THE VALUE OF FLEXIBILITY IN POWER SYSTEMS WITH A HIGH SHARE OF HYDRO GENERATION: CASE BRAZIL

Brazil is fortunate to have the excellent hydro resources installed, allowing the country to rely less on fossil fuels for power generation. However, the system is reliant on weather as most of the system's demand is met with the dispatchable hydro generation. As the country, like the rest of the world, looks to decarbonize and add more wind and solar power, the power system dependence on the weather will only continue to increase. This study looks for a way to optimally balance the power system; new flexible generation is required to maintain system reliability, to balance renewables and to further reduce carbon emissions.

CONTENTS

EXECUTIVE SUMMARY

An optimized long-term power system expansion model for 2020-2027 emphases the need for adding flexible resources to the power system in Brazil to manage all potential weather conditions. This conclusion is very similar to that of EPE (Empresa de Pesquisa Energética) concluded with both models looking to take advantage of the competitive renewable energy prices while adding flexible generating capacity (Flexibility) to help effectively balance the system.

Flexible thermal generation would allow Brazil to minimize the use of fossil fuels and the costs of electricity.

When comparing the technology options to provide the necessary flexibility, RICE (Reciprocating Internal Combustion Engines) are an excellent complement to a Brazilian power system that is going to be heavily relying on the intermittence of renewables. This technology would allow Brazil to minimize the use of fossil fuels and the costs of electricity, and to continue decarbonizing and adding more wind and solar power. It will also help solve the concern of dry seasons forcing periods of blackouts (unserved energy). Reciprocating Engines would enable future addition of wind and solar as its technology's characteristics are an ideal fit for balancing and minimizing the curtailment of intermittent energy while assure firm capacity is available to maintain security of supply. By adding more flexibility, the power system becomes more friendly to large scale intermittent renewable energy.

Another challenge that needs to be resolved in high hydrothermal systems, is how to encourage the procurement of flexibility for times of low renewable generation, including hydro. The creation of a flexibility market should be considered as a policy recommendation. A market with clear definitions for procurement process of the adequate quantity of flexibility at system level should be contemplated and in which its costs is paid by all the system agents. In hydro systems, the procurement of flexibility can be seen as a system insurance policy: if everything happens according to the positive expectations, meaning, there is sufficient renewables resources to serve the grid with cheap energy and balancing services, then, the cost of this insurance is very low compared to the benefit of having the system running in low cost renewables. If the worst-case scenario materializes, the market will be operated in an optimal way using the necessary flexible resources installed for that application, saving the excessive costs of blackouts or much more expensive sources of system flexibility.

At the same time, a new metric for the procurement of flexibility must be created. Flexibility cannot be priced using the same terms of the procurement of energy, because its energy may in wet years not be necessary to the grid during prolonged periods of time, discouraging investments by the free market agents. As shown in the results of the study, since the economic benefits of incrementing system flexibility will be achieved on a system level, in systems with high hydro participation the procurement of this new attribute should be encouraged by the system's long-term planner, by using new tools to accomplish this task and contracted with long term contracts. This would reduce the risks for the investor and to increase project bankability.

As the addition of flexibility in a system reduces the total operating costs and risks, it is necessary for the procurement process to assess the value of the flexibility by looking to the avoided costs of electricity when this feature is added to the system.

The present study suggests a proper way of estimating the cost savings of operating the system when flexibility is added: a future simulation of the grid for a complete year, in sub-hourly time granularity for each available source of flexibility. By doing this exercise, it is possible to understand how flexible assets should operate in the system, as well as the value of each flexible technology for each hydro scenario, considering all its costs (CAPEX and OPEX) and its estimated benefits on system level. The avoided cost of operation for each flexibility option can be used in creating a new metric for procuring this flexibility, comparing fixed costs for each option with its avoided costs to the power system.

Using an optimization model capable of carrying out this task is crucial, highlighting the need for new tools that can assess the true value of flexibility, especially in the short-term scale, when the impacts of wind and solar are higher. It is, then, noteworthy that the greater the granularity of the simulation, the greater the precision of the results obtained from the system operation.

INTRODUCTION TO BRAZILIAN ELECTRICITY

Few countries in the world enjoy the same availability of natural resources as Brazil. With several hydrographic basins, hydroelectricity is the country's main source of power generation. According to recent data from the National Electric Energy Agency (ANEEL), Brazil currently has approximately 172GW of installed generation capacity, of which more than 63%, or 109GW, is hydroelectric capacity (ANEEL, 2020)

Thermal power generating resources have a significant role in the Brazilian power system, to complement the hydro generation. Wind and solar power are newer forms of renewable energy that continue to grow in the Brazilian system. Wind's importance has increased over the past decade and is expected to play a fundamental role going forward. Especially the Northeast region of the country offers great wind potential, which was evident after a positive showing in the countries last new energy auctions. Solar PV, which currently has a small share, is also showing enormous potential as prices are declining, and becoming extremely competitive.

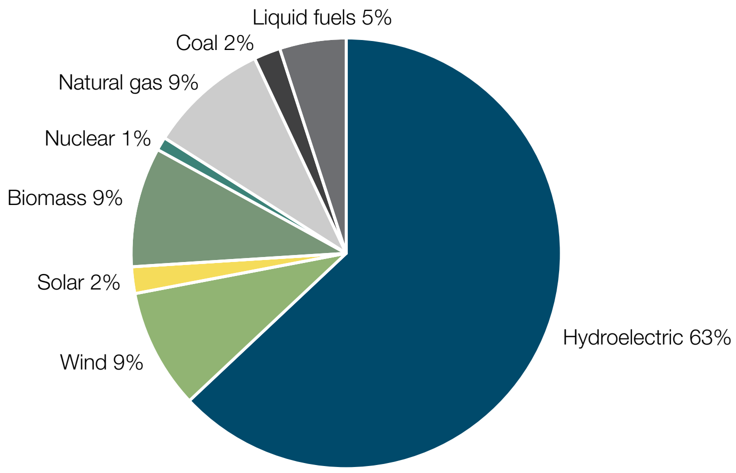


Figure 1. Brazilian power generation capacity by fuel type (ANEEL, 2020)

The generation of energy from the hydro resources is directly dependent on the rainy season.

Although there is a large installed base of Hydro power, the generation of energy from the hydro resources is directly dependent on the rainy season. In years with good hydrology (above average rain fall), hydro resources can be relied upon and are able to generate most of the country's electricity. The opposite is true in years with unfavourable rain. Thermal power plants generation profiles are opposite of hydro as below average rainfall periods result in more dependence on thermal plants.

Another feature of the Brazilian electrical system is the large transmission network. The national interconnected system (SIN) covers most of the country and connects all state capitals, excluding Boa Vista city. The country can be divided into five major electrical regions, four of which are interconnected forming the SIN, South (S), Southeast / Mid-west (SE / CO), North (N) and Northeast (NE). The SIN connects over 99% of the Brazilian population being the remaining 1% formed by small cities in the interior of the North region, where interconnection becomes expensive and local electricity generation is based on diesel thermal source.

