Decarbonization Pathways for Paraguay's Energy Sector

SimSEE Simulation: Technical Report

CRECE

Columbia Climate School
The Earth Institute

Columbia Center on Sustainable Investment
A joint center of Columbia Law School and the Earth Institute, Columbia University

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Sustainable Development Solutions Network
A Global Initiative for the United Nations

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By

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III. INTRODUCTION

This document assesses future electricity supply and demand scenarios between countries of the Southern Cone of South America, with focus on Paraguay. For this purpose, a regional power flow model presented by the World Bank and constructed in the framework of the SimSEE platform is used as a benchmark. The developed model includes parameters resulting from discussions between SDSN, the Ministry of Finance of Paraguay and CRECE.

The model aims to:

- Show and understand the scope of Paraguay's future electricity needs
- Explore alternatives for electricity supply
- Assess the schedule for the commission of new power plants
- Estimate expectations upon not-supplied energy and the need of imports

The model runs a weekly power dispatch algorithm that minimizes the system's supply cost by seizing the "opportunity cost" of using the cheapest energy resource available (that of zero-marginal cost – hydro, solar, wind, etc.). This involves a centralized power dispatch; thus, the resulting energy exchange does not consider any commercial rules or contracts that may exist between agents of the power system (*i.e.,* ITAIPU with ANDE/ELETROBRAS).

It is worth to point out that the idea behind the model is to provide with an overview of the long-term evolution of the electricity system in terms of energy needs and supply alternatives. In that sense, the model offers:

- Paraguay's power demand and supply projections in different scenarios.
- Representation of the long-term behavior of Brazil's and Argentina's electricity markets in terms of the projection of market prices.

The remainder of this Report is organized as follows. In the first section – Model Overview, we present the World Bank's model. Mainly, it presents and describes the following parameters: energy demand, generation, and transmission network for Paraguay, and markets prices for Argentina and Brazil. Next, we present our demand growth model, where two key parameters are considered: the hourly demand from the base year (2019) and the annual projection of electricity consumption for the simulation period. Once the demand modeling process is described, input parameters for the proposed SimSEE's model are detailed. Some of the necessary parameters are the projection of demand for Paraguay, Argentina, and Brazil; the plan of generation investments for Paraguay; the projection of marginal operating costs in Argentina and Brazil, among others. Finally, the proposed scenarios with their corresponding results are presented. These scenarios are summarized in Table 1.

Most of the scenarios have two settings – so-called Closed and Open Market – which define whether there is the possibility of energy exchange between neighboring countries. More details on the used parameters are given in the chapter corresponding to the scenarios.

Results obtained allow to identify the alternatives that could be consider for Paraguay to satisfy its future demand needs. Identifying these scenarios is extremely important for the national government and other institutions, for instance, for determining where the economic efforts should be directed to ensure energy security, reduce external dependence, and preserve a sustainable ecosystem.

Table 1: Proposed assessment scenarios

Item	Scenario
SC01	Base Scenario – Top-down, exponential growth of demand, with fixed growth rate of ~ 5 %/year
SC02	Alternative Scenario – Bottom-up demand projection obtained with the LEAP model for a Carbon-neutral Scenario
SC03	Application of ANDE's Generation Master Plan 2021-2040
SC04a	Application of ANDE's Generation Master Plan 2021-2040 + Construction of new Binational Hydropower Plants
SC04b	Application of ANDE's Generation Master Plan 2021-2040 + Construction of new Binational Hydropower Plants + Renewables and Batteries from 2040 on
SC05a	High investment in renewables + batteries, seeking to reduce not-supplied power
SC05b	High investment in renewables + batteries, seeking to reduce not-supplied energy

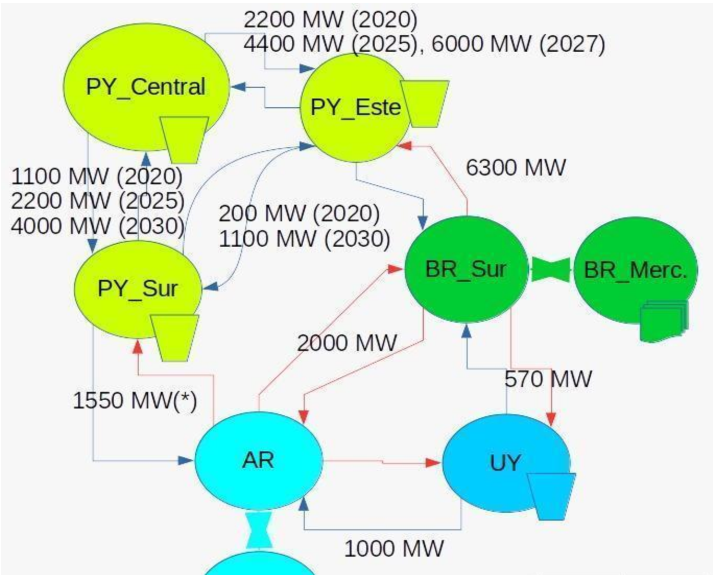
1. Assumptions

The model simulates the dispatch of the electricity system by minimizing operating costs according to available supply resources and demand. Only conventional, thermal generation technologies have variable, operating costs (e.g., fuel costs) since the marginal cost of renewable plants, *i.e.*, hydropower – Itaipú, Yacyretá, is zero. In the framework of power system economics, and taking the hydropower technology as an example, this means that no cost is associated to the use of water to produce 1 additional MW of electricity. Here, the system operating cost represent an opportunity cost in terms of the convenience of using supply resources according to the current, observed and the future, expected level of renewable resources, *i.e.*, water, solar irradiation, wind, etc., and demand.

2. Paraguay's electricity system model

The model includes an equivalent of the power system projected by ANDE in its Generation and Transmission Master Plan 2016-2025. According to the scope of our contract and our work schedule, investments are not optimized, and new generation and transmission investments are integrated over time according to the rising supply needs. In that sense, each of the proposed scenarios discusses a different schedule of generation investments. Figure 1 shows the model's nodes and branches, together with the projection of transmission capacity over time.

Figure 1: Equivalent model proposed by the World Bank in SimSEE.



	50%-PY
Fecha	MW-Acum
desde inicio	1550.0
01/01/23	1705.0
01/01/24	1914.8
01/01/34	2460.0
01/01/32	3290.0
01/01/38	4730.0

Source: World Bank Presentation

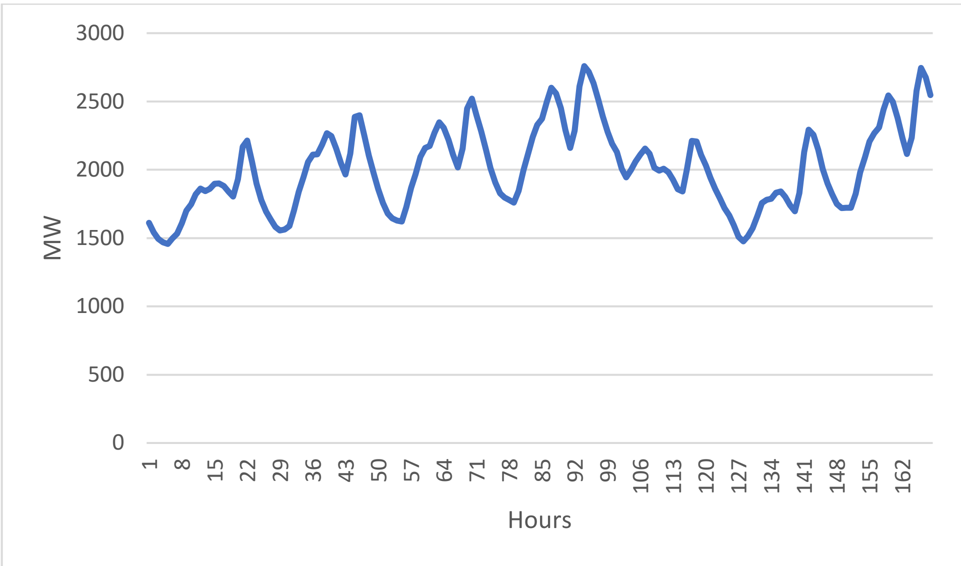
Paraguay is described by means of three interconnected nodes – Py_Central, Py_Este and Py_Sur. The regional markets with which Paraguay could exchange electricity are Argentina – AR – and the Southern region of Brazil – BR_Sur.

Transboundary electricity exchanges are valued by the surplus/deficit of the exporting/importing country times the marginal cost of the importing country at a given node. Thus, for the exchange to exist, there must a price difference between importing and exporting nodes. An additional restriction is included in term of a ''toll'' or transmission fee. These fees are called Delta Export (DE) and, within the model, range from 10 to 10,000 USD/MWh. By performing sensitivity analysis on the DE variable, one can deliberately ''open'' or ''close'' a country to transboundary energy exchanges. For instance, a DE of 10,000 USD/MWh, which is higher than any value of loss load, denotes a closed transboundary transmission link.

3. Paraguay's demand model

The demand model is based on two parameters: the hourly demand from the base year, in MW; and the yearly consumption projection for the simulation period, in MWh. The former parameter denotes the short-term pattern, while the latter represents the long-term, expected trend. Figure 2 shows the hourly demand from the year 2018, for the first week, i.e., 168 hours.

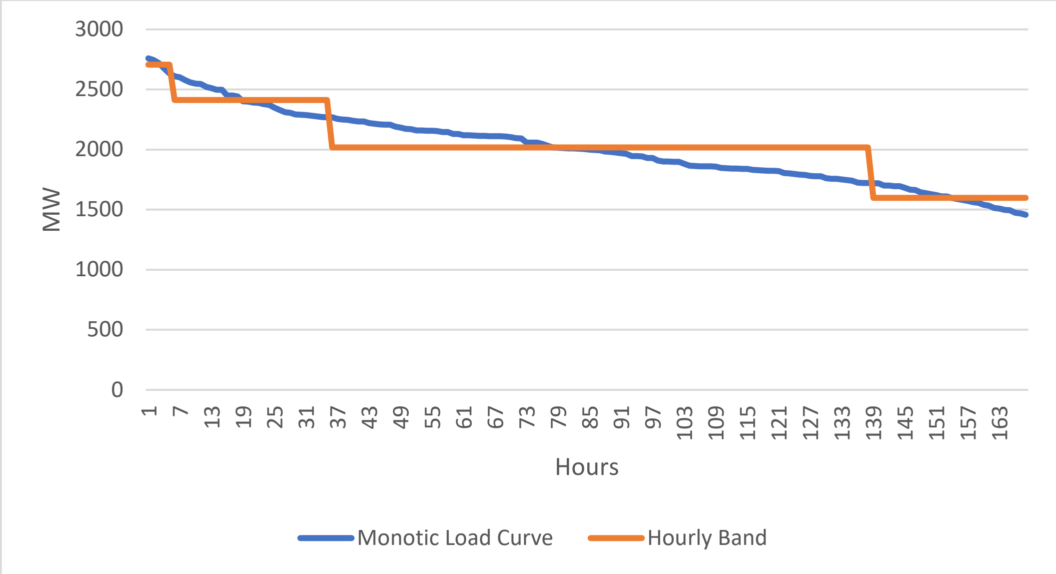
Figure 2: Hourly demand of the first week of 2018.



The main task involves assigning the short-term pattern to each year within the simulation horizon. For that purpose, the method applied is quite straightforward as the hourly data is distributed in proportion to the relation of annual energy consumption between the given year and the base year.

Next, a load duration curve is created for each week. The duration curves are composed of four steps or bands, denoting peak (P1), high (P2), medium (P3), and low (P4) demand values. For one week of 168 hours, these demand values account for 5, 30, 91, and 42 hours, respectively. In order to calculate the value of each band or step, the chronological, hourly demand is sorted in a decreasing order. Thus, the value for the peak demand band is the mean of the first 5 hours; for the high demand band, the value is the mean of the next 30 hours. This process is repeated to obtain the medium and low demand values. Besides abandoning chronological rigor, and according to the planning scope of the model, this simplification allows to save substantial computation time. For each week, the amount of optimization runs is reduced from 168 to 4. In one year, this represents a reduction from 8760 runs to 205, roughly 98%. This can be seen in **Figure 3**, where the four load bands overlap the decreasing load curve.

Figure 3: Demand model composed by 4 load bands overlapping the decreasing weekly load curve.



4. Input Parameters

Input parameters of the World Bank's model include:

- Projection of future demand for Paraguay
- Plan of generation investments for Paraguay
- Projections of future marginal operating cost for Brazil and Argentina.
- Water inflow to hydropower plants
- Oil prices
- Natural gas prices
- Toll for transboundary exchanges

To update and enhance the model for our purposes, we propose these modifications for the input parameters of Paraguay's:

- Demand growth projections:
  - The base scenario is associated to a deterministic demand growth rate of 5.46 %/year, in contrast to the growth rate used by the World Bank, which was of 8.14 %/year
  - The alternative scenario is associated to a demand growth projection resulting from the LEAP model for the Carbon-neutral Scenario (SC3)
- Investment scenarios:
  - Application of the new ANDE's Master Plan of Generation 2021-2040
  - Construction of new Binational Power Plants on the Paraná River (with Argentina)
  - High penetration of renewable energy resources, including batteries

5. Scenarios & Results

With the objective of assessing regional energy exchanges, focusing on Paraguay, the eventual review of Annex C from the Itaipú Treaty in 2023, and the achievement of a carbon-neutral power system by 2050, we suggest base and alternatives scenarios as presented in the following sections.

To assess the impact of transboundary energy exchange, each scenario accounts for two settings: Closed and Open Market. In the former, the transmission links are switched off and no transboundary exchange is possible; in the latter, the transmission lines are switched on and exchanges are triggered whenever there is a price difference between markets. It is worth to mention that a Delta Export valued at 10 USD/MWh is also included as an Export/Import toll fee.

Some of the figures included in the report are:

- Supply/Demand Energy Balance of the 95th percentile of not-supplied energy: Yearly demand and supply by generation source (in GWh) corresponding to the 95th percentile of not-supplied energy cumulated over the simulation time;
- Supply/Demand Power Balance for peak-demand level (P1), associated to the 95th percentile of not-supplied energy: Yearly-equivalent moving-average of weekly power dispatch for the peak-level of demand (P1) (in MW), corresponding to the 95th percentile of not-supplied energy cumulated over simulation time;
- Power supply failure for the peak- (P1), high- (P2), mid- (P3), and low-demand (P4) levels: Weekly probability of occurrence of not-supplied power for the 4 demand levels (P1, P2, P3, and P4) (in %) taken from 250 stochastic realizations of the dispatch algorithm (a yearly-equivalent moving-average overlaps the weekly data);
- Marginal cost in exporting/importing nodes for the peak-demand level (P1), associated to the 95th percentile of not-supplied energy: Weekly marginal cost in exporting/importing nodes (PY-East, BR_South, PY-South, AR) for peak-level of demand (P1) (in $/MWh), corresponding to the 95th percentile of not-supplied energy cumulated over simulation time (a yearly-equivalent moving-average overlaps the weekly data).

5.1. SC01 – Base Scenario

Scenario SC01 denotes slight structural modifications of the World Bank model's parameters. This includes the update of demand projections and the marginal cost in Brazil. Demand up to 2019 is updated and is now based on ANDE's ''Proyecciones de la Demanda Nacional de Electricidad Período 2020-2040'' [1]. A demand growth rate of 5.46% is used. The demand projection for the time horizon can be seen in Figure 4. The marginal operating costs in Brazil are also updated considering the latest projection made by the EPE in their Decennial Expansion Plan [2]. EPE is the institution in charge of the planning of the Brazilian energy system.

This scenario aims to assess power and energy supply needs up to 2050 without long-term adequation of generation resources. Figure 5 shows the supply and demand projection for the 95th percentile of cumulated not-supplied energy in a Closed Market setting. In 2037, not-supplied energy starts to be greater than 1.0% of energy demand, reaching 11.4% in 2042, when energy demand equals energy supply at roughly 58,000 GWh. Supply resources include existing domestic and binational hydropower plants, namely, Acaray, Yguazú, Itaipú, and Yacyretá. As Aña Cua is already being constructed, it is added to Yacyreta's generation capacity.

