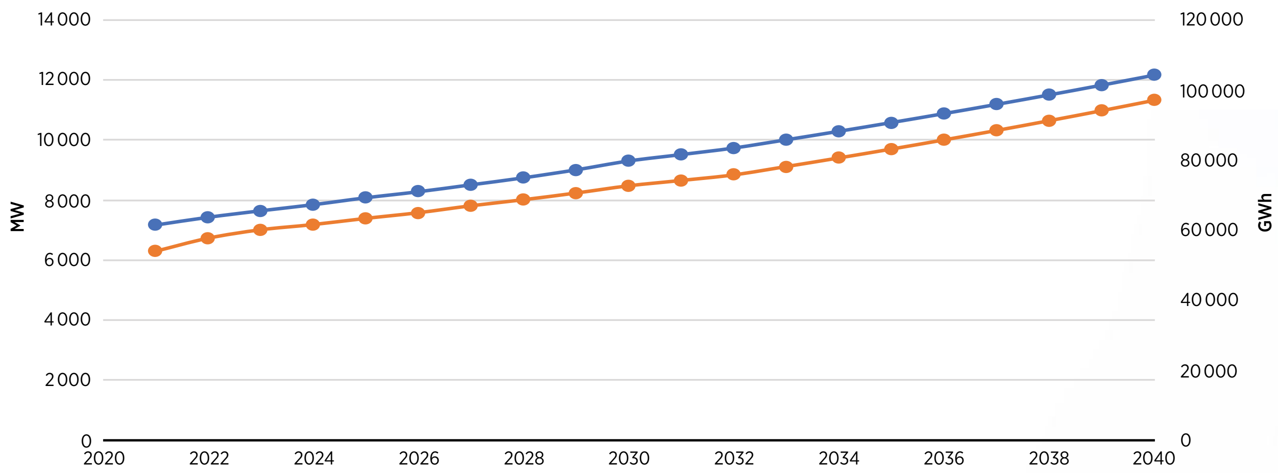
EFFECTIVE CAPACITY	2025	2030	2035	2040
Combined cycle - CC	**3 121**	**3 121**	**3 121**	**3 121**
Diesel oil	0	0	0	0
Natural gas	3 121	3 121	3 121	3 121
Motor-generator - MG	**136**	**136**	**136**	**136**
Biogas	12	12	12	12
Diesel oil	101	101	101	101
Natural gas	23	23	23	23
Gas turbine - GT	**3 405**	**3 405**	**3 405**	**3 405**
Diesel oil	2 257	2 257	2 257	2 257
Natural gas	1 148	1 148	1 148	1 148
Steam turbine - ST	**115**	**115**	**115**	**115**
Bagasse	54	54	54	54
Coal	0	0	0	0
Residual 500	61	61	61	61
Hydroelectric	**5 399**	**5 399**	**5 399**	**5 399**
Run of River	1 343	1 343	1 343	1 343
Reservoir	4 056	4 056	4 236	4 236
Solar	**397**	**697**	**1 247**	**1 247**
Wind	**838**	**1 338**	**1 888**	**1 888**
TOTAL	**13 411**	**14 211**	**15 491**	**15 491**

The energy demand scenarios are reported in the annexes to the transmission expansion plan. Four main demand categories are separately considered for predictions:

- Vegetative demand
- Special loads
- Big projects
- Incorporated loads

The demand projections are then rescaled to the COES level, removing the self-producers and adding losses to the system and the self-consumption of auxiliaries. The plan reports the demand growth up to 2032. For the following years, a constant increase equal to the average annual demand growth rate is assumed. The COES demand projection is shown in Figure 4.

Figure 4 Demand evolution in the scenario



The profile of demand in the scenario has been obtained by rescaling in accordance with the demand projection average of the profiles for 2019, 2021 and 2022, excluding 2020 owing to the influence of the pandemic on population habits.

OTHER SPECIFIC ASSUMPTIONS

The hourly generation profile for 2021 of solar, wind, biomass, biogas and run-of-river hydro capacity has been developed through the elaboration of the data from the COES website, with a 15-minute/quarter of an hour discretisation. For the elaboration of the reservoir hydro profile, the data have been organised to produce a monthly resolution profile. Concerning the scenarios, the profile for each source has been obtained per unit through the average of the profiles for 2019, 2021 and 2022.

During the data collection, data on the actual and future presence of BESS in the country have been recorded. From the information available:

- For the base scenario, the presence of the BESS Ventanilla (14 MW/7.8 MWh), owned by Enel Peru, has been examined. The power device is incorporated into the Ventanilla thermal power plant, with an effective power of 469.4 MW.
- For the future scenarios, the 30 MWh BESS project awarded in May 2022 to the group NHOA from Engie Energía Perú has been added. The storage system will be installed on-site at the 800 MW Chilca thermal power plant. The same ratio (power/capacity) of the BESS Ventanilla has been applied, adding 53.85 MW of installed power starting from 2025.

For primary frequency regulation requirements, the reserve margin is calculated every year by the COES and proposed to the Organismo Supervisor de la Inversión en Energía y Minería, OSINERGIMIN, which approves it. For 2022, it is equal to 2.8% of total demand. This is shared among the power plants, the economic dispatch of which is constrained and reduced to take into account the reserve margin as a percentage of the maximum effective capacity. Given the lack of data in the future scenarios, they consider the same reserve margin.

Fuel prices are retrieved from the COES data related to thermal power production. They represent an average value of the fuel price of all the different technologies. In the Annex, "Futuros de combustible" of the COES transmission plan, the forecasted evolution of fuel prices for natural gas is provided up to 2040, as well as the cost of Residual 500 and diesel in 2032, which have been interpolated with the fuel cost in 2021 to obtain the trend for all the scenarios' target years (Table 7).

Table 6 Fuel prices for power stations in Peru, 2019, 2020 and 2021

FUEL	TOTAL FUEL PRICE (USD / MWH)		
	2019	2020	2021
Coal	17.04	19.56	25.07
Diesel	68.91	65.82	66.91
Gas	2.74	3.98	12.77
Residual 500	48.88	39.63	58.99

Table 7 Fuel price evolution in the scenario

YEAR	PRICE (USD/MWh)		
	NATURAL GAS	DIESEL	RESIDUAL 500
2025	13.1	68.6	62.2
2030	13.6	70.8	66.5
2035	14.1	73.1	71.1
2040	14.6	75.5	76

CONCLUSIONS

The official national sources provide a detailed description of the current power system of the country and of expected developments in the future. The electricity generation mix of Peru is mainly based on thermal and hydro power plants, with some solar and wind in recent years. In the future, the roles of solar and wind will increase; but as electricity demand is projected to increase significantly, thermal generation will remain relevant and complemented by some new hydro capacity.

Citation: IRENA and Enel Foundation (2023), *Energy transition pathways in South America: Data collection and analysis*, International Renewable Energy Agency and Enel Foundation, Abu Dhabi and Rome.

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