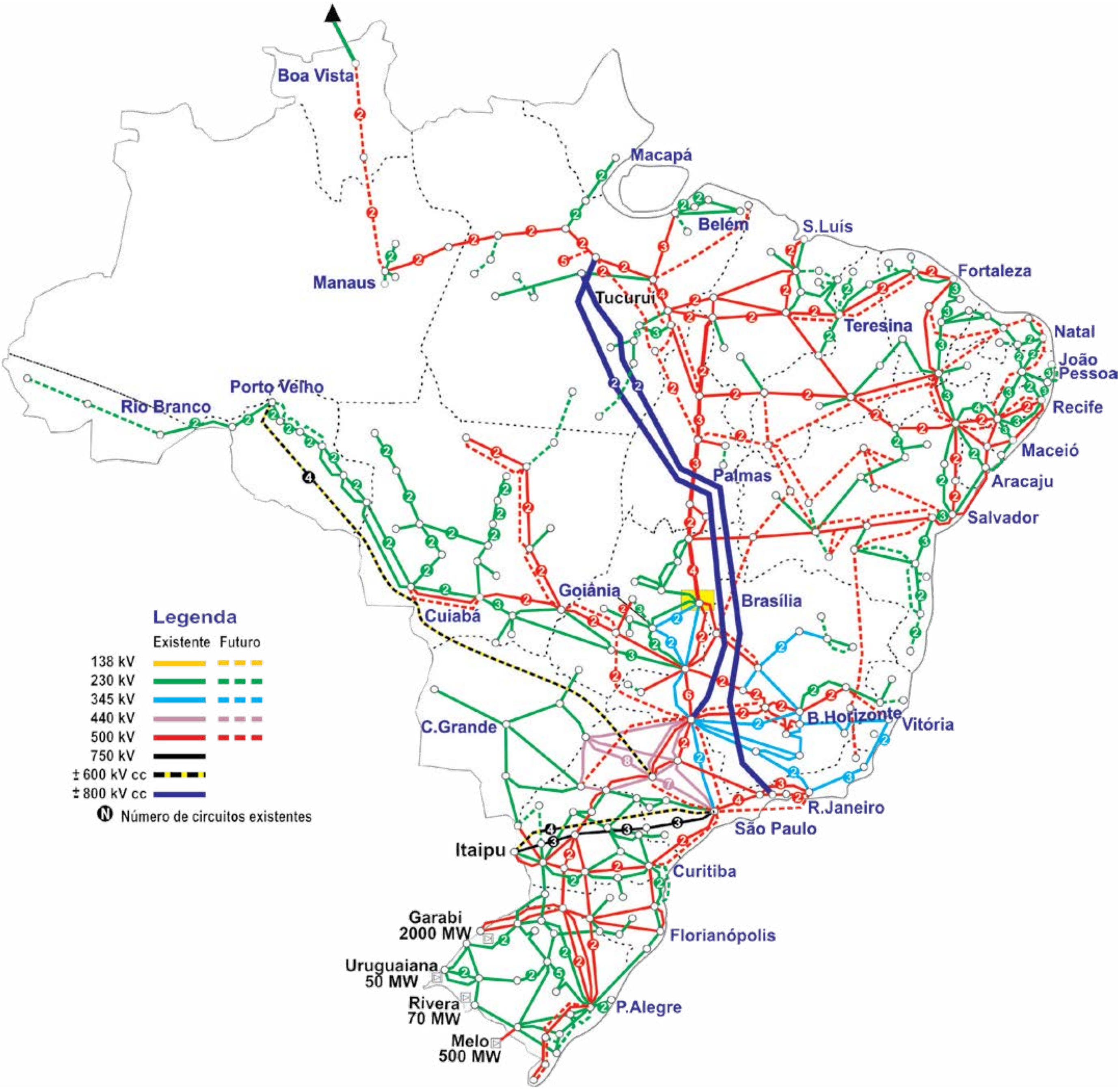


Figure 2. Brazilian Planned Interconnected Grid (Source: ONS, 2020)

The main advantage of operating such a sophisticated transmission system is capturing and balancing the seasonality of each region. For example, when the rainy season ends in the southeast region, it begins in the north and south. Wind production in the northeast region and the availability of biomass in the southeast region are strongest in dry months. Thus, it becomes possible to make the most of the natural potential of each region, optimizing the generation of energy from low cost renewable sources by transmitting large blocks of energy between the different regions of Brazil.

For the future, the long-term planning of the Brazilian power system indicates a limited growth in new hydro plants and a large growth of wind and solar capacity with a decrease of the participation of the hydro source in the mix (Ministério de Minas e Energia, 2018)1. As the consumption is expected to continue growing, another collateral effect is the reduction of the relative storage capacity of the hydro system (same storage capacity to serve a higher demand). During the dry years, specially, the system will have extremely limited flexibility from the hydro plants, since its capability to balance short term variability is limited by the water available in the dams and by the restrictions in water flows of the rivers. This path, toward more intermittency in generation with less hydro flexibility, starts to increase the need to exam whether the future grid will be able to handle the intermittency of substantial amounts of renewable generation.

When integrating large scale of variable renewables into the grid, flexibility must be assessed on a system level.

When discussing system flexibility, one must consider the ability of a grid to quickly respond to fluctuations in load and in intermittent generation. When integrating large scale of variable renewables into the grid, flexibility must be assessed on a system level, because the system flexibility is a combination of: (i) the flexibility of each generating set installed in the grid, (ii) how the renewable sources are correlated with each other and (iii) the level of transmission availability in the grid. Though, flexibility is a term that must be used to define a power generating portfolio's ability to supply Energy, Balancing and Critical Power efficiently and cost effectively in response to any changes in the grid.

Typically, a hydro-thermal power system is one with at least a moderate share of hydro generation which is then dispatched together with thermal capacity. Thermal plants are used to balance variations between rainy seasons. Dispatchable hydro generation can store water in a reservoir and release it when power system needs more generation. In the case of the Brazilian system, there is approximately 290 GW-month of equivalent storage capacity installed to serve the grid with system flexibility. Hydro plants with reservoir are typically very flexible assets, in absence of environmental restrictions. These plants are freely dispatched to balance power system while they can also provide ancillary services, such as frequency regulation.

Even though many hydro plants are dispatchable, flexible, and have low operational cost their potential and performance can be limited for some reasons:

- Firstly, **hydro generation is not scalable technology** as it requires specific site with enough hydro inflows available and/or waterfalls. For example, in Brazil, there is limited number of sites available for new hydro capacity, which is now concentrated in the Amazon rainforest.
- Secondly, **hydro generation varies from year to year and season to season,** and this variation can be radically different and correlated with environmental phenomenon, such as El Niño and La Niña for example.
- Thirdly, **the river where the hydro plant is located usually provides other services to society** in addition to power generation, such as water supply for human consumption and irrigation. These constraints typically limit flow variations in rivers and maximum and minimum allowed flows.
- Lastly, **rivers may often have several hydro plants,** i.e., the plants are cascaded. Cascading plants makes their operation more challenging as there are delays in water flows. For example, when water is released from upstream, it can take several hours or even days for the released water to reach the next plant. And if the next plant is run-of-river without storage, the released water increases the generation of the run-of-river plant with delay.

During dry periods and dry years, thermal or other type of generation must replace the reduced hydro generation. Dry periods result in low water level in reservoirs. In such case, the plants cannot generate their nominal output and thus they provide less flexibility to support the system during peaking demand periods. Wet periods, instead, result in high inflows in the rivers. These water masses are difficult to control and there is risks of spilling water. Spilling or bypassing flows is not wanted as these inflows basically represent free energy. Wet periods limit the flexibility of hydro generation to avoid energy waste through spills.