Figure 4: Energy demand projection 2020-2050 for the Base Scenario

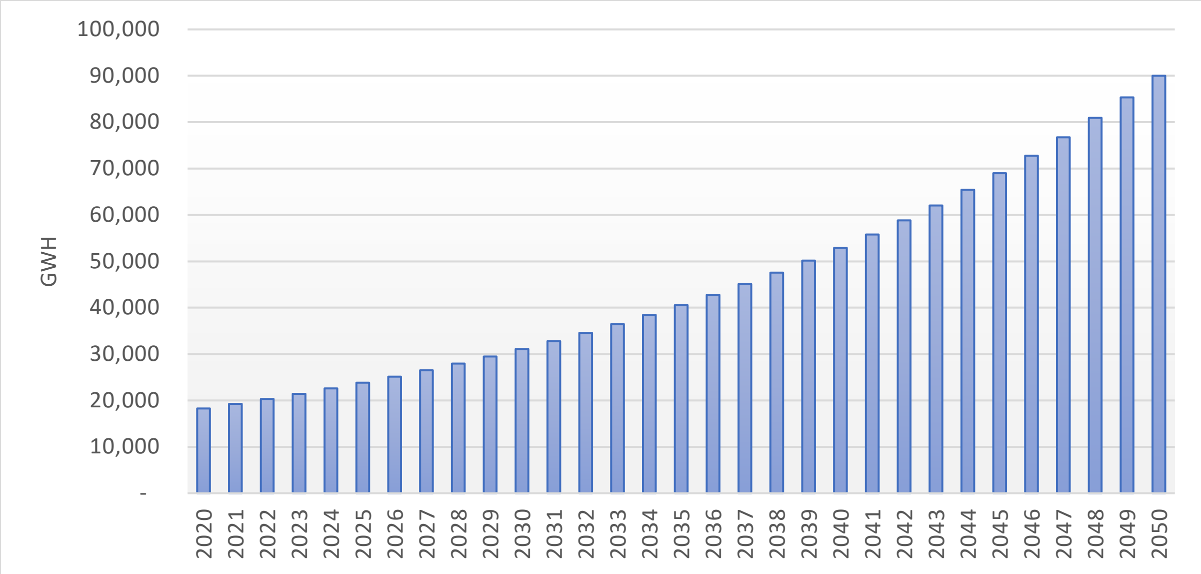
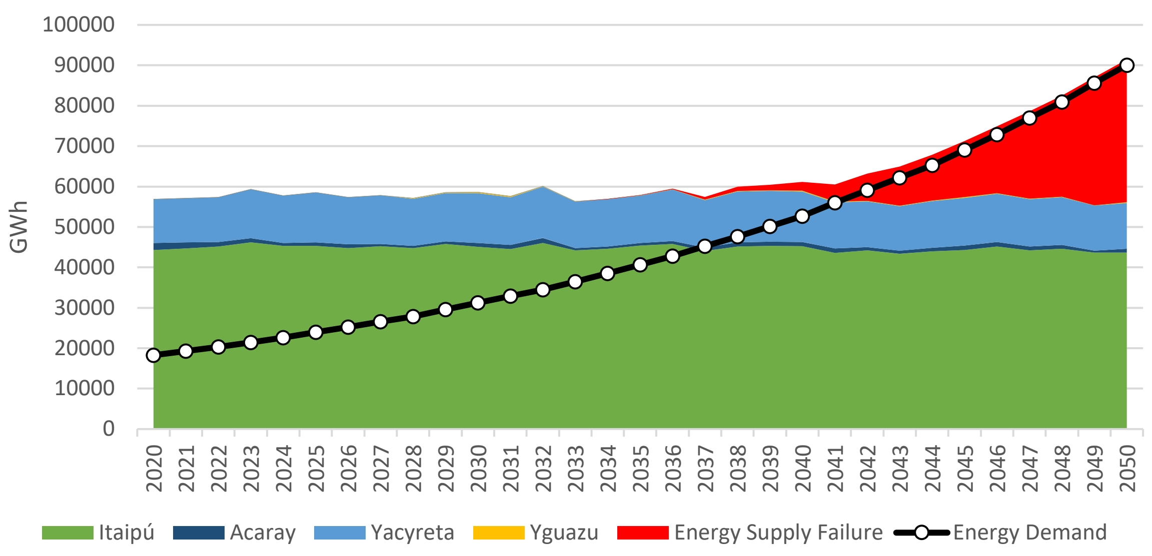


Figure 5: Energy balance for the 95th perc. of cumulated not-supplied energy – SC01 Closed Market



Not-supplied power for peak demand starts to grow from 2030, as can be seen in Figure 6 and Figure 7. This is because peak demand growth there begins to surpass the available installed capacity, considering all the stochastic variables involved in the model. Here, it is worth to mention that peak demand is modeled by assuming the chronological pattern of 2019 for all years within the simulation horizon. In that sense, it is worth to mention that ANDE's load factor, *e.g.*, the relation between average and peak load, is now coincidentally at significantly low values (55% in 2019) [3].

Figure 6 shows the power dispatch of each generator. Two interesting facts happen since 2025 on. When the second 500-kV transmission line between the Itaipu dam and ANDE's Villa Hayes substation

Figure 6: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC01 Closed Market

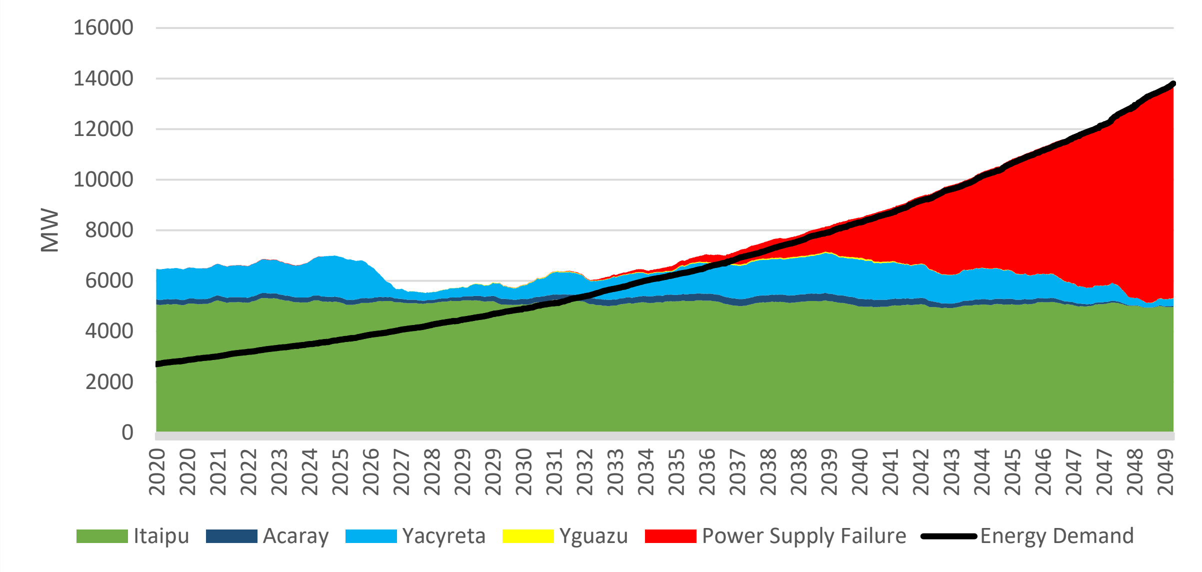
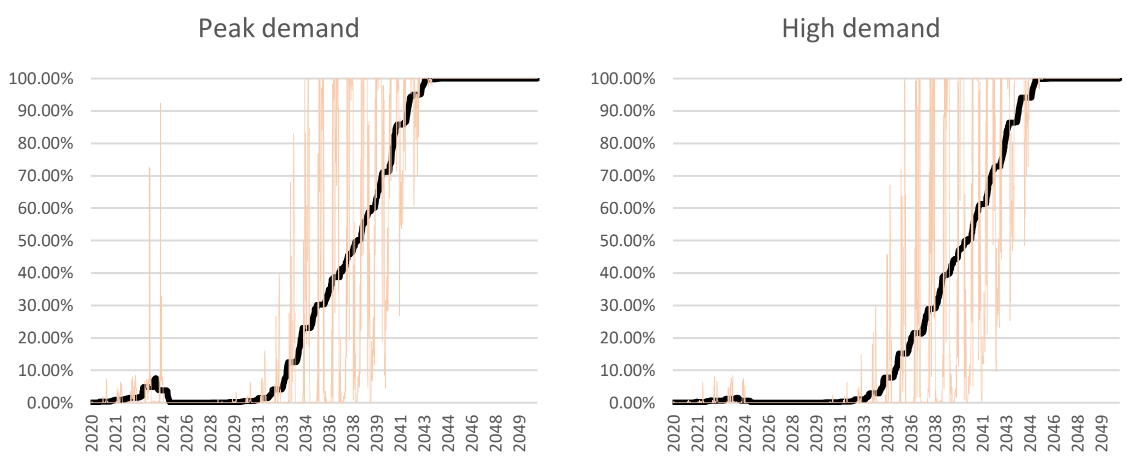
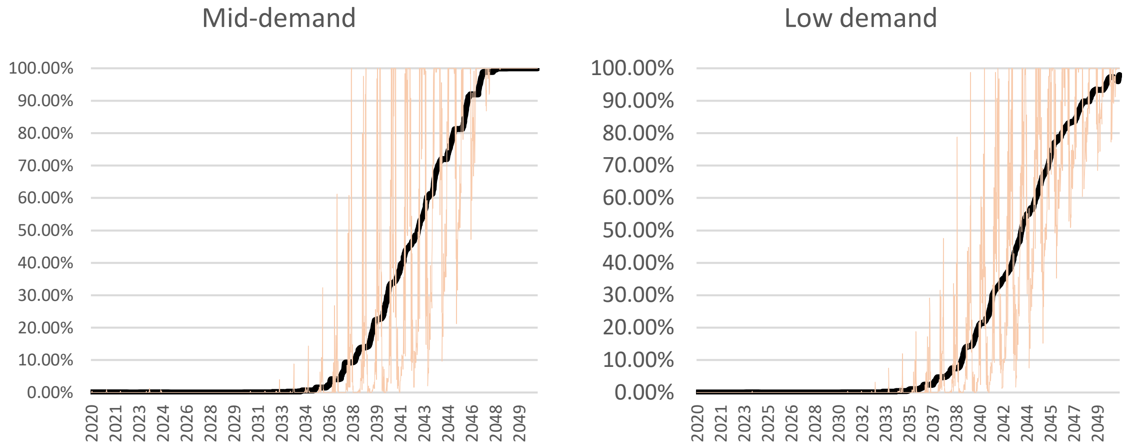


Figure 7: Power Supply Failure Frequency – SC01 Closed Market





starts to operate, the power dispatch from Yacyreta for the peak demand (P1) is reduced. This occurs again when the failure frequency in low demand (P4) starts to rise **(Figure 7).**

For the low demand (P4), the frequency of not-supplied power starts to grow in 2032. This means that problems with supply will start being critical ever since, mostly over high-demand season (summer and spring). Oscillations perceived in **Figure 7** represent the seasonal failure frequency, due to the difference in summer and winter electricity demand.

By looking at the nodes at both ends of any transboundary link, when switched-off, we can see how $ would it cost to supply 1 extra MWh at the Paraguayan-end of the link, with domestic generation resources, as well as at the neighboring end, with their own supply resources. In that sense, we can see how much the supply would cost in these nodes in each of the proposed scenarios and compare these results with the cost at the other end of the border, thus arguing over an "opportunity cost" of importing. By analyzing scenarios with enhanced generation resources, we can see how much the marginal supply cost decreases – thanks to new domestic power plants helping to cover the initial, expected not-supply power.

Figure 8 and **Figure 9** show: first, results from the model referring to the marginal supply cost at the Paraguayan-end of the border – with a weekly resolution (in gray); second, the yearly moving-average of such weekly results – this seeks to smooth the short-term seasonality and to depict a long-term trend (in orange); and third, the marginal supply cost at the neighboring-end of the border (in blue). We can see that the opportunity cost of importing from Brazil and Argentina is lower than the cost of relying on domestic generation resources ever since 2033, because there are no new power plants in place to satisfy the growing demand needs.

Figure 8: Marginal cost in Paraguay's East and Brazil's South nodes for P1 and 95th perc. of cumulated not-supplied energy – SC01 Closed Market

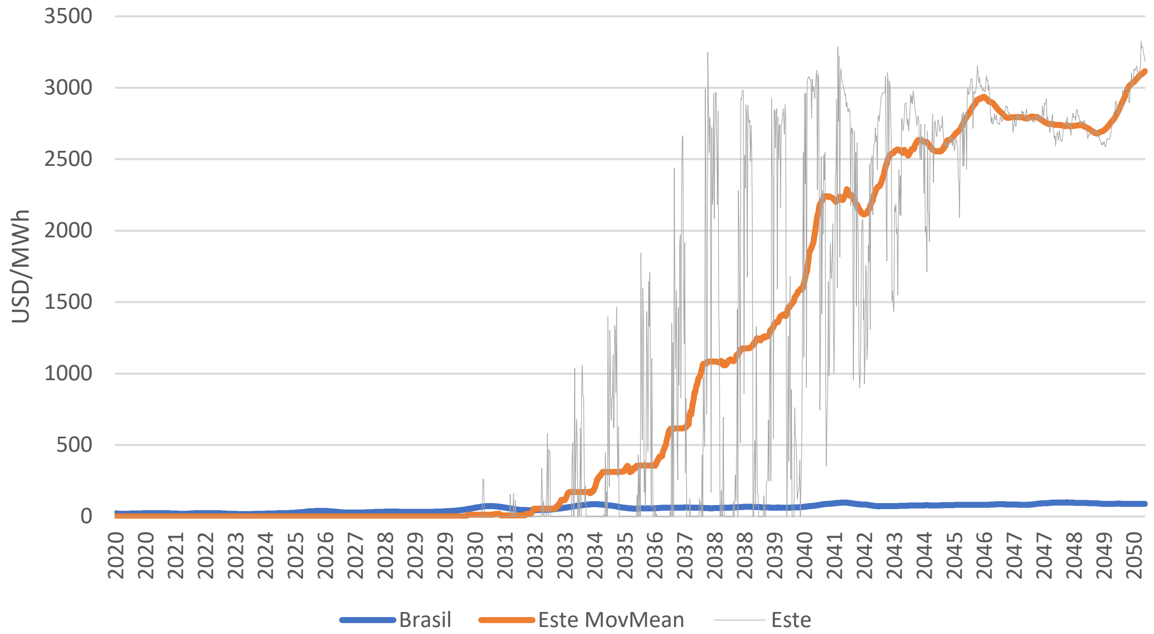
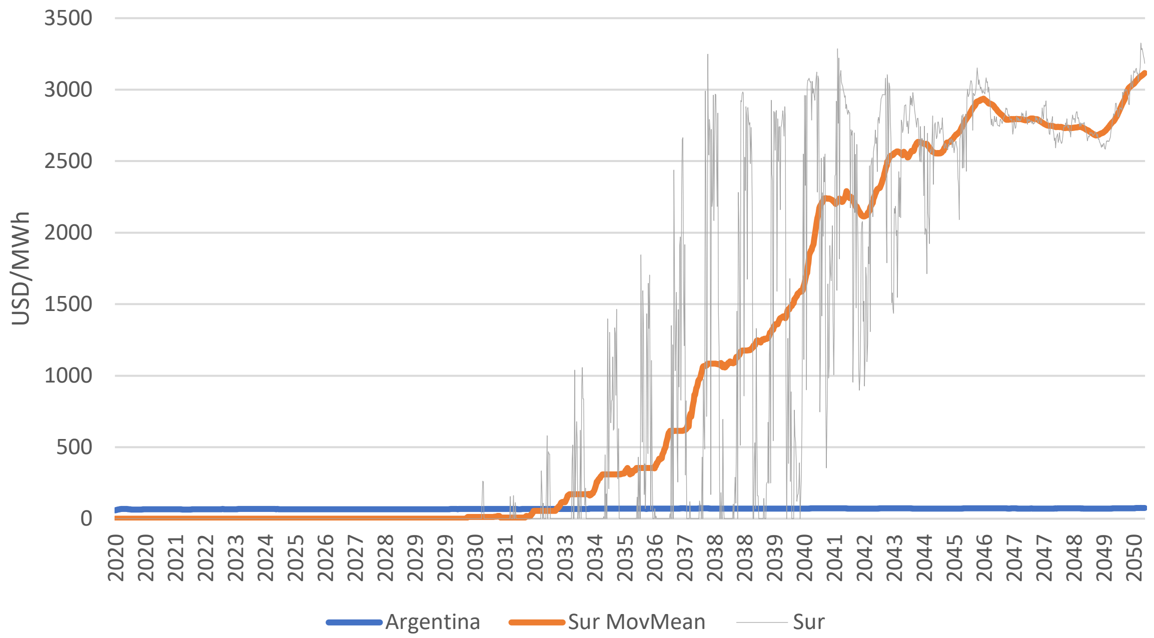


Figure 9: Marginal cost in Paraguay's South and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC01 Closed Market



The energy balance in the SC01 Open Market is shown in **Figure 10**. Here, the increased energy needs are met by imports from Argentina and Brazil. However, not-supplied energy does not disappear. Many reasons can make the system to have not-supplied energy. One possible reason for it is that generation capacity was insufficient in one or more stochastic realizations. Besides that, the model considers the possibility of transmission failures. These failures could affect both the national and the international transmission lines. So, there could be realizations where the generation was sufficient but one or more transmission lines went out of service. In addition, the model also considers the possibility of unavailability of both the Brazilian and Argentinian markets. So, even when the market is open, there could be realizations when transmission lines are online but the neighboring market is unavailable.

The power balance for P1 load is shown in **Figure 11.** By 2050, imported power from Argentina and Brazil would amount roughly 1400 MW and 4500 MW, respectively. Not only imports are limited by the capacity of the transmission links, but also by the capacity of the internal transmission lines connecting the East and South nodes with the Central Node, where the main demand of Paraguay is. As mentioned before, several factors are being considered in the dispatch model, thus, not-supplied energy still exists even though there is a possibility for international exchanges. **Figure 12** shows how frequently the ENS will be for the peak demand (P1), starting to be more than 5% in 2036.

In the Open Market setting of SC01, Paraguay's energy surplus is traded with Argentina and Brazil considering electricity market rules. Requirements for exports are, first, the existence of energy surplus, next, network availability, and importer's marginal costs higher than exporter's. If there is energy surplus and transmission lines are available, but there is no such price difference, the energy surplus goes to the sink, which allows to account for energy that is available but not being harnessed, as the spilled water in the hydropower plants. All the values can be seen in **Figure 13**, where the mean value of the 250 stochastic realizations is shown. As a measure of consistency, the total sink from the Closed Market setting equals the sum of exports and sinks from the Open Market setting.

Figure 10: Energy balance for the 95th perc. of cumulated not-supplied energy – SC01 Open Market

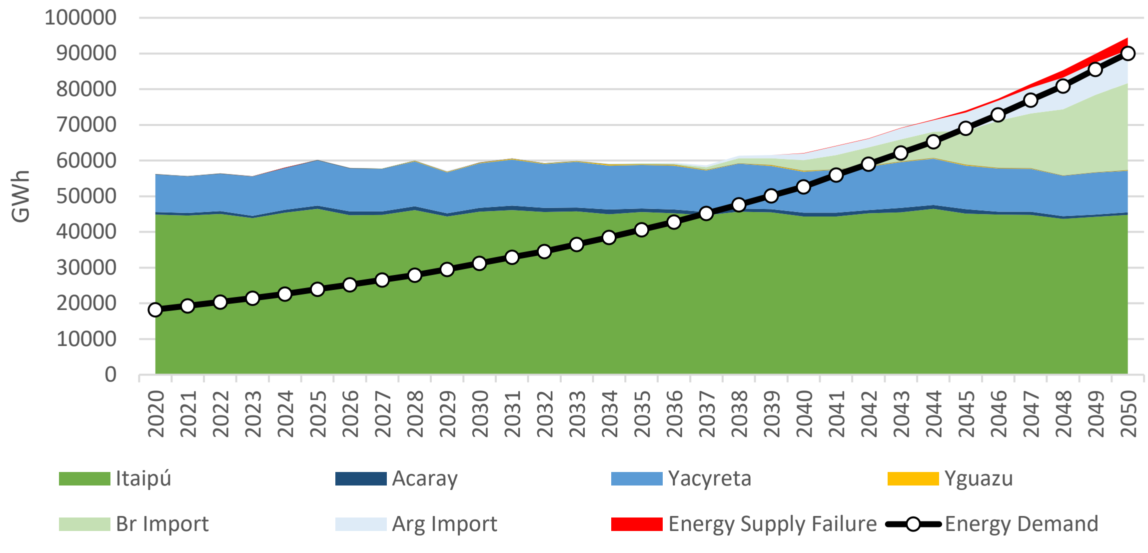


Figure 11: Power balance for P1 load and 95th percentile of cumulated not-supplied energy – SC01 Open Market

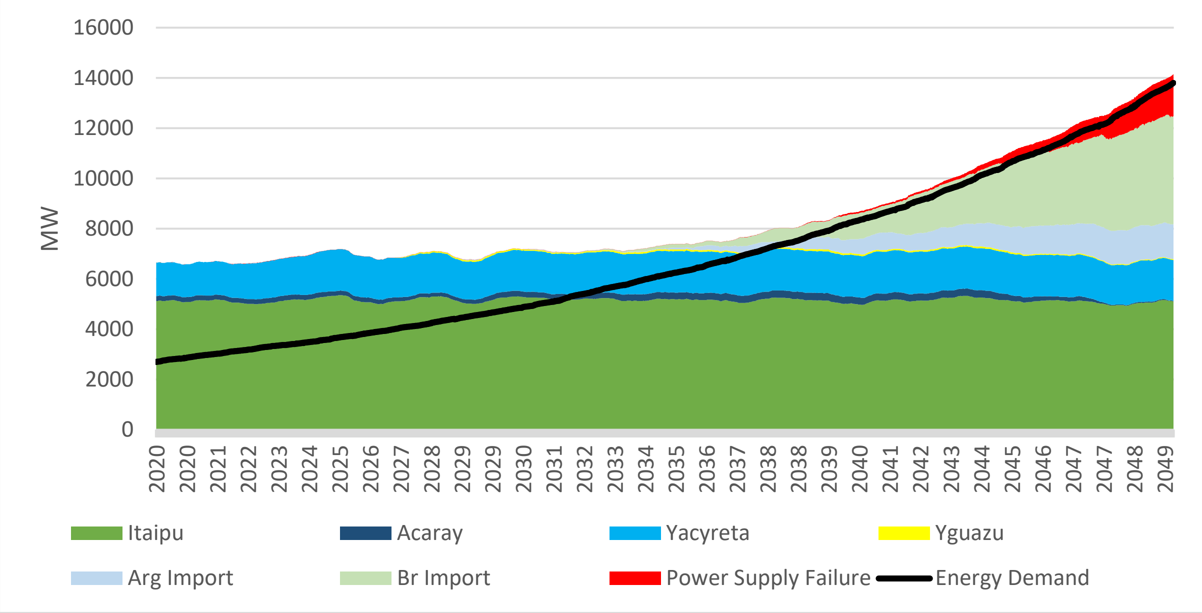


Figure 12: Power Supply Failure Frequency – SC01 Open Market

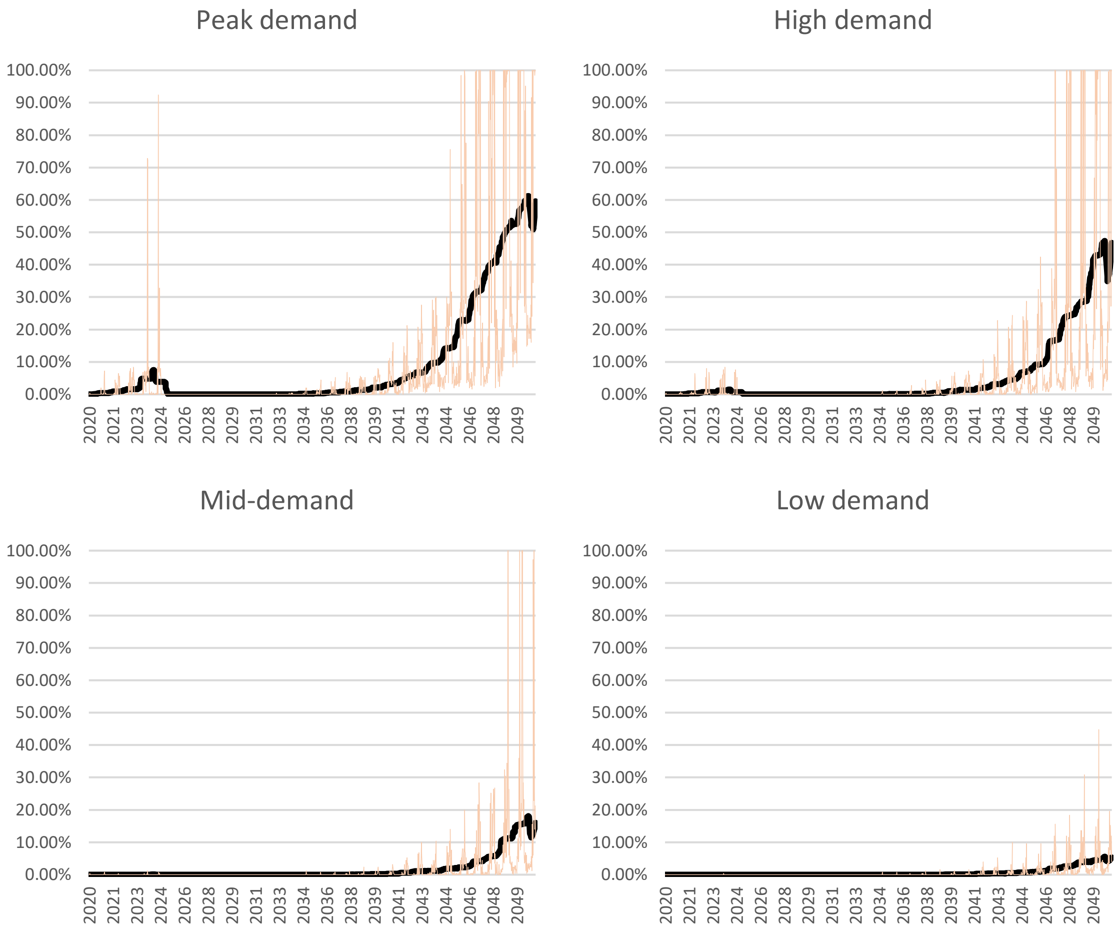
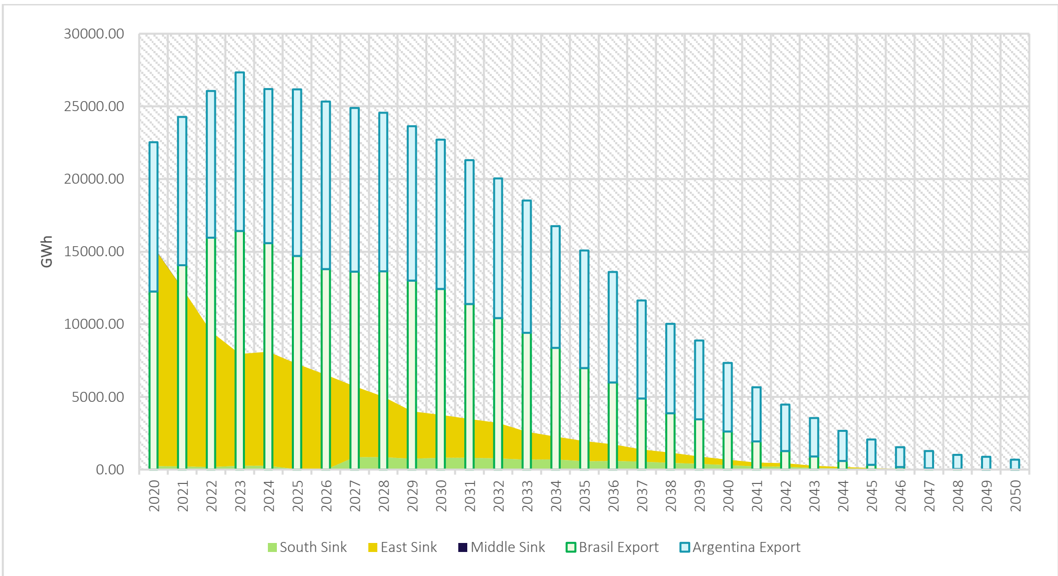


Figure 13: Exports and sinks for the 95th perc. of cumulated not-supplied energy – SC01 Open Market



Paraguay's projected peak demand is shown in Figure 14. As explained in the demand model section, these values represent the mean of the 5 hours of the week with the highest demand. The values for 2025, 2035, and 2050 are 4725 MW, 8050 MW, and 18,000 MW, respectively.

In Table 2, numerical results for 2030, 2040 and 2050 from SC01 can be observed. It can be seen that the peak demand triples in value from 2030 to 2050. It can also be observed that the energy supply failure occurs already in 2040.

Figure 14: Annual peak demand – SC01

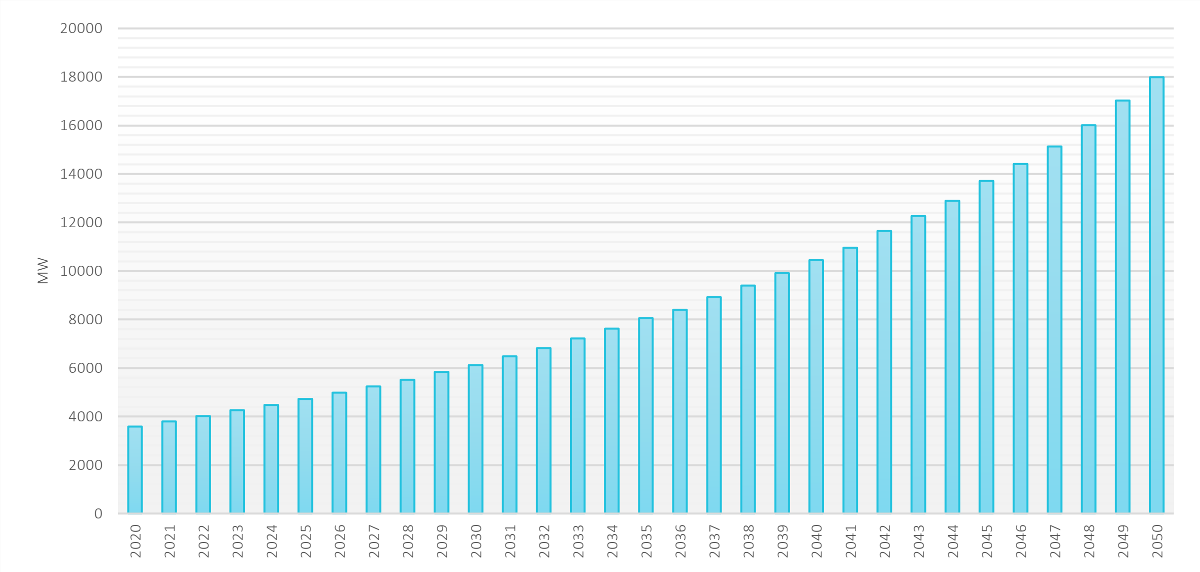


Table 2: Numerical results for key parameters at key years – SC01 Open Market

Component	Unit	2030	2040	2050
Peak Demand	MW	6119	10445	17988
Exports to Brazil	GWh	12426	2631	3.4
Exports to Argentina	GWh	10277	4710	682
Imports from Brazil	GWh	22	2466	25779
Imports from Argentina	GWh	220	1813	8112
Sinks (Argentina and Brazil)	GWh	3761	688	2.70
Not-supplied Energy	GWh	0.00	31	2869
Output from Itaipú	GWh	45022	44913	45040
Output from Yacyretá	GWh	12110	12039	12004
Output from Acaray	GWh	1121	1059	842
Output from Yguazú	GWh	227	191	144

5.2. Alternative Scenarios

5.2.1. SC02 – Alternative Demand (Carbon-neutrality for Paraguay by 2050)

SC02 assesses power and energy supply needs up to 2050 by assuming a carbon-neutral pathway for Paraguay's energy system, still without long-term adequation of generation resources. Based on LEAP results (Product 1), the annual energy demand of the Carbon Neutrality Scenario (SC3) was used to project energy needs. This scenario implements the substitution of biomass, and hydrocarbons for electricity in all sectors, *i.e.*, residential, industrial, commercial & services, and transportation. Demand for green hydrogen production is also included. In addition, the scenario considers major efficiency gains in all end-uses. The energy demand calculated with LEAP involves the final consumption. Thus, transmission and distribution losses need to be included in order to obtain the energy demand for our purposes. For representing an eventual progression of network efficiency, a projection of reduction in transmission and distribution losses is considered. Here, this projection is based on goals set by the National Energy Policy 2040, meaning a reduction of total losses from 25.5% in 2020, to 15.5% in 2040, and to 15% in 2050.