As the amount of renewable energy (RE) increases, power systems face new challenges not only in maintaining system reliability and resilience, but also in balancing variations in renewable generation and demand, especially in shorter periods of time like minutes and hours. Without adequate and detailed planning, the overall cost of generation may increase despite the addition of cheap renewable energy. This is true because the thermal portfolio installed in the hydro system is not flexible enough to deal with short term intermittency of the newcomer wind and solar. Only with advanced new planning tools and methodologies, coupled with the appropriate balancing technology and energy storage, can it be measured whether high levels of RE utilization can be achieved within a grid system while reducing the overall cost of generation.

In summary, **dynamic flexible thermal generation** is needed even in hydro systems:

- for seasonal balancing of hydro generation
- to balance annual hydro variability
- to help in real-time balancing of wind and solar power
- to provide peaking capacity and load following
- provide fast system reserves to cover forecast errors of wind and solar generation
- to ensure system adequacy (capacity reserve margin)

OBJECTIVES OF THE STUDY

The purpose of this paper is to study the optimal mix of expansion in a hydro-based system, such as Brazil, considering the massive deployment of intermittent renewable generation in the coming years. Another purpose of the study is to estimate the effectiveness and reliability of hydro power as a system balancer when substantial amounts of wind and solar are introduced to the power system. Hydro is a flexible resource that can help support power systems with the intermittency of renewable energy, but this is only true when adequate amount of water is available specifically for that purpose. Additionally, the study aims to emphasize the role of affordable and fast thermal flexibility in the future Brazilian power system with more wind and solar generation, suggesting regulatory improvements to allow a smooth and efficient integration of high shares of renewables, addressing its main impact. To observe this, two cases were studied:

- A long-term expansion of the power system from 2020 to 2027 with the Long Term-optimization software Plexos, from Energy Exemplar©
- A comparison of different flexibility options in the year 2027 using the in-detail accurate short-term dispatch model of Plexos.

The Power System Study has been conducted utilizing PLEXOS® Energy Simulation Software. Plexos is a software developed by Energy Exemplar and has a robust simulation capability across electric, water and gas systems focusing on full user control, transparency and accuracy across numerous constraints and uncertainties. This software is widely used by system operators, utilities, and consultants for power system analysis as well as system planning and dispatch optimization. Modelling related details are given in next section and Appendix.

STUDIED SCENARIOS

The first portion of the results, titled "Optimizing the System Capacity Planning from 2020 to 2027", involves a long-term capacity expansion model for Brazil, optimized from 2020 until 2027. The Plexos model is asked to find the lowest electricity generation costs by optimally selecting the addition of generating capacity to adequately meet the electricity demand under different hydrology conditions, and by optimally dispatching the assets. The model includes three hydrologies: 1) long-term average, 2) dry (15% lower than the average), and 3) wet (13% higher than the average). Optimal generation capacity will supply the demand at the lowest cost, over the studied period. The reported costs include (1) Capital costs (CapEx) (2) Fixed operation and maintenance costs (FO&M) (3) Operating costs (OpEx), such as such as fuel and start-up costs.

Plexos can add wind, solar PV, battery storage, combined cycle gas turbines, open cycle gas turbines (heavy duty and aeroderivative), and reciprocating engines to the power system at any time during the study period provided that these make economic sense. The investment costs assumptions for the technologies are given in Appendix in Table 5 and Figure 8. Other technologies, i.e., biomass, nuclear, small, and large-scale hydro, are added as per PDE2027[1]. Furthermore, also following the PDE2027, the expansion of wind and solar is limited on annual basis in the expansion model.

The PDE2027 performed with a similar goal of determining the optimal long-term expansion plan for Brazil. With that in mind comparing the results for the PDE and the optimized long-term Plexos model should give validation to the current strategy from EPE. At the end of this section both the determined optimal capacity build-out and the EPE build out for the period until year 2027 will be compared.

In part two of this study, titled "Comparison of Flexible Technologies," the year 2027 is studied in higher detail of resolution with a short-term dispatch optimization model (ST). The short-term model optimizes the hourly system operation through the year for the given installed capacity, using all the real-life technical constraints that different technologies have (like starting time & starting costs). The purpose of this section is to determine the optimal flexible thermal technology for the power system in 2027. Here, the capacity mix for 2027 is taken from the PDE2027.

1 Plano Decenal de Expansão de Energia (PDE) 2027 by the energy agency Empresa de Pesquisa Energética (EPE).

RESULTS AND COMMENTS

Optimizing the System Capacity during 2020-2027

This exercise outlines the optimal long-term expansion results for the Brazilian power system for years 2020 to 2027. Figure 3 displays the optimized capacity build out and the amount of generation by technology for the studied period. The Figure also presents the current capacity in the system, capacity additions and system peak load.

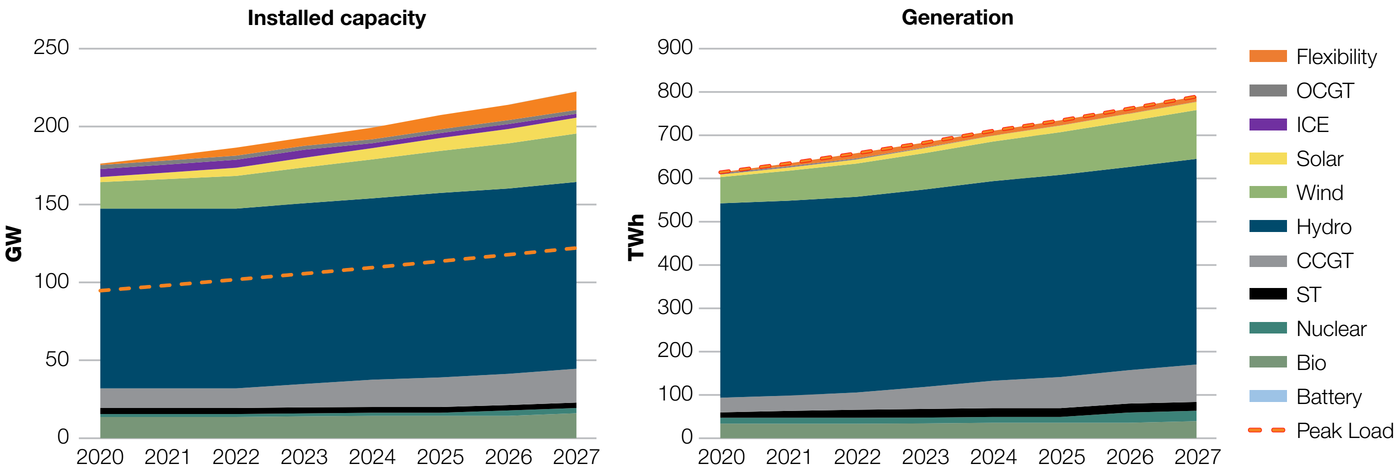


Figure 3. Optimized capacity builds out and generation by technology type from 2020-2027

From 2020 to 2027, the annual electricity demand increases from 600 TWh to nearly 800 TWh. Throughout this period, Plexos is mainly adding new wind and solar power (since these are the least cost options for energy), flexible gas, and some new baseload gas plants for dry year balancing. Renewables and flexibility are added every year while new baseload combined cycle gas (CCGT) plants are added from 2023 onwards. As per the plan from PDE (Plano Decenal de Expansão de Energia), some new hydro, biomass, and nuclear is also installed throughout the studied period, but not in a significant amount.