Results are very similar to those from SC01. The reason is that the energy demand resulting from final consumption plus losses is only little less behind the demand from the base scenario. This can be seen in the energy balance of Figure 15. Nevertheless, growth rates during the time horizon are different. For instance, this scenario includes higher growth rates at the beginning of the period, resulting in higher absolute demand, even though electricity losses are reduced. As a result, the frequency of not-supplied energy for the peak demand starts to grow in 2029, one year before than in the base scenario, as can be seen in Figure 16 and Figure 17.

When analyzing marginal costs at the border nodes, values are as well similar to those from SC01 as shown in Figure 18 and Figure 19. In this case, marginal costs at the Paraguayan nodes surpass the neighboring countries costs in 2032, one year before than in SC01.

Figure 15: Energy balance for the 95th perc. of cumulated not-supplied energy – SC02 Closed Market

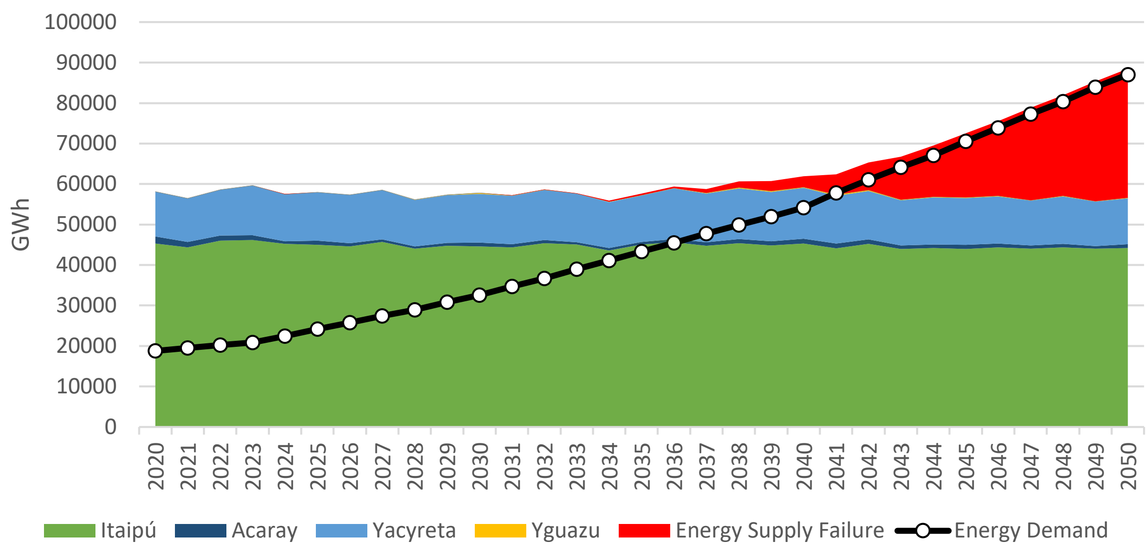


Figure 16: Power balance for P1 load and 95th percentile of not-supplied energy – SC02 Closed Market

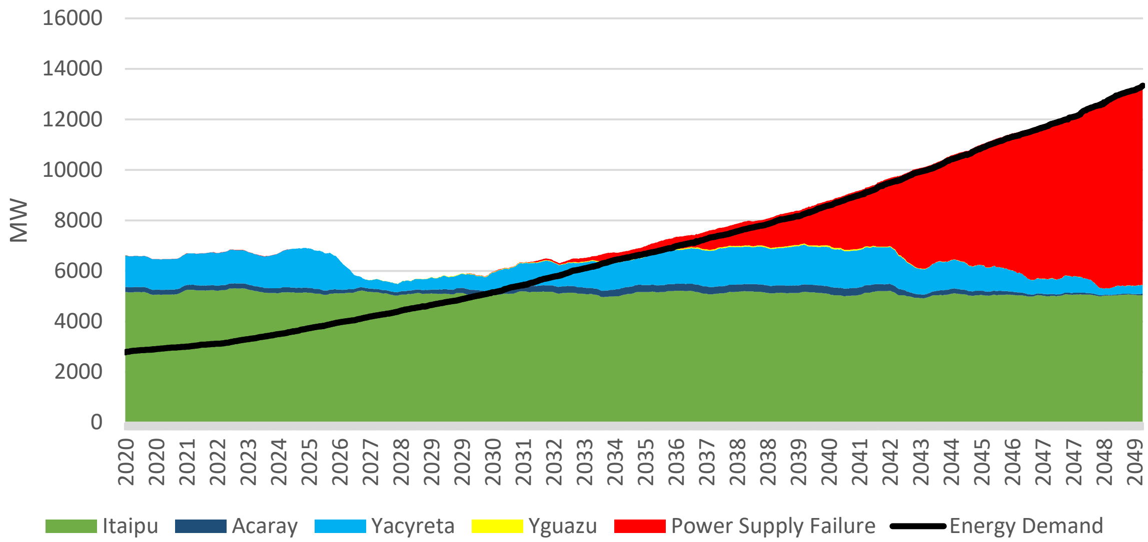


Figure 17: Power Supply Failure Frequency – SC02 Closed Market

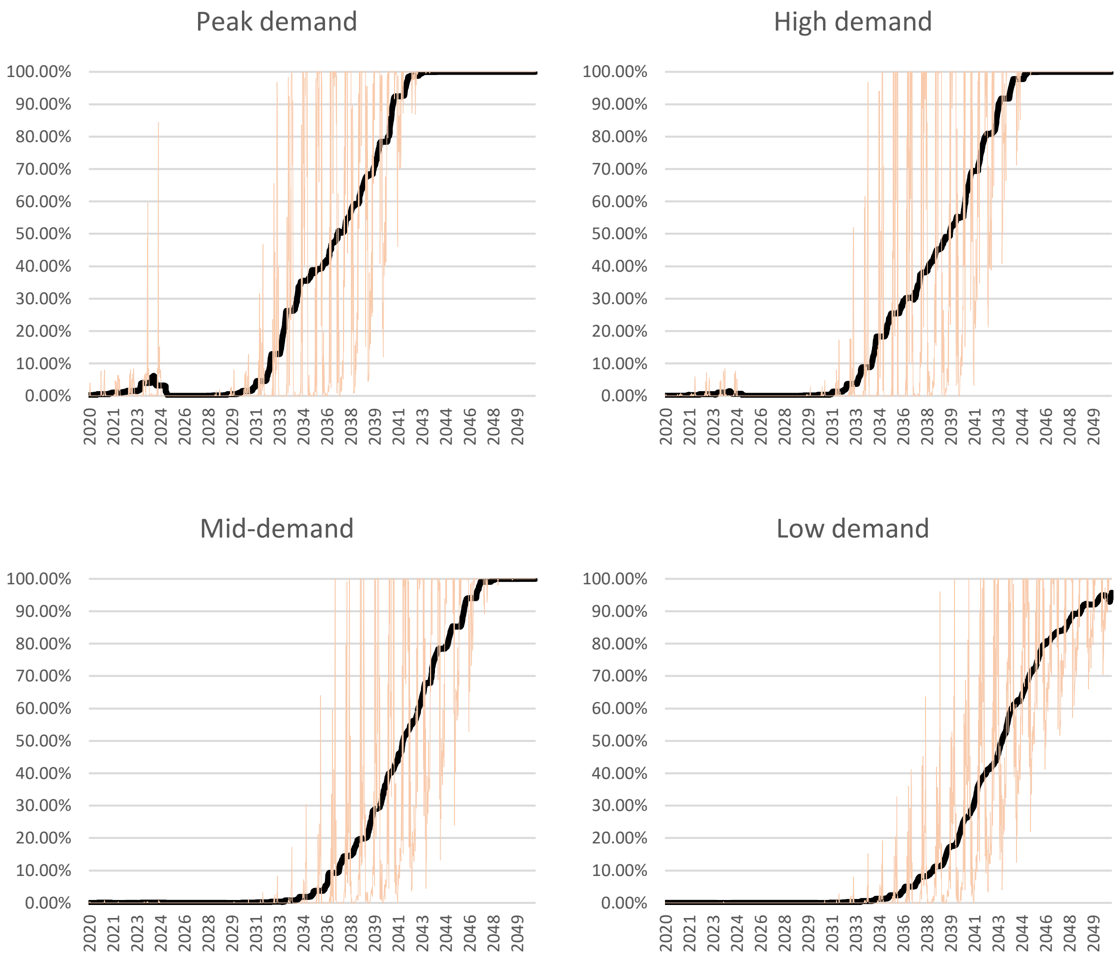


Figure 18: Marginal cost in Paraguay's East and Brazil's South nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC02 Closed Market

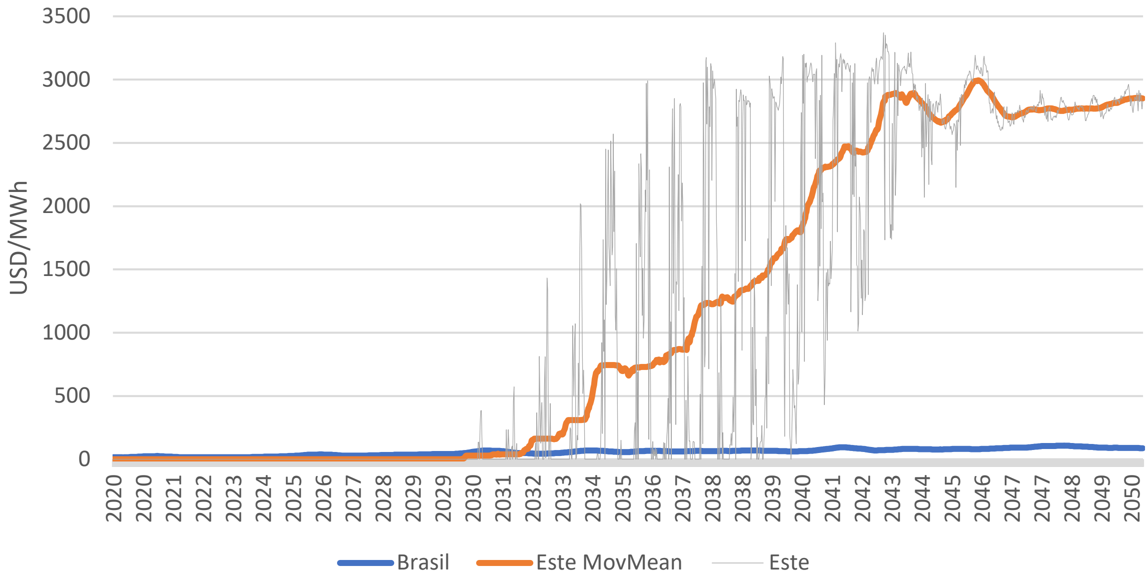
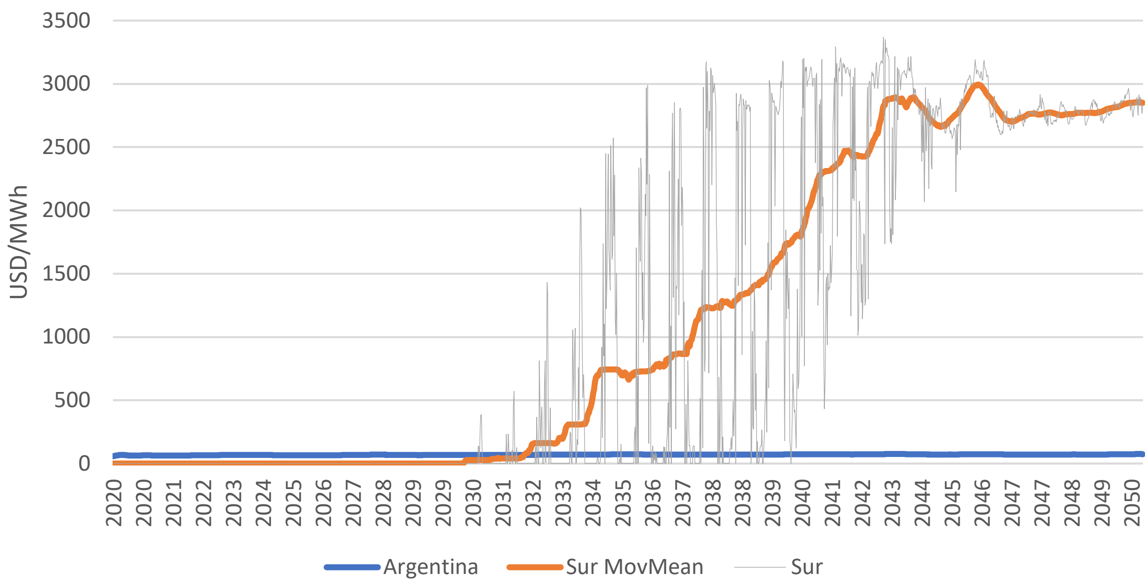


Figure 19: Marginal cost in Paraguay's East and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC02 Closed Market



In the Open Market setting, the energy balance (Figure 20) shows a slight difference in comparison to SC01: not-supplied energy is less and grows more gradually. The reason can be that demand growth follows a linear pattern, in contrast with the exponential growth model assumed for the demand in SC01. The failure frequency for peak and low demand (Figure 21) has a similar pattern to SC01. The reason is that demands converge in the last part of the horizon, at the same time when not-supplied energy starts rising in the Open Market case.