Wind and solar is added annually to match the continued load growth. In 2027, the installed wind capacity is 31 GW and solar 10 GW, an impressive growth over the 7 years period. Due to the competitive costs the model adds as much renewable energy as it can feasibly every year. This suggests that adding even more renewables in the years after 2027 would also be an economic choice. The maximum amount of feasible wind and solar additions annually are assumed to be 2 GW and 1 GW, respectively, following the limit assumption PDE2027 uses starting from 2023.

With the increased amount of variable renewable wind & solar generation, a large addition of new flexible gas generation is needed to balance renewables and to meet the increasing demand. Over the studied period it is necessary to add approximately 12 GW of new flexible generation capacity. The role of this flexible capacity is further studied in the next section.

The model adds approximately 9 GW of new baseload gas generation (CCGT). This inflexible fossil baseload addition can be explained by the rising system load that requires firm capacity for maintaining security of supply. However, it should be mentioned that the new base load gas plants are only economical due to the annual renewable additions being limited in the PDE2027. Allowing Plexos to make higher expansion of renewable generation than planned by PDE would results in lower generation cost and decrease the need of new based load gas plants.

With the large addition of wind and solar the amount of inflexible baseload plants should be limited as these are not capable of providing fast wind and solar balancing service, especially from stand-still. Another concern of adding too much inflexible generation is that such plants could limit the addition of clean renewable power in the future. The resulting capacity build out from 2020-2027 (Table 2) is quite similar to the PDE study. The table summarizes the cumulative additions (in GW) of different technologies and compares PDE 2027 and the Plexos expansion model results.

		By 2023	By 2025	By 2027
PDE 2027	Wind	4	8	12
	Solar	2	4	6
	Flexibility	1	8	13
	CCGT	3	8	9
	Other*	1	4	8
Optimized	Wind	8	12	16
	Solar	4	6	8
	Flexibility	5	9	12
	CCGT	3	6	9
	Other*	1	4	8

* Other includes hydro, biomass and nuclear, of which addition is not optimized

Table 2. Cumulative additions in GW by 2023, 2025 and 2027 in PDE expansion and the optimized expansion

When observing both the current PDE and the optimized scenario simulated with Plexos, it is possible to conclude that they are remarkably similar. Both take advantage of the competitive renewable energy prices while adding flexible generating capacity (Flexibility) to help effectively balance the system. The next section will take a closer look at the 13 GW of Flexible Generating capacity that the PDE plan suggests adding.

Comparison of Flexible Technologies

As seen in the previous section, just as the Empresa de Pesquisa Energética PDE 2027 expansion, the Plexos long-term modeling shows the need for new flexible generation capacity. There are multiple technologies that could fit the definition of "flexible" in terms of thermal power generating assets. This section will use an accurate short-term dispatch model for the year 2027 to evaluate and compare the total generation costs and security of supply provided by different flexibility technologies. The aim is to identify which would be the best technology mix economically and operationally to use as the necessary flexible capacity. Again, the optimization is done over three different types of hydro years as with the expansion model. The generation mix for the simulations was taken from the PDE 2027. The capacity mix for 2027 is shown in Figure 4.

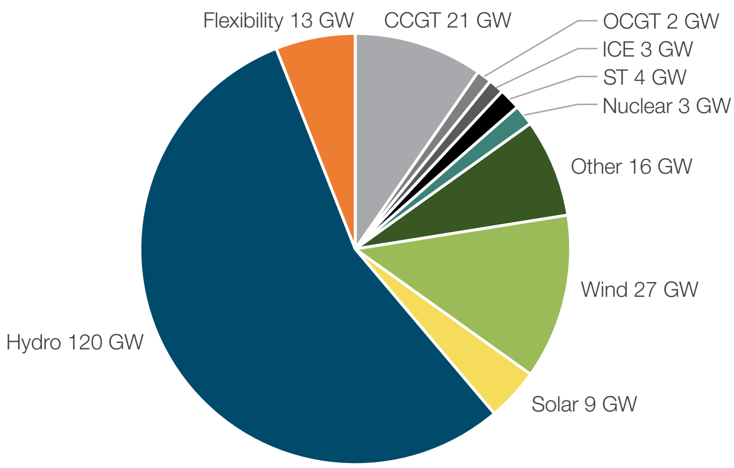


Figure 4. Generating technologies by technology type (GW) in 2027.

The short-term simulation for 2027 is repeated six times, as shown in Table 3.

Comparison of flexibility options	
Scenario	**Description**
No New Flexibility	No new flexibility added
RICE 13 GW	13 GW Reciprocating Internal Combustion Engines
GT AERO 13 GW	13 GW GT Aeroderivative Gas Turbines
GT HD 13 GW	13 GW GT Heavy Duty Gas Turbines
BESS 1h 13 GW	13 GW of 1h Battery Storage Systems
Pump Storage 13 GW	13 GW and 39 GWh of Pump Storage

Table 3. Studied scenarios for 2027 flexibility comparison. Thermal plants run on natural gas.

The results and comparisons for all six scenarios are outlined in Figure 5.

Figure 5-A displays the total power system generation cost comparison for the studies scenarios. The total cost includes total operational cost of the Brazilian power system (fuel, variable operation and maintenance cost, start and stop costs, ramp costs) for the year 2027, annualized investment in the new flexible capacity as well as the cost of unserved energy, as per the Brazilian regulations. Unserved energy means the system is not capable of supplying electricity to some users during certain hours – the cost for such unserved energy is from ANEEL.