Figure 20: Energy balance for the 95th perc. of cumulated not-supplied energy – SC02 Open Market

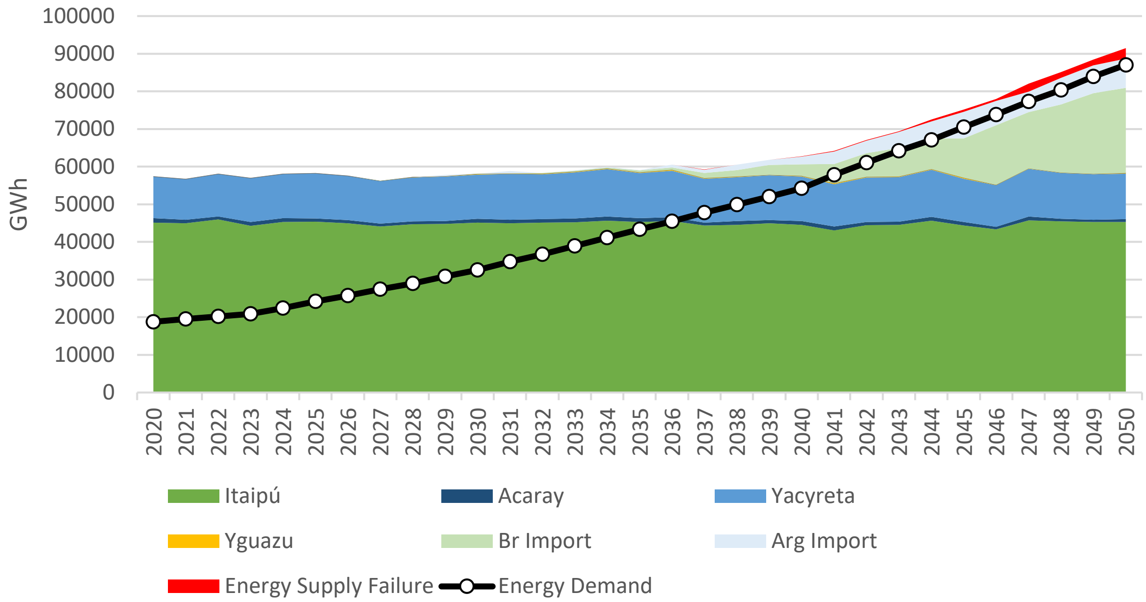
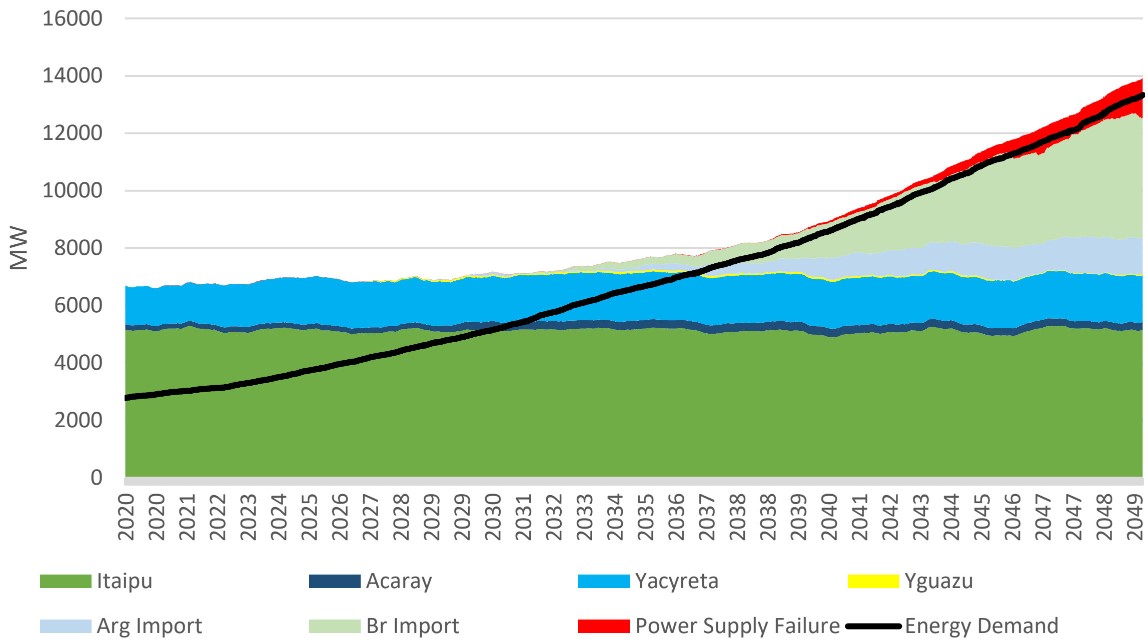


Figure 21: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC02 Open Market



According to the power dispatch shown in **Figure 21**, at the end of the time horizon, the difference in not-supplied energy with respect to SC01 is significant. The main reason is that the transmission line linking the East Node (where the generation and the access to imports are) and the Central Node (where the demand is) starts to be congested. Therefore, not-supplied energy grows at almost the same rate of demand.

Figure 22: Power Supply Failure Frequency – SC02 Open Market

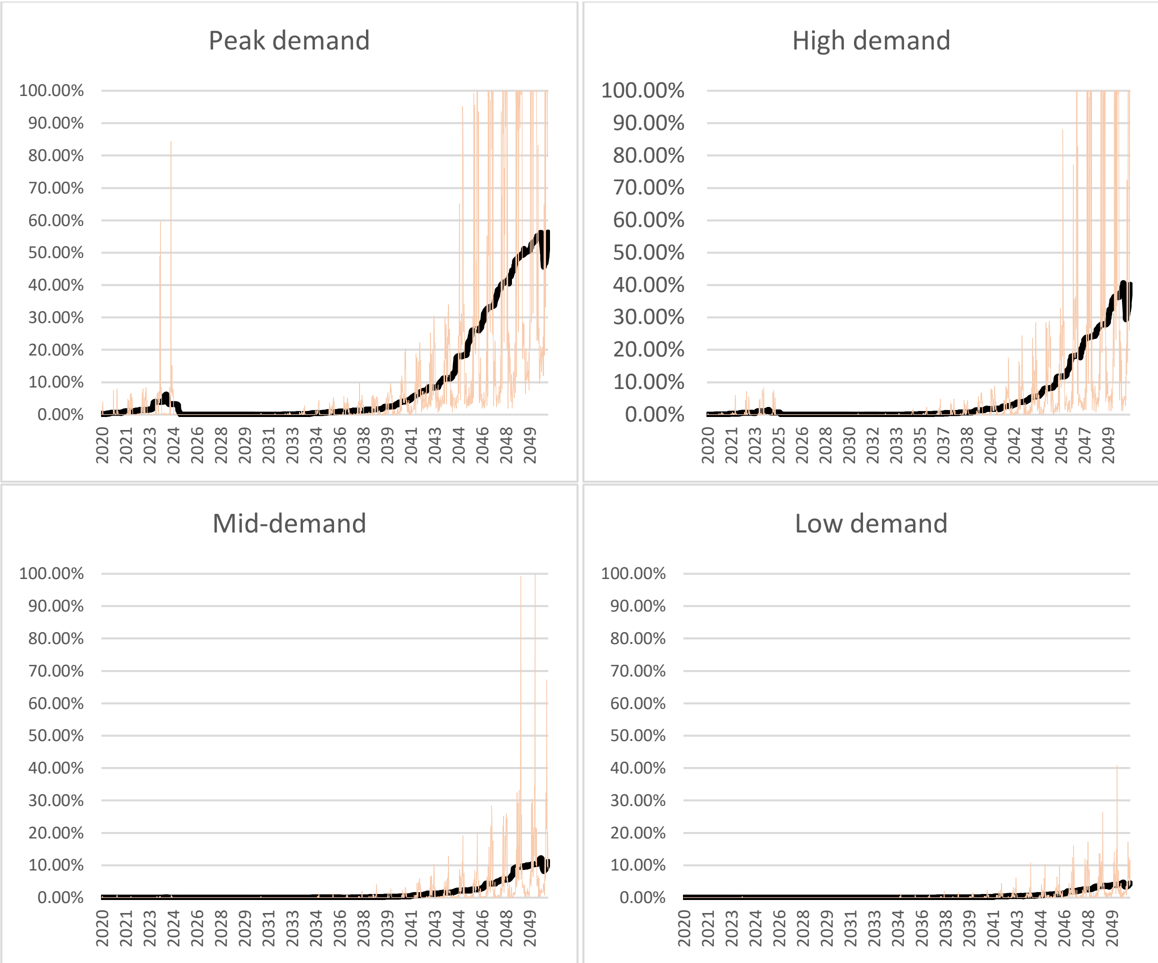
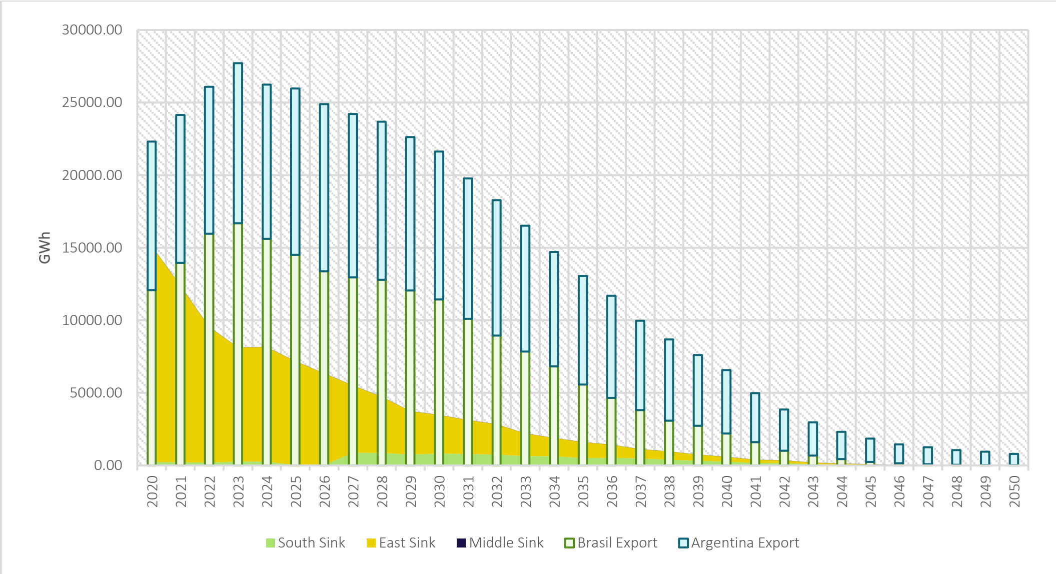


Figure 23: Exports and sinks for the 95th perc. of cumulated not-supplied energy – SC02 Open Market



Failure frequencies for the four load bands are shown in **Figure 22.** For the peak and high demand, these probabilities reach 60% and 40%, respectively, by 2050. On the other hand, for the mid and low demands, the percentages are much lower, 10% and 5%, respectively. That can be explained in terms of the low load factor together with line congestion.

In **Figure 23**, mean exports and sink values are shown. Exports are reduced more rapidly between 2030-2040 in comparison to SC01. Finally, numerical values of generation output, imports, exports, and peak demand for 2030, 2040, and 2050 are shown in **Table 3**.

Table 3: Numerical results for key parameters at key years – SC02 Open Market

Component	Unit	2030	2040	2050
Peak Demand	MW	6388	10746	17368
Exports to Brazil	GWh	11449	2208	8.8
Exports to Argentina	GWh	10167	4353	785
Imports from Brazil	GWh	36	2957	23692
Imports from Argentina	GWh	232	2008	7738
Sinks (Argentina and Brazil)	GWh	3484	592	6.1
Not-supplied Energy	GWh	0.00	38.8	2237
Output from Itaipú	GWh	45022	44913	45040
Output from Yacyretá	GWh	12111	12040	12005
Output from Acaray	GWh	1113	1039	847
Output from Yguazú	GWh	232	210	148

5.2.2. SC03 – ANDE's Generation Master Plan 2021–2040 (with Carbon-neutral demand)

For the definition of ANDE's Master Plan of Generation 2021-2040 [4], several factors were taken into account, such as: topological configurations of the interconnected system, requirements of reliability, quality, and availability of existing generation plants, demand growth scenarios and availability of energy resources in Paraguay.

In that sense, the Short, Medium and Long-term Generation Master Plan was developed based on:

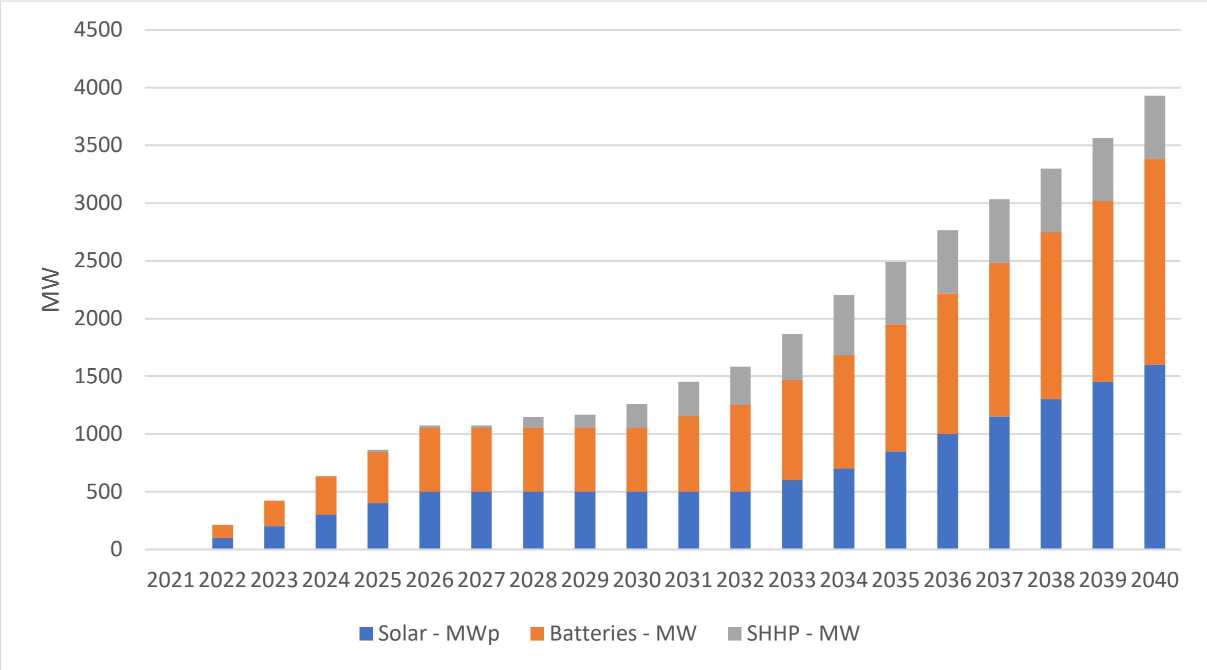
- The adoption of an electricity market scenario with an average annual growth rate of 4,88 % over 2021-2040
- The "Inventory of Hydro-Energy Resources of the River Basins of the Tributary Rivers of Paraguay in the Eastern Region of Paraguay" [4], with the aim of identifying sites with usable hydropower potential of 1 MW or more, targeting small and medium hydropower plants
- The premise of accompanying and ensuring the development of the Western or Chaco region, and promoting the use of Non-conventional Renewable Energies (NCRE);
- The analysis of generation reserve, sustainability, primary energy sources and energy reserves in Paraguay.

Figure 24 shows the aggregated capacity to be put in place according to the Master Plan schedule. In 2040, the aggregated capacity would be: 550 MW of hydropower plants and small hydropower plants, with 322 aMW[1] of firm energy; 1600 MWp of solar photovoltaic; and 7100 MWh of battery storage, with a maximum output power of 1780 MW, over 4 hours.

In that sense, SC03 considers the supply expansion as scheduled by ANDE's Generation Master Plan while demand is associated to the projection of the carbon-neutral scenario resulting from the LEAP model. In comparison to the Carbon-neutral Scenario without investments, here the expected not-supplied energy for the 95th percentile is reduced from 0.12% to 0.08% in 2033, and from 4.88% to 3% in 2040. With the availability of transboundary exchanges, not-supplied energy is reduced from 0.06% to 0.04% in 2040, and in 2050 is reduced from 3.3% to 2.4%. These values are illustrated in Figure 25 and Figure 30.

[1] aMW: average Megawatts

Figure 24: Aggregated capacity in ANDE´s Master Plan 2021-2040 – SC03



The power dispatch for the peak demand is shown in Figure 26. Here, results again show a reduction of the contribution of Yacyreta when the critical situation starts. Figure 27 shows that the probability of failure for the peak and low demand start being more than 5% in 2033 and 2038, respectively. It is worth to note this, because, despite the investments, apparently only little can be done to delay the occurrence of critical supply situations. This can be explained in terms of the lack of chronological coincidence of demand and new supply resources, namely solar (with peak at noon) and demand (with peak at night).

In this scenario, new investments in small hydropower plants, solar PV, and batteries delay the time when the marginal cost in the East Node of Paraguay surpasses the Brazilian marginal costs for the peak demand, from 2032 without investments, to 2034 with investments (Figure 28 and Figure 29).

Figure 25: Energy balance for the 95th perc. of cumulated not-supplied energy – SC03 Closed Market

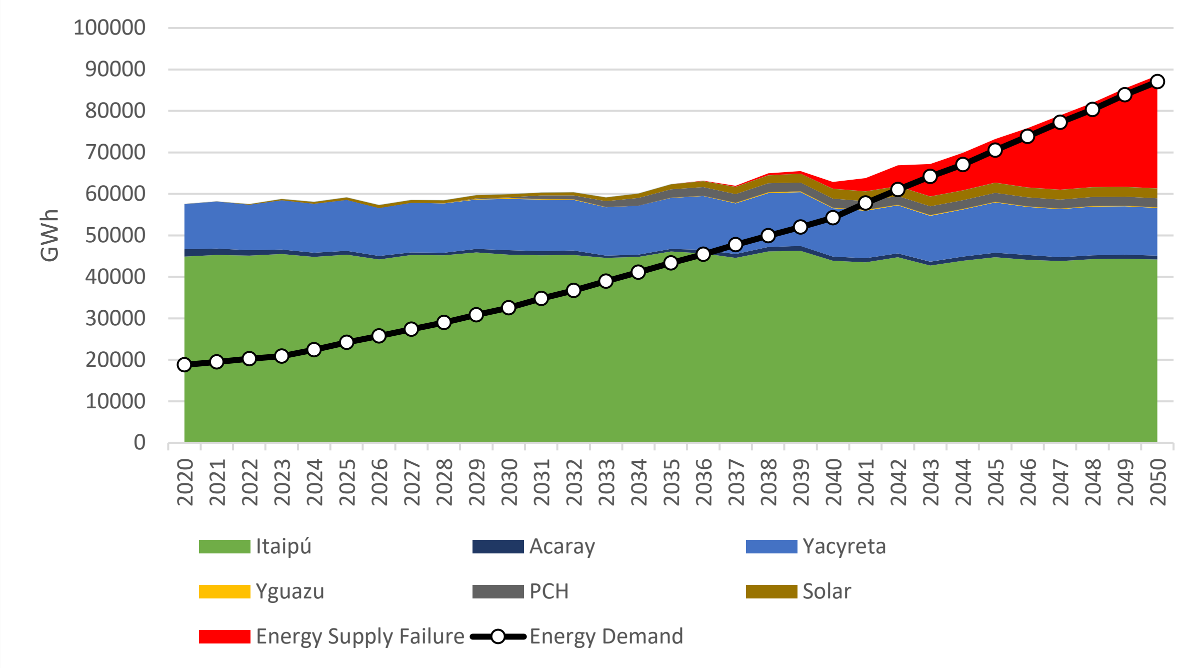


Figure 26: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC03 Closed Market

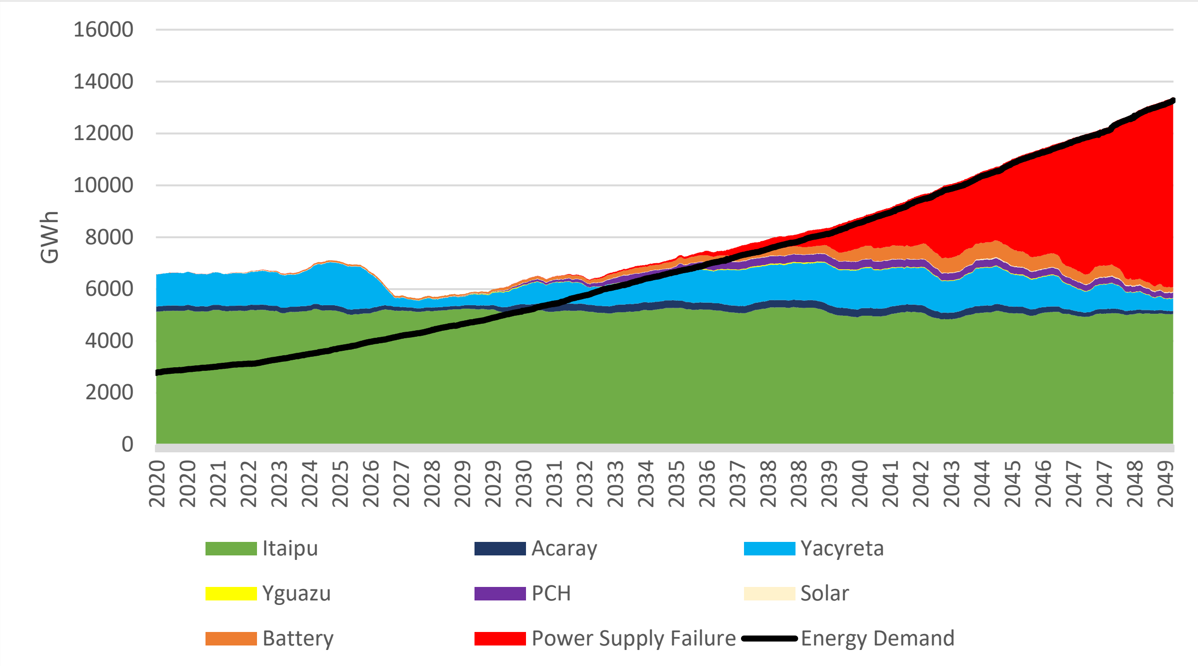


Figure 27: Power Supply Failure Frequency – SC03 Closed Market

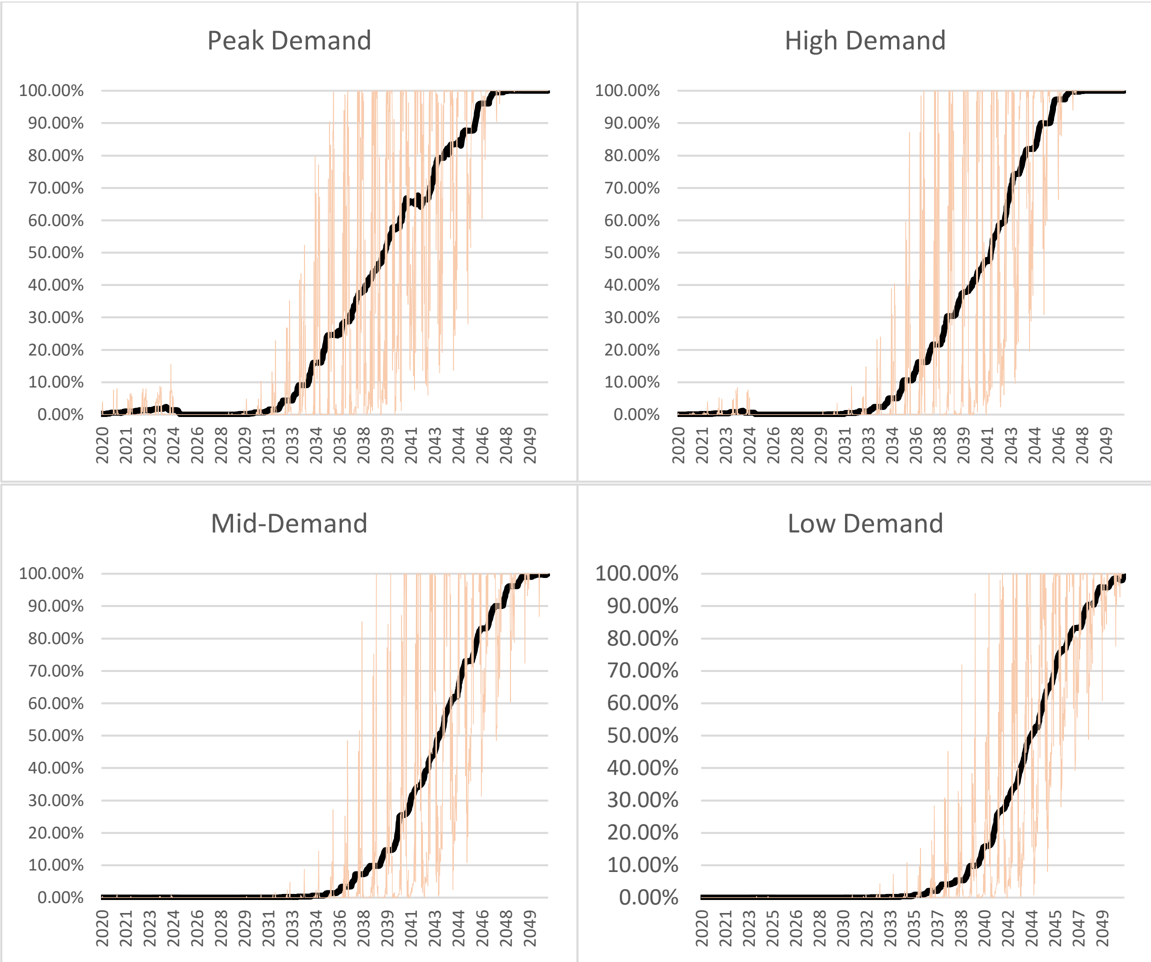


Figure 28: Marginal cost in Paraguay's East and Brazil's South nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC03 Closed Market

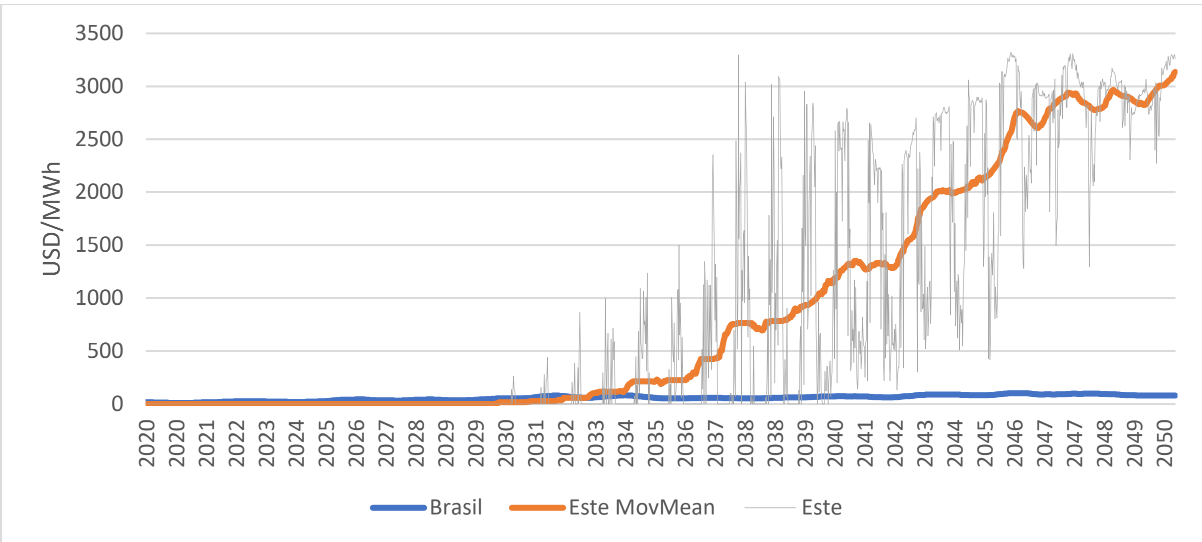


Figure 29: Marginal cost in Paraguay's East and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC03 Closed Market

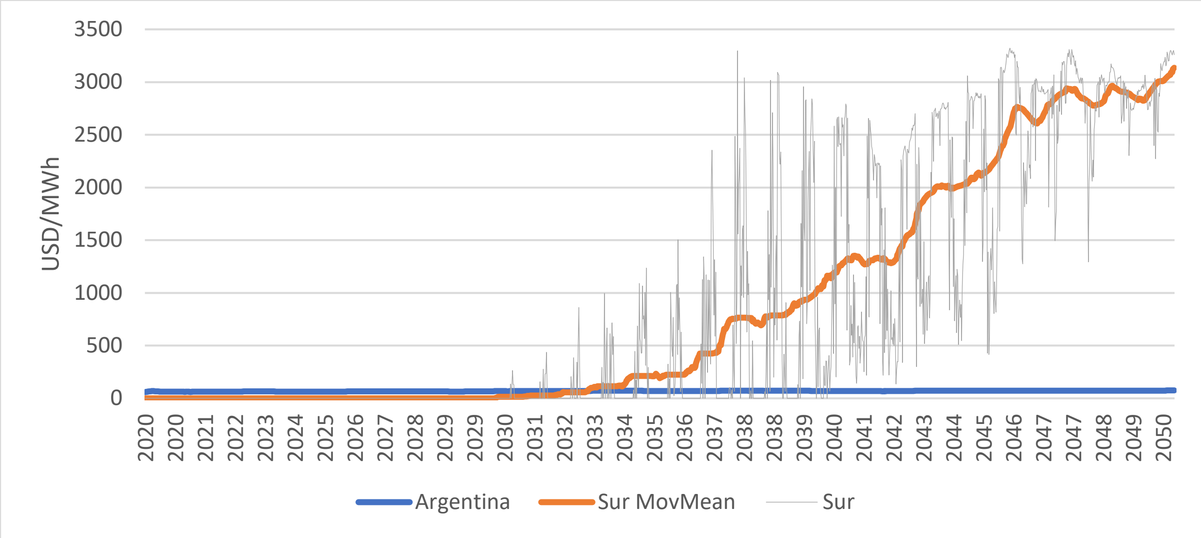


Figure 30: Energy balance for the 95th perc. of cumulated not-supplied energy – SC03 Open Market