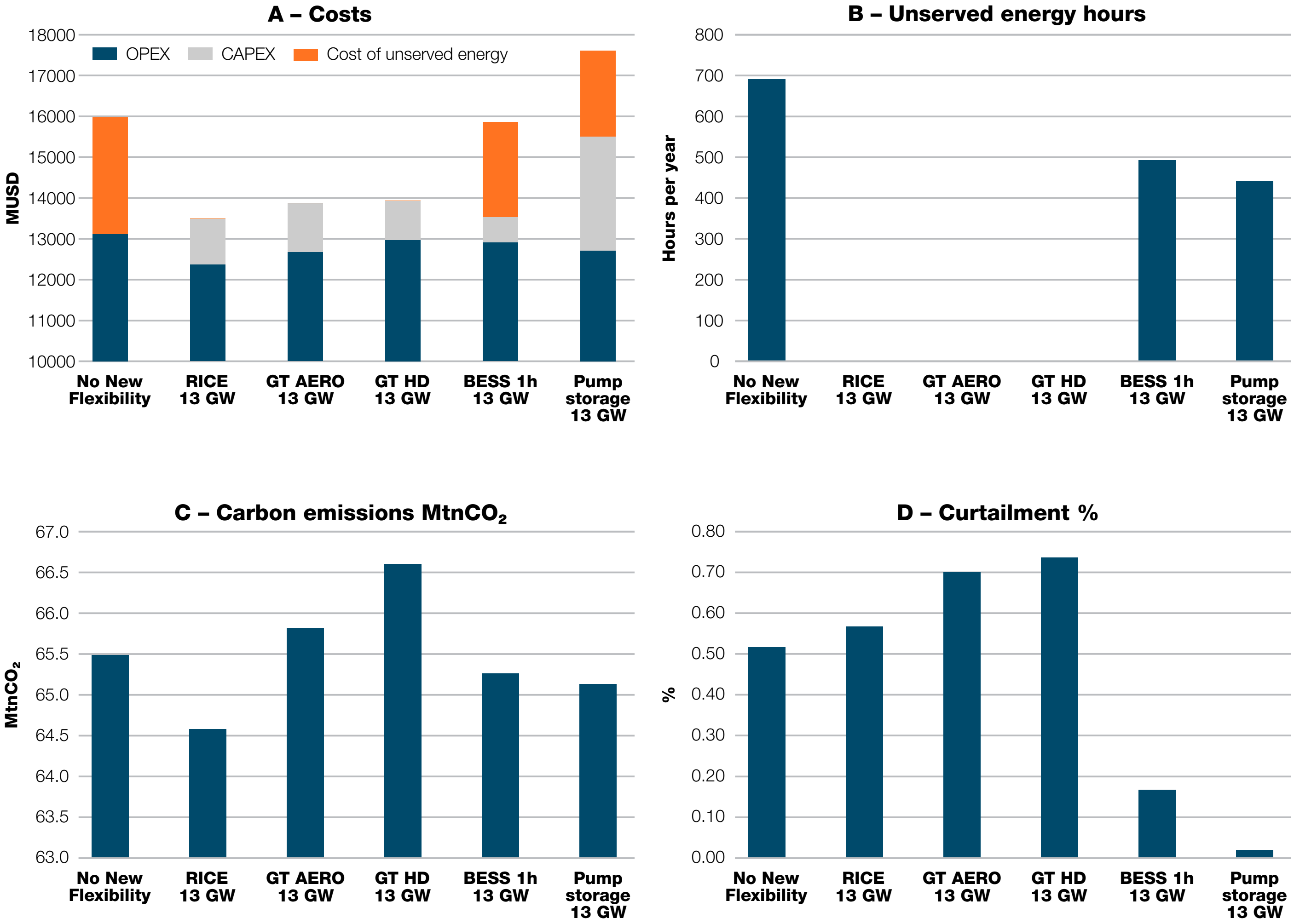


Figure 5. Results of the 2027 flexibility comparison, Total generation costs (A), Unserved energy hours (B), Carbon emissions in metric tons (C), and percentage of wind & solar curtailment (D). The numbers are an average over different hydrologies.

The least cost scenario estimated by the short-term model from Plexos is the one where 13 GW of Reciprocating Combustion Engines (RICE) are installed. Most savings can be attributed to lower Operational Costs (OPEX), specifically higher thermal efficiency and lower start-up costs. Aeroderivative gas turbines (GT AERO) and Pump Storage also reduce the operational cost of the system, however, pump storages overall cost is highest due to its high investment cost.

Without thermal flexibility in the system, the unserved energy increases, and this increases the total cost (value of unserved energy assumed to be 5,000 R$/MWh, equivalent to 1,200 USD/MWh (Brazilian Regulation Agency, 2020). Unserved energy hours, presented in Figure 5-B, represents number of hours per year when the power generating portfolio is unable to meet the system load.

Storage options help the system reduce unserved energy compared to the No New Flexibility scenario but do not address the problems during dry years when there is no excess energy to shift.

Carbon emission for the different scenarios are shown in Figure 5-C. Emissions include emitted CO_2 from all gas, coal, oil, and diesel fired generation in the power system. When comparing with the other thermal options, RICE scenario reduces nearly 1.2 million tons CO_2 annually so remarkably less fuel is combusted than in the other scenarios. When comparing with both storage options, one should note that the substantial amounts of unserved energy cuts emissions because total generation of the system is lower, naturally reducing the system overall emissions.

Figure 5-D displays the percentage of curtailed energy. The addition of storage assets (in the storage scenarios) allows for better storing of excess wind and solar. The 13 GW of Pump storage shows lower curtailment compared to the battery storage due to its larger storage size. When comparing the thermal options, the RICE scenario is the one which produces minimum wind and solar curtailment.

To achieve a reliable system and to avoid any periods of unserved energy, dispatchable thermal generation is needed in the power system. It ensures that energy and dispatchable capacity are available when hydro or wind and solar generation are not available. This becomes especially important during dry years as the hydro generation is down and only short-term storage options are available to carry the system through longer periods of cloud cover and low wind.

There are differences in results between thermal generating technologies that are worth observing. Installation of reciprocating engines as flexible capacity results in lower total cost, carbon emissions and renewable curtailment compared to aeroderivative gas turbines and heavy-duty gas turbines. The thermal generation options are further studied in the next section.

Thermal Technology Comparison

This section will dive deeper into the flexible open cycle generating technologies that could be added to the Brazilian system. The studied technologies include:

- 13 GW Reciprocating Internal Combustion Engines (RICE)
- 13 GW GT Aeroderivative Gas Turbines (GT AERO)
- 13 GW GT Heavy Duty Gas Turbines (GT HD)

The operation of the flexible generation technologies during wet, dry, and normal years is illustrated in Figure 6. The example week in the figure is in September 2027, which is considered a late dry season month when demand has begun to increase, wind generation is still high but hydro inflows and water storage levels remain low.