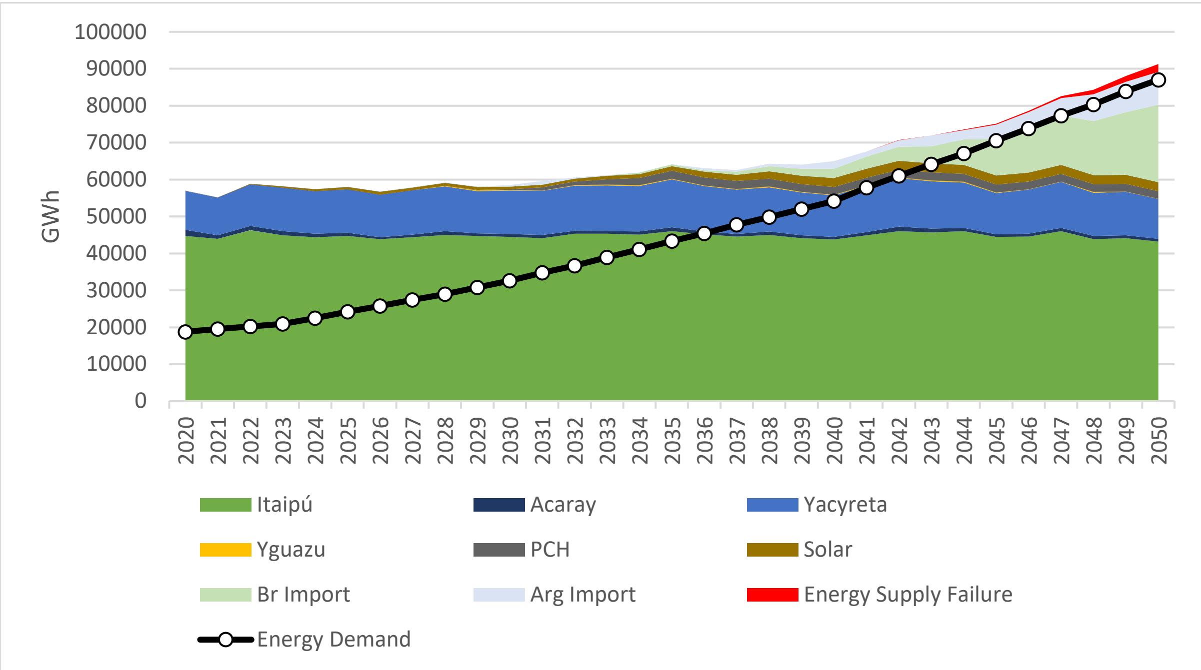


Figure 31: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC03 Open Market

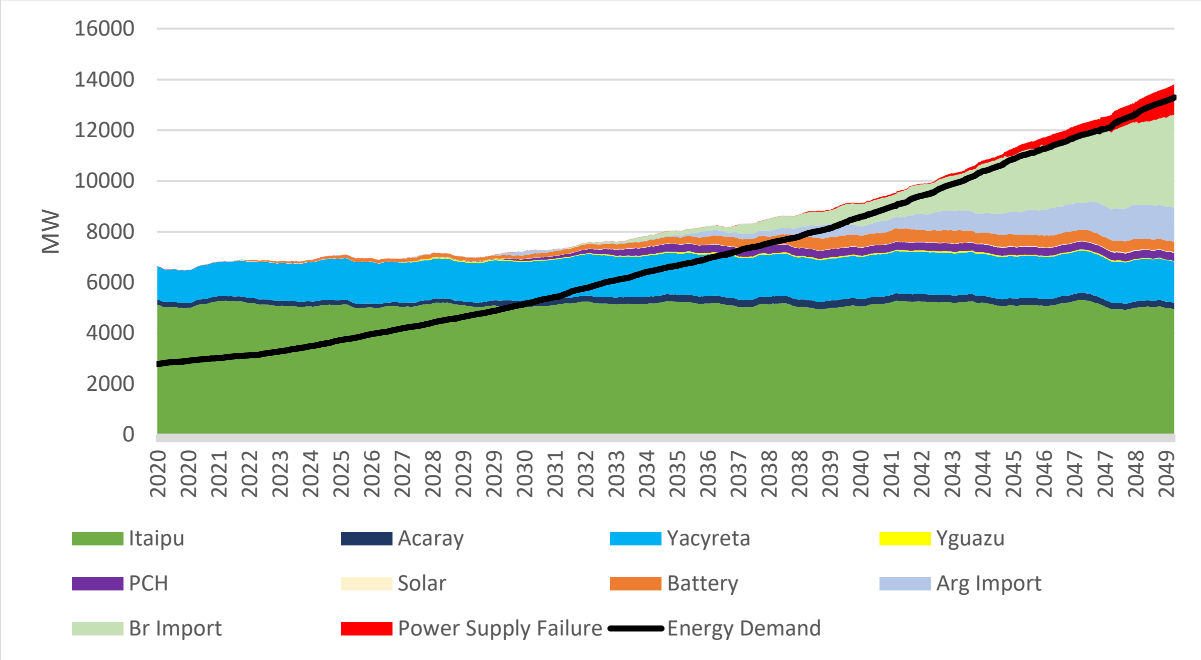


Figure 32: Power Supply Failure Frequency – SC03 Open Market

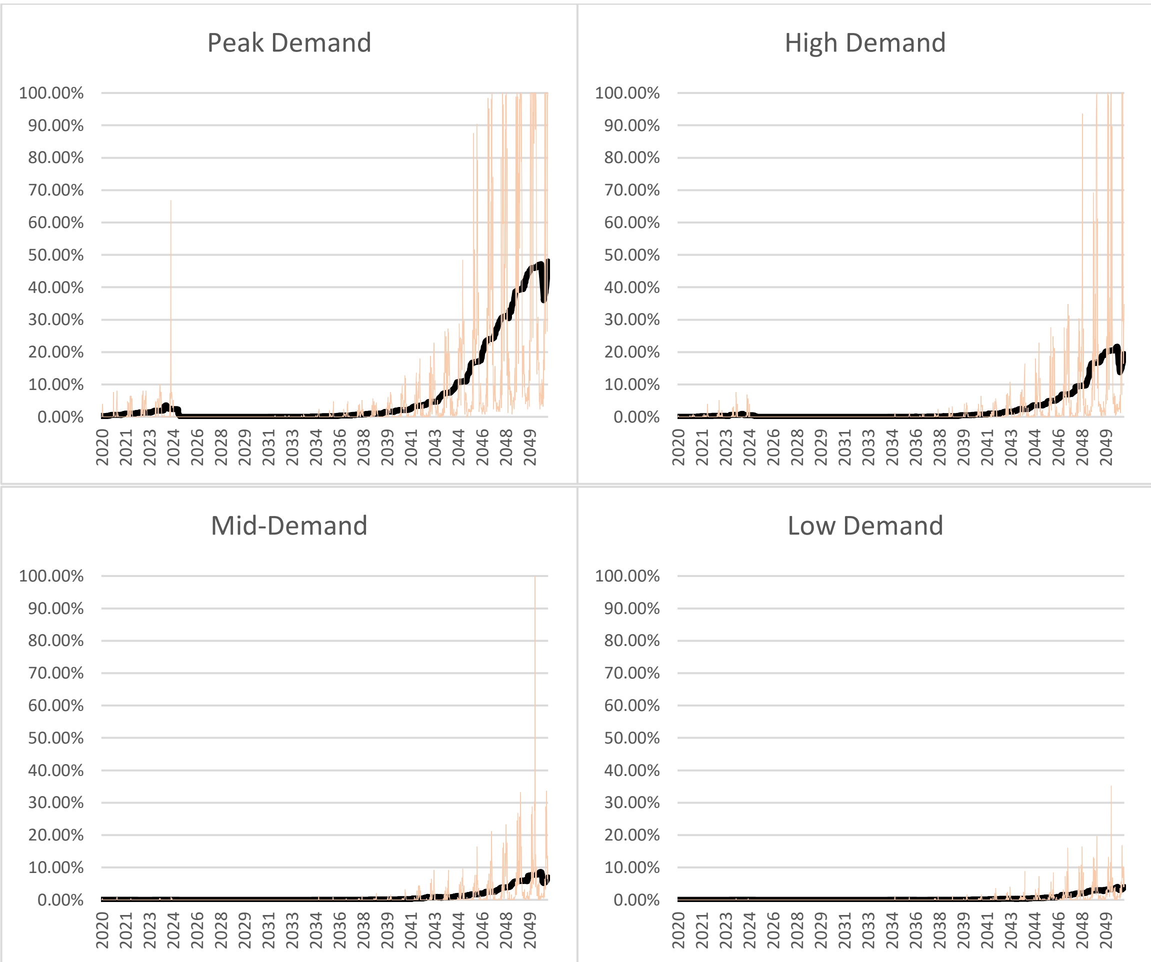
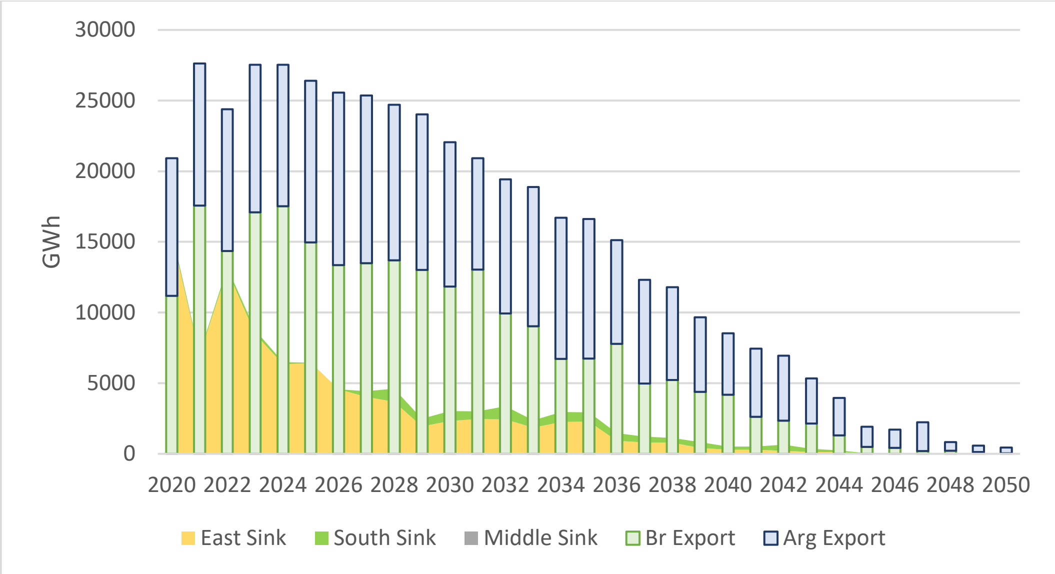


Figure 33: Exports and sinks for the 95th perc. of cumulated not-supplied energy – SC03 Open Market



The energy and power balances for this scenario when considering an Open Market setting are shown in **Figure 30** and **Figure 31**, respectively. Here, failure frequencies for the peak load start to be greater than 5% in 2039 (**Figure 32**).

Exports for the period 2020-2035 increase in this scenario, as the new generation accounts for zero marginal cost, thus almost all the new energy surplus is exported, as can be seen in **Figure 33**. Finally, in **Table 4**, numerical results of generation output, imports, exports, and peak demand, for 2030, 2040, and 2050 are shown.

Table 4: Numerical results for key parameters at key years – SC03 Open Market

Component	Unit	2030	2040	2050
Peak Demand	MW	6388	10746	17368
Exports to Brazil	GWh	11882	4328	29
Exports to Argentina	GWh	10192	4335	400
Imports from Brazil	GWh	106	2519	20931
Imports from Argentina	GWh	299	2022	8945
Sinks (Brasil and Argentina)	GWh	2994	500	0.00
Not-supplied Energy	GWh	0.00	23	2105
Output from Itaipú	GWh	44486	43816	43229
Output from Yacyreta	GWh	11789	11244	10840
Output from Acaray	GWh	746	680	594
Output from Yguazu	GWh	188	146	90
Output from New Small Hydro Plants	GWh	130	2123	2063
Output from Solar	GWh	752	2425	2425

5.2.3. SC04a – ANDE's Generation Master Plan 2021-2040 + new Binational Hydropower Plants (BHP) (with Carbon-neutral Demand)

Paraguay still has the possibility to develop large Binational Hydropower Plants (BHP), namely, Corpus Christi and Itati-Itacora, both with Argentina. Moreover, the Itati-Itacora development would allow Yacyreta to be expanded with another ten turbines. To assess this expansion, this scenario simulates the construction of new binational hydropower plants according to the schedule shown in **Figure 34.** Here, generators come online progressively, according to ANDE's Master Plan schedule. Furthermore, after 2030, investments in Solar PV and Batteries are disregarded as it is described in Table VI of ANDE's Master Plan. Small hydropower plants are constructed in both cases.

Figure 34: Aggregated capacity of new Binational Hydropower Plants, and proposed schedule – SC04

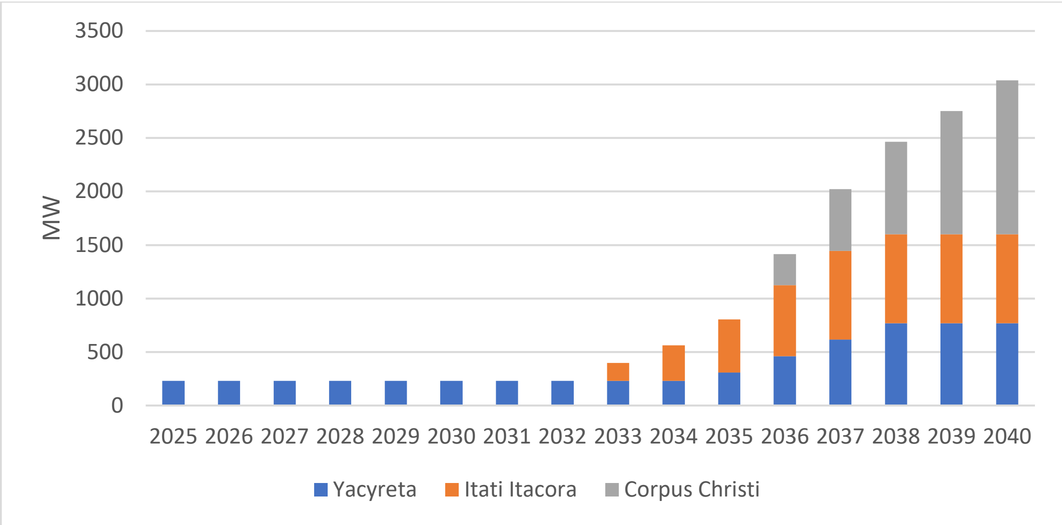


Figure 35 shows the energy balance when the new BHP are considered. Since 2040 on, Paraguay's firm energy amounts nearly 79,000 GWh, thus significant occurrences of not-supplied energy are delayed until 2044. Now, when Corpus Christi starts to operate in 2036-2040, Itaipu loses some generation output. The reason is that the creation of Corpus Christi's reservoir, downriver from Itaipu, determines the rise of the river level in Itaipu's discharge, thus reducing the height of the water level difference upstream and downstream the Itaipu dam.

Results from this scenario regarding the energy balance (**Figure 35**) and power dispatch (**Figure 36**) are noteworthy in two ways. First, the new BHP make possible to have firm energy available to supply the peak demand, thanks to their operational flexibility. However, the problem is that all the resources are in the southern and eastern zone of Paraguay, away from the main consumption center (Asunción). Therefore, if the transmission system does not expand properly up to 2050, then the transmission capacity would become a constraint, despite how many new power plants come online to satisfy the growing demand. The timely adequation of the transmission system is even more important when international exchanges are possible. However, according to recently released ANDE´s Transmission Master 2021-2030, there will be four 500kV transmission lines from the East Node (8000 MW), and two from the Southern Node (4000 MW). As a result, the transmission capacity will be enough to carry all the energy from the BHP and imports.

Figure 35: Energy balance for the 95th perc. of cumulated not-supplied energy – SC04a Closed Market