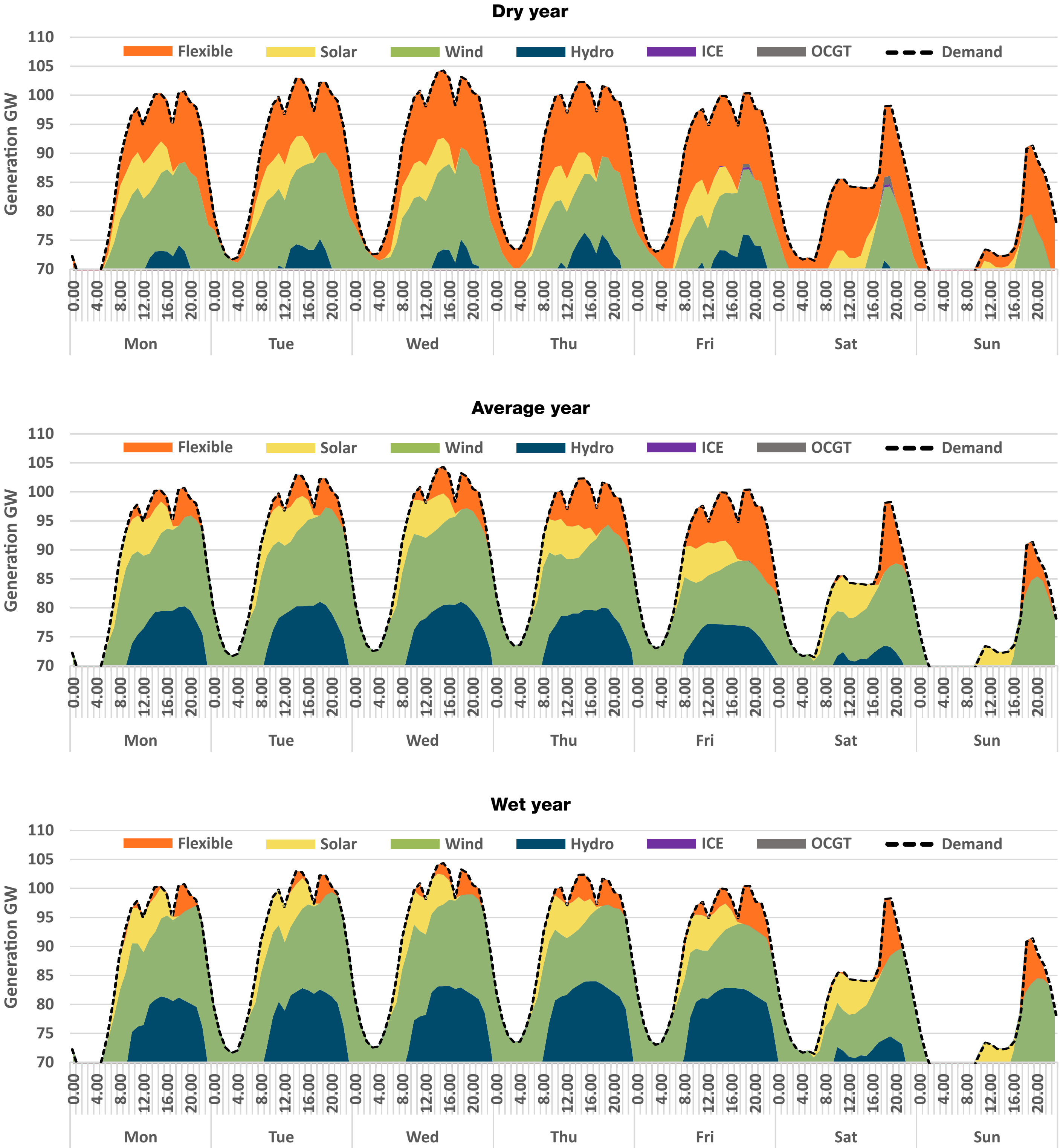


Figure 6. Thermal generating capacity operation during a week in September for dry, average, and wet years. Figures present only the upper part of weekly generation dispatch to highlight wind, solar and flexible generation. Most of generation is from hydro (below the 70 GW mark on the Y-axis).

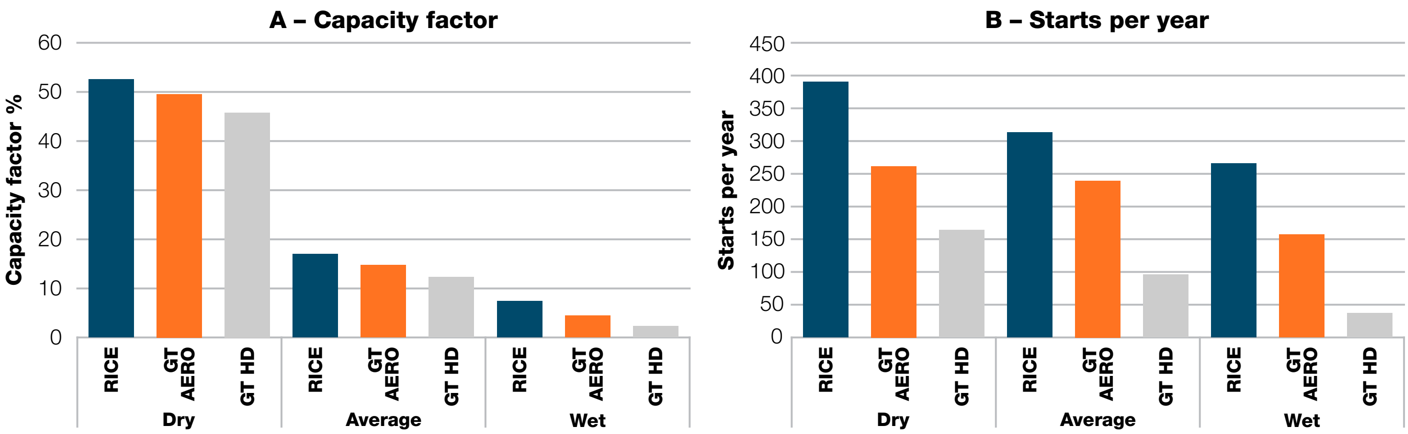
During dry years, the flexible gas capacity is relied upon to run heavily to back up reduced hydro output. Due to high running hours (capacity factor ~ 50 %), high efficiency open cycle technology cuts fuel cost and results in lower system operation cost.

In average rain years the flexible capacity balances renewables, provides short term load following and daily peaking, but the running hours are strongly reduced (capacity factor ~ 15 %) compared to dry years. As seen in the Figure 6, the power plants typically have several starts per day. During the example week, wind generation drops towards weekend and it is replaced with flexible thermal and hydro if available.

During wet years, the capacity is used for occasional peaking (capacity factor ~ 5%) and the renewables can supply most of the energy and other system needs. It is important to highlight, however, that even in wet years there is still a significant amount of starts and stops for the flexible plants. The model is dispatching RICE more than the other technologies every year. This is due to higher efficiency compared to the other options, and lower start-up cost compared to the heavy-duty gas turbines (GT HD).

Figure 7 summarize the annual operation of the three studied open cycle thermal technologies in different hydro years. Figure 7-A presents the capacity factors while Figure 7-B displays the annual starts calculated per units installed.

The impact of annual rainfall on the utilization of flexible capacity is also clear. Nevertheless, in all hydro cases wet, average, or dry, Reciprocating engines (RICE) have the higher capacity factor and more starts, i.e., providing more balancing services to the power system compared to the other flexible technologies.



Figures 7. Capacity factor (A) and Annual starts per installed power plant unit (B) for thermal generating assets for dry, average, and wet years.

Table 4 below compares the costs in each of the scenarios (average costs, considering wet, dry, and average years). The total costs for each scenario include annualized investment cost in the new flexible generation and the operation cost of the entire system (Fuel cost, Variable O&M and start costs). Based on the results:

- The scenario with reciprocating engines results in lowest total cost. The annual savings are 439 and 381 MUSD compared to heavy duty gas turbine and aero gas turbine scenarios, respectively.
- The savings are mainly from the operational cost of the entire system – installation of certain kind of technology affects the operation of the rest of the power system. Truly flexible technologies reduce the system cost more in long run, which should be rewarded in the flexibility procurement process.

		13 GW of RICE	13 GW of GT AERO	13 GW of GT HD
System level OPEX	MUSD	$12,378	$12,682	$12,969
Investment in flexibility	MUSD	$1,110	$1,188	$958
Total cost	**MUSD**	**$13,488**	**$13,869**	**$13,927**
Total savings with engines	**MUSD**		**$381**	**$439**

Table 4. Total cost and saving for system operation for all thermal technologies. Numbers are an average over different hydrologies.

SUMMARY AND FINAL RECOMMENDATIONS

To balance the power system, new flexible gas generation is required to maintain system reliability and avoid periods of unserved energy.

The Brazilian power system is fortunate to have excellent hydro resources that allow the country to rely less on fossil fuels. However, the system reliance is instead on weather as most of the system's demand is met with the dispatchable hydro generation. As the country, like the rest of the world, looks to decarbonize and add more wind and solar power, the power system dependence on the weather will only continue to increase. To balance the power system, new flexible gas generation is required to maintain system reliability and avoid periods of unserved energy.

The optimized long-term model results from 2020-2027 emphasized the need for adding flexible generation to the country´s power system. This conclusion is very similar to that of EPE with both models looking to take advantage of the competitive renewable energy prices while adding flexible generating capacity (Flexibility) to help effectively balance the system.

When comparing the technology options to provide the necessary flexibility, RICE (Reciprocating Internal Combustion Engines) are an excellent complement to a Brazilian power system that is going to be heavily relying on the intermittency of renewables. This technology would allow Brazil to minimize the costs of electricity, and to continue decarbonizing by adding more wind and solar power. It will also solve the concern of dry seasons forcing periods of unserved energy or in other words blackouts. Reciprocating Engines would enable to foster future addition of wind and solar as its technology's characteristics are an ideal fit for balancing and minimizing the curtailment of intermittent energy while assure firm capacity is available to maintain security of supply.

Policy Recommendations

According to the International Energy Agency (2014), the key features of solar and wind sources are:

1. zero marginal cost
2. low predictability, which increases uncertainty related to the generation, especially in the short term; and
3. intermittency or volatility in production, caused by sudden changes in wind and sun conditions that lead to sharp variations in the power generation curve.

The combination of these characteristics, together with the large-scale expansion of these sources in the power systems, raises the need for flexibility in electrical systems. In other words, the large-scale integration of these sources in the electrical grids challenge the operation and planning of the systems, as it requires gradual transition of the old thermal power system to a new one, favourable to their development. Traditional power systems were based on large centralized steam power plants using coal, nuclear and gas as fuel, and they are highly inflexible. Without adequate flexibility, the wind and solar assets cannot be utilized efficiently, which has been already seen in High-RES regions like Germany and California where curtailment is becoming an everyday phenomenon.

Without adequate flexibility, the wind and solar assets cannot be utilized efficiently.

In hydrothermal systems, when there is energy storage available, it is possible to optimize the grid with relative penetration of wind and solar energy using part of the flexibility of the hydroelectric plants, as could be noted in the wet year results shown in Figure 5. However, given the uncertainty of the future availability of rain, the priority of using water for other uses, and the environmental impact of operating hydroelectric plants to balance the system, even in hydrothermal systems, mechanisms to expand systemic flexibility should be studied. In addition, that system must be designed so that it operates reliably in all weather conditions, even if some weather events with an exceptionally low probability of occurrence.

Presently, one of the challenges to resolved in high hydrothermal systems, is how to encourage the procurement of flexibility for times of low renewable generation, including hydro. As much of the systemic flexibility can be provided by hydroelectric storage, energy prices can remain relatively low for extended periods of time, inhibiting the installation of flexible generation capacity by market agents. The large-scale deployment of wind and solar energy will create even more pressure to lower the average energy prices in the markets. However, as this study shows, flexible technologies are needed in order to lower the overall costs of the system and to avoid risk of unserved energy even during the years with good average rain fall. In addition, in the event of prolonged severe drought and scarcity of other renewable resources, the flexibility of the hydroelectric plants is drastically reduced and, without sufficient time for the installation of flexibility, the system will suffer from a shortage of resources, especially during peaking times. It is recommended then, that the procurement of system flexibility should be part of the long-term planning of hydrothermal systems.

The creation of a flexibility market should be considered as a policy recommendation. A market with clear definitions for procurement process of the adequate quantity of flexibility at system level should be contemplated and in which its costs are paid by all the system agents. In hydro systems, the procurement of flexibility can be seen as a system insurance policy: if everything happens according to the positive expectations, meaning, there is sufficient renewables resources to serve the grid with cheap energy and balancing services, then, the cost of this insurance is very low compared to the benefit of having the system running in low cost renewables. If the worst-case scenario materializes, the market will be operated in an optimal way using the necessary flexible resources installed for that application, saving to the system the excessive costs of blackouts or much more expensive sources of system flexibility.

Investments in flexible generation and storage systems must be properly incentivised to make the system more friendly and reliable for large scale renewable development. When procuring energy only for the system, it is recommended that the metrics for energy procurement to be adapted to price the new attributes that were not important in the past but are currently fundamental to the optimal operation. A correct choice for energy procurement metrics can be optimized and should even reduce the need of incremental system flexibility. The current metrics used to procure energy in the power markets, such as the LCOE (Levelized Cost of Energy) and the Brazilian ICB (Cost-Benefit Index), must be sophisticated enough to price not only the cost of MWh produced by each resource, but also its value contribution to the grid at the moment when it is generated, in the short-term period.

At the same time, a new metric for the procurement of flexibility must be created. Flexibility cannot be priced using the same terms of the procurement of energy, because its energy may not be necessary to the grid during prolonged periods of time. As shown in the results of the study, since the economic benefits of incrementing system flexibility can be achieved on a system level, in systems with high hydro participation, the procurement of this new attribute should be encouraged by the system's long-term planner, using new tools to accomplish this task and contracted with long term contracts, in order to reduce the risks for the investor in flexibility and increase project bankability.

As the addition of flexibility in a system reduces the total operating costs and risks, it is necessary for the procurement process to assess the value of the flexibility by looking to the avoided costs of electricity when this feature is added to the system.

The present study suggests a proper way of estimating the cost savings of operating the system when flexibility is added: a future simulation of the grid for a complete year, in sub-hourly time granularity for each available source of flexibility. By doing this exercise, it is possible to understand how flexible assets should operate in the system, as well as the value of each flexible technology, considering all its costs (CAPEX and OPEX) and its estimated benefits on system level. The

avoided cost of operation for each flexibility option can be used in creating a new metric for procuring this flexibility, comparing fixed costs for each option with its avoided costs to the system.

Another important matter when designing the flexibility market is how to guarantee that the flexible asset will be built into the grid. Even though the use of the flexible assets may be more concentrated in certain periods, when severe dry years occur, these assets must also be available in the system when good rainy years happen. It is the role of the system planner, when deciding the future market framework, to consider the procurement of flexible assets through long-term contracts, with a flow of income to the investors even during the years when there is minimum use of flexibility. This is very important for the financing of these type of assets and it is a guarantee that they can pay for themselves with part of the benefit they create to the system when they are available.

Given the uncertainty related to the wind and solar production and the future availability of water and storage for both power generation and ancillary services, the real use of the flexible assets will be constantly changing. As seen earlier, in years with good rainy season, it is possible for the grid to deal with wind and solar variability by using the hydro flexibility and other sources of grid flexibility main remain idle for extended periods. However, when needed, the dispatch profile of the flexible thermal resources can be intermittent, with a lot of starts, stops and partial loading. It is especially important to consider this uncertainty when procuring flexibility for the grid, to avoid future claims from market agents due to unseen operational profile (e.g. thousands of starts per year). The operation mode of the flexible asset must be a risk of the flexible agent.

Using an optimization model capable of carrying out this task is crucial, highlighting the need for new tools that can assess the true value of flexibility, especially in the short-term scale, when the impacts of wind and solar are higher. It is, then, noteworthy that the greater the granularity of the simulation, the greater the precision of the results obtained from the system operation.

APPENDIX

PLEXOS® Energy Simulation Software

Plexos is a simulation software for studying and dispatching of a power system. The software uses mathematically based optimization techniques to realistically represent the operation of a real-life power system.

A Plexos model is a combination of power system data and advanced mathematical formulation, which captures the characteristics of the studied system. Figure 1 shows the power system data used in a model. This data, combined with the mathematical formulation, is a Plexos model, representing the power system with each of its techno-economic detail. The formulation models system features, such as the characteristics of power plants (e.g. efficiencies, dynamic features), the nodes and lines in the electrical grid, ancillary service requirements, and supply-demand balance.