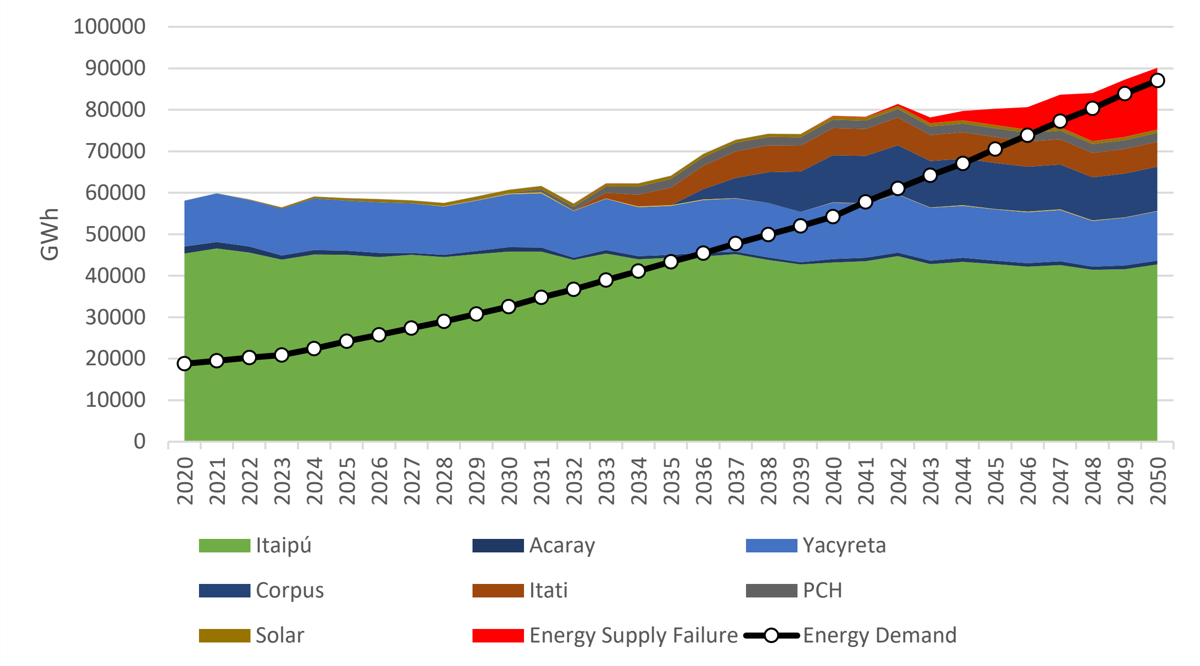
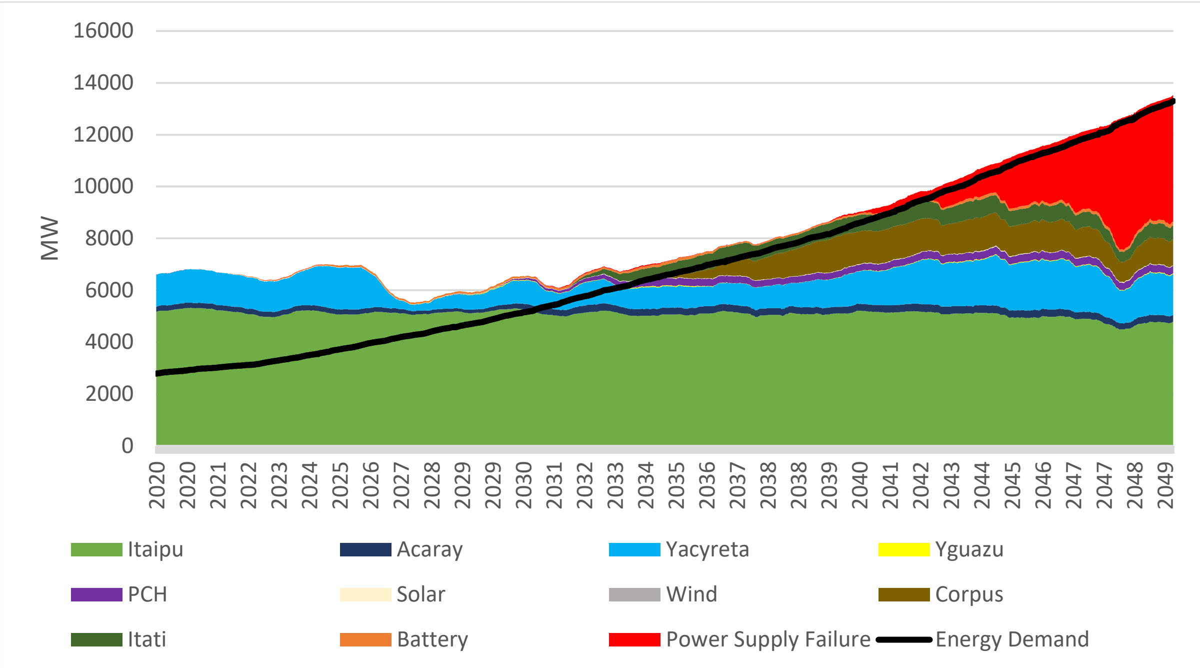
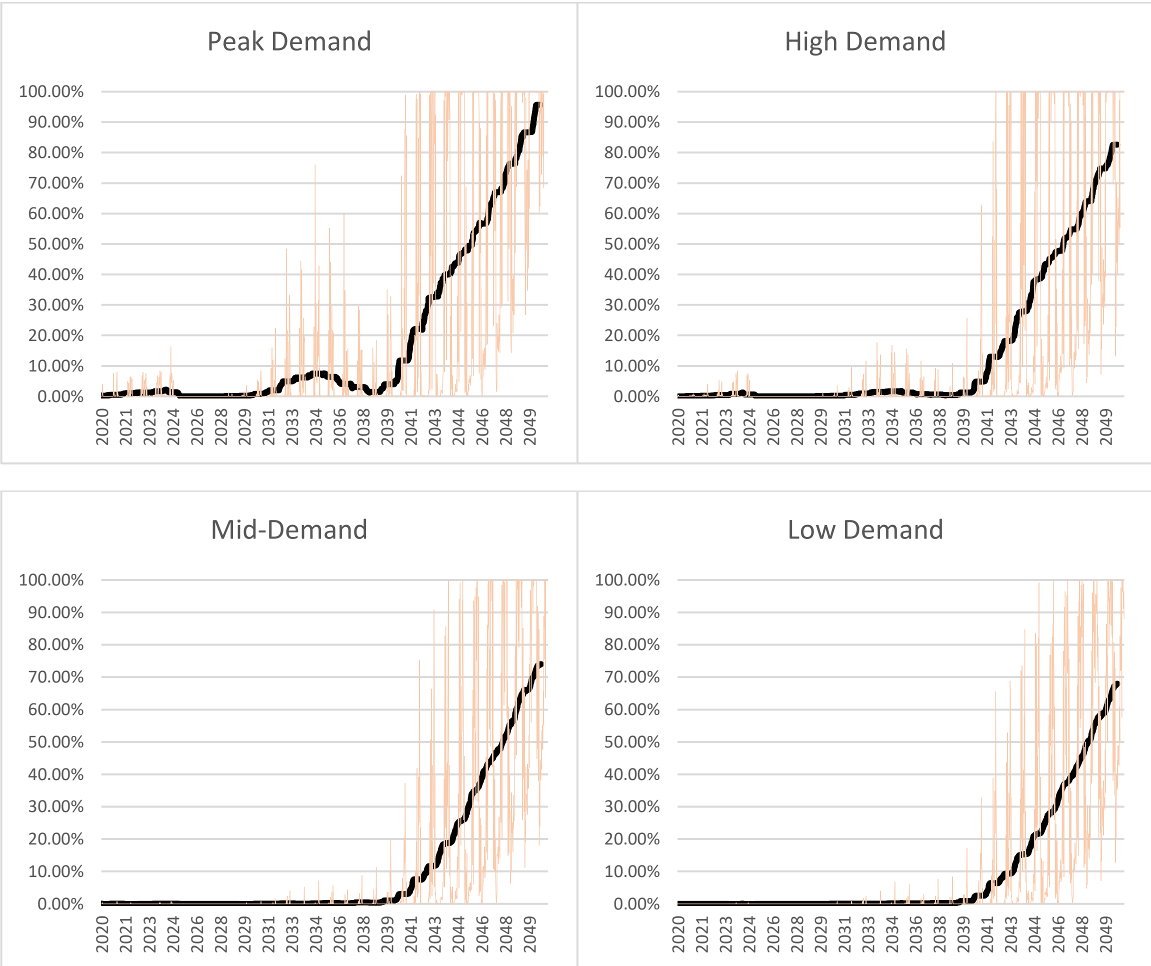


Figure 36: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC04a Closed Market



As shown in **Figure 37**, the failure frequencies for the four load bands start to rise in 2031, but are reduced again thanks to the progressive coming to operation of Itati-Itacora, the newer Yacyreta's generators, and finally Corpus Christi. Thus, the ENS frequency failures are reduced almost to zero. Before, all the generators of the BHP were put in operation in one year, as was modelled in the World Bank Model; now, they are put in operation according to the estimated schedule of ANDE's Master Plan. In addition, the failure frequencies for the four load bands depict a similar timing and pattern. Thus, the addition of BHP help to cope the low load factor. The construction of Itati-Itacora, the expansion of Yacyreta, and the construction of Corpus Christi make possible to keep the marginal costs in the exporting nodes of Paraguay low until 2040. Since 2041 however, prices in the neighboring nodes are lower than in the Paraguayan nodes, as shown in **Figure 38** and **Figure 39**.

Figure 37: Power Supply Failure Frequency – SC04a Closed Market



Now, **Figure 40** and **Figure 41** show that the international exchanges help reduce further the problem of energy supply, although there still are values of not-supplied energy. According to **Figure 42**, the failure frequency for the P1 demand is still high by 2050 (40%). Finally, **Figure 43** shows that the sink energy does not increase with the new available generation, thus all this new energy is allocated in the Brazilian and Argentinian markets thanks to the lower marginal generation costs. Finally, in Table 5, numerical values of generation output, imports, exports, and peak demand for 2030, 2040 and 2050 are observed. In this scenario, new small hydroelectric plants from the Master Plan 2021-2040 are complemented with the generation of the new BHP, Itati-Itacora and Corpus Christi.

Figure 38: Marginal cost in Paraguay's East and Brazil's South nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC04a Closed Market

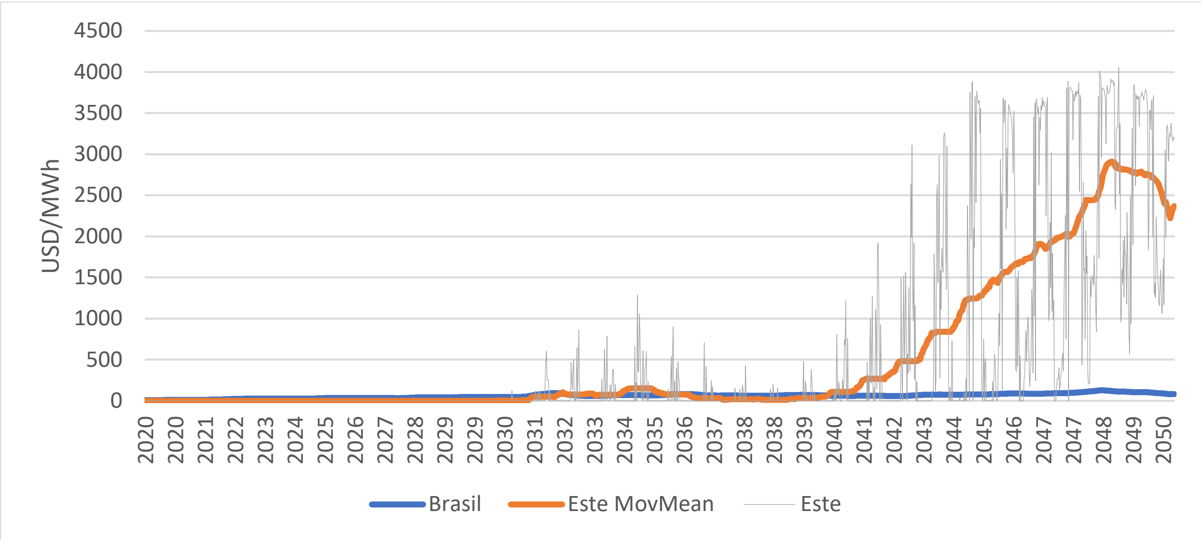


Figure 39: Marginal cost in Paraguay's East and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC04a Closed Market

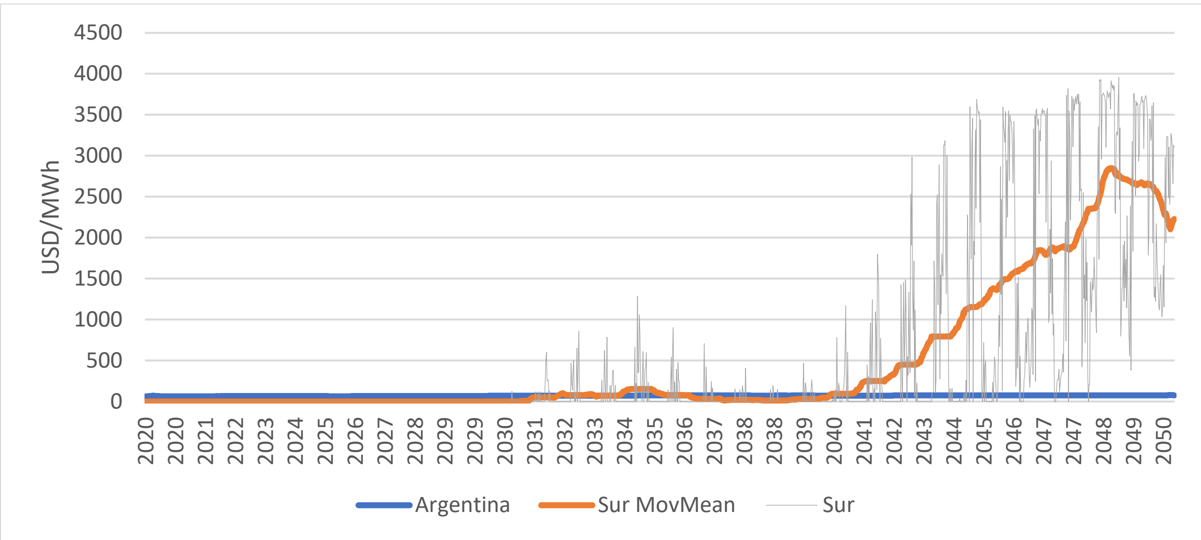


Figure 40: Energy balance for the 95th perc. of cumulated not-supplied energy – SC04a Open Market

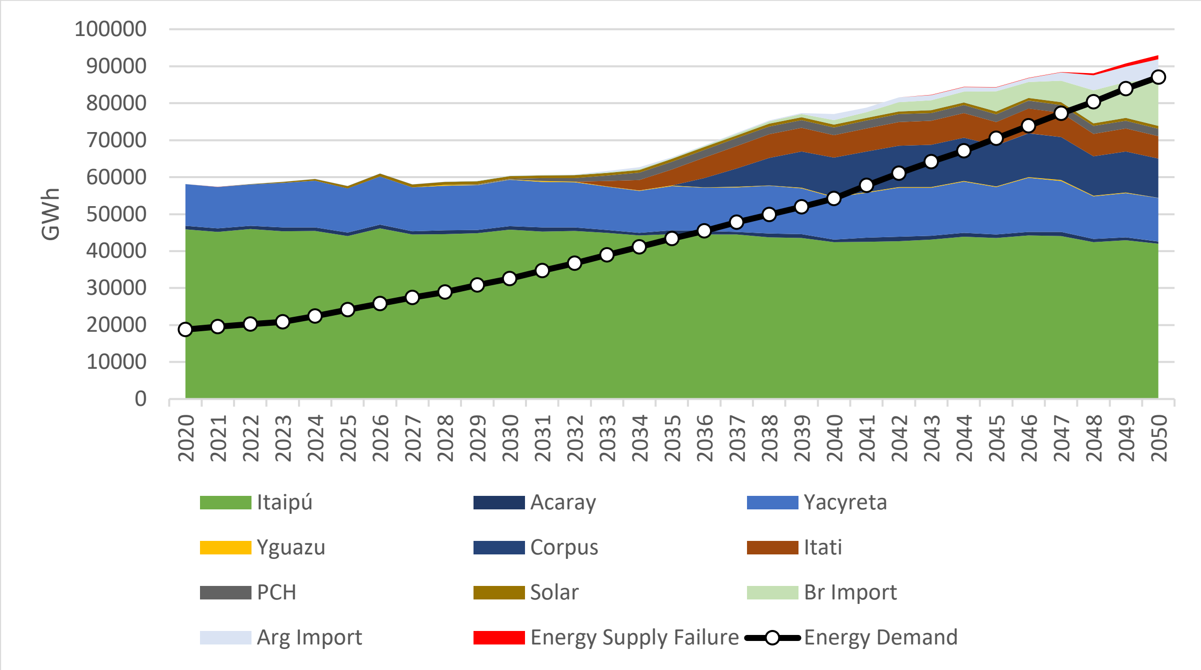


Figure 41: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC04a Open Market

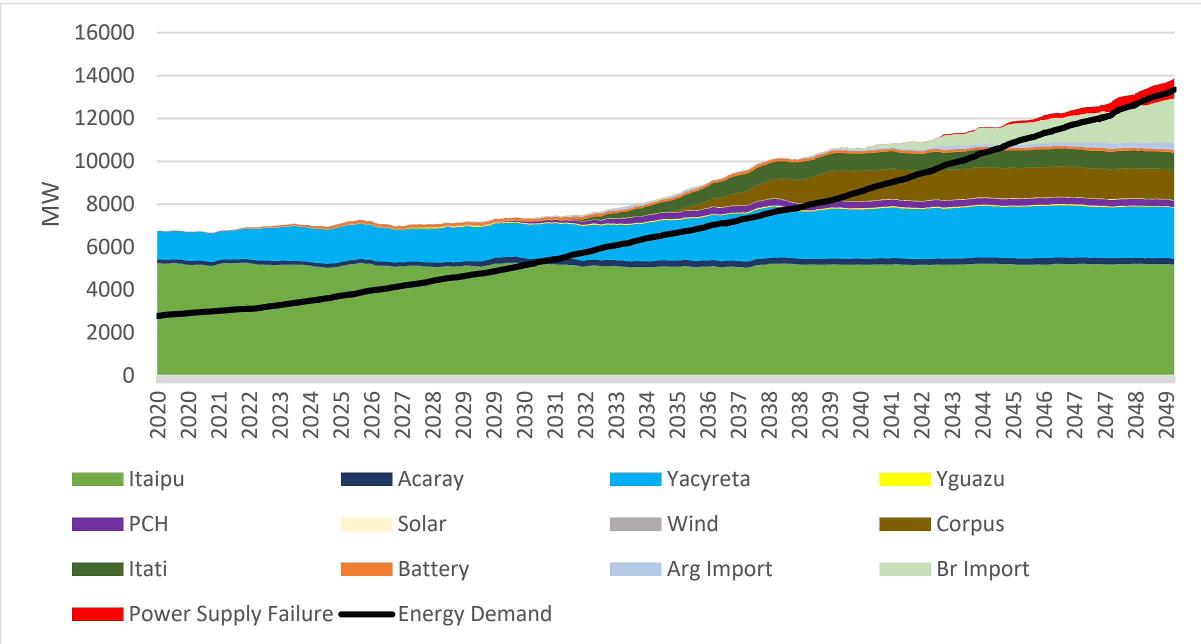


Figure 42: Power Supply Failure Frequency – SC04a Open Market