The model is fed to a solver that produces the results shown in the Figure. The solver optimizes the power system. In a long-term expansion model, the optimization objective is to find the optimal (lowest cost) generation capacity additions to supply the future electricity demand. In a short-term model, the objective is to minimize the power system operation cost for the study period. Due to the complex nature of the power system capacity optimization modelling some simplifications and compromises are typically needed. But it is noteworthy to mention that these simplifications should not severely impact the end results, which means that all compromises need to be carefully investigated and chosen.

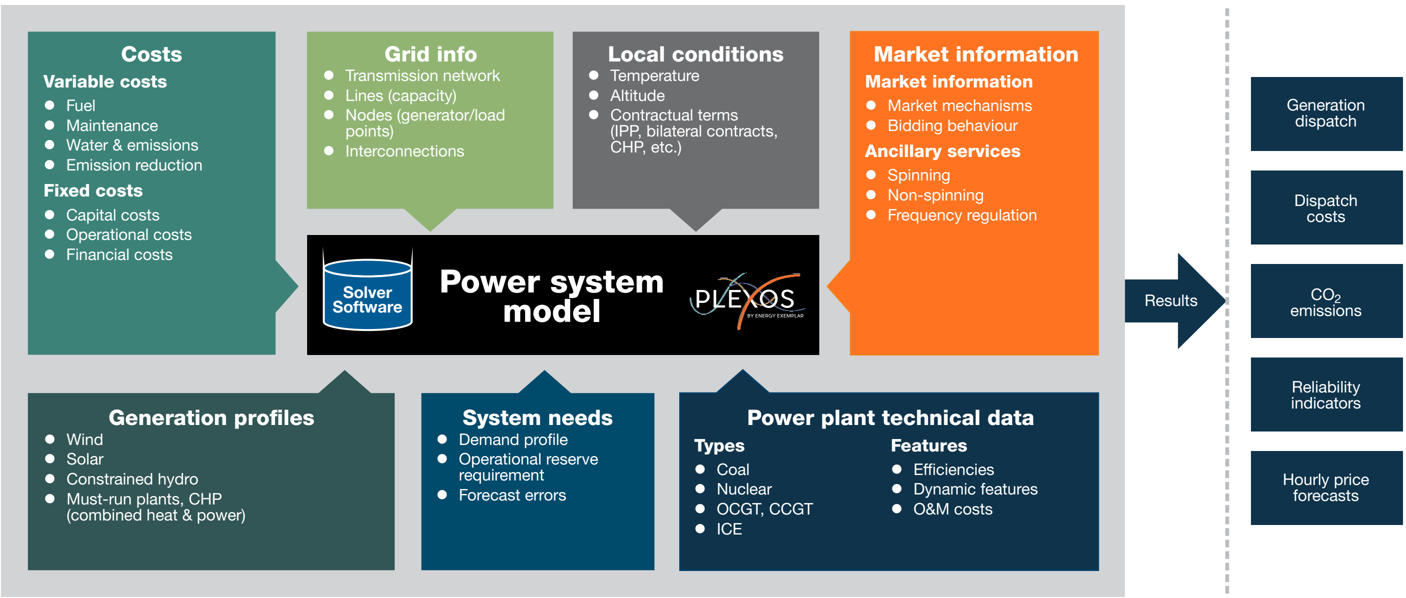


Figure 8. Plexos power system modelling software.

Model Inputs

The expansion model used in this study is based on true chronological dispatch with hourly data for future load, wind, and solar production, for the eight-year horizon. This approach provides the most accurate picture of the systems actual dispatch, and provides accurate analysis of costs, fuel usage, emissions, and system reliability. For each thermal technology, several characteristics such as size of plant, minimum stable load, part load heat rates, VO&M, FO&M, start-up cost, and investment cost are included.

Since the Brazilian system relies on large-scale hydro generation, the dispatch of other types of generation depends heavily on the available hydro generation: thermal generation gets high capacity factors in dry years (low rainfall and thus inflows) whereas hydro generation is more sufficient when inflows are high. Due to this year by year variability, the capacity expansion would result in different outcomes depending on the hydro year. To tackle this issue, the long-term planning is using stochastic expansion model, which solves several hydro years simultaneously and find the optimal capacity mix given different hydrologies. In this study, three hydrologies from dry (15% below long-term average) to long-term average and wet (13% above long-term average) years are used in the expansion model.

Hydro generation is represented by ten aggregated hydro power plants each with their reservoirs, inflows, and generators. Aggregation is based on river basins since the inflow patterns vary from area to area. Each large river also has several cascaded hydro plants, of which dispatch and available energy depends on the other plants in the river. The flexibility of the plant is limited, for example, because of river flow delays between plants and possible environmental constraints.

The short-term dispatch model built on the top of the expansion model is more granular. The dispatch model is run with one-hour resolution and with integer unit commitment economic dispatch decisions, which better captures the net load variability and system inflexibilities.

The model also includes necessary system operational reserves for maintaining the balance and reliability of the system. Spinning reserves are included together with additional future reserve requirement for wind and solar PV balancing due to weather forecast errors.

Battery storage and pump storage are assumed to have two-way efficiency of 85% and 75%, respectively.

	Heat Rate, GJ/MWh	VO&M Charge $/MWh	FO&M $/kW,a	CAPEX $/kW
ICE NEW (18V50SG)	7.82	5	15	600
OCGT HD	9.73	3	15	500
OCGT AERO	9.0	4	15	650
CCGT	6.55	3	15	900
Pump Storage	–	–	15.9	1700

Table 5. Generating technology parameters used for this study.

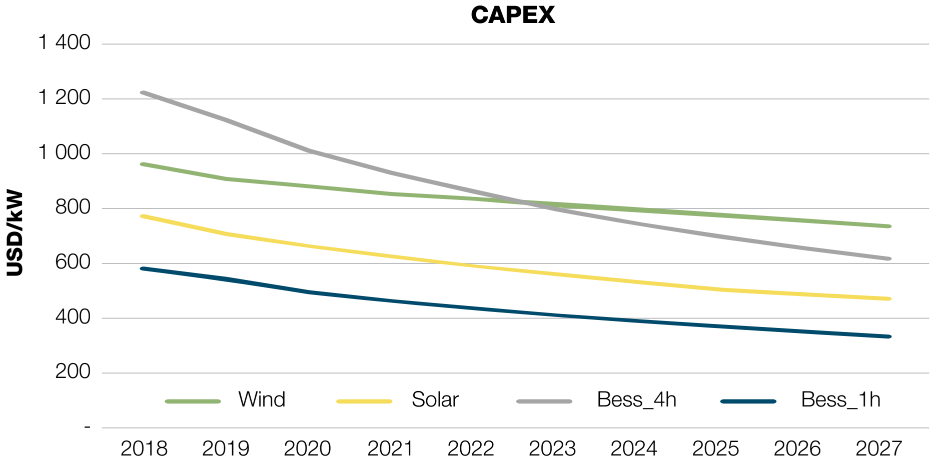


Figure 9. Wind, solar, and storage learning curves observed for this study.

Fuel	Price 2017 ($/GJ)	Price 2027 ($/GJ)
GAS	8.4	12.7
DIESEL	25.6	41.50
COAL	4.9	4.9
OIL	17.1	27.7
URANIUM	0.66	0.66

Table 6. Fuel prices observed for the studied scenarios.

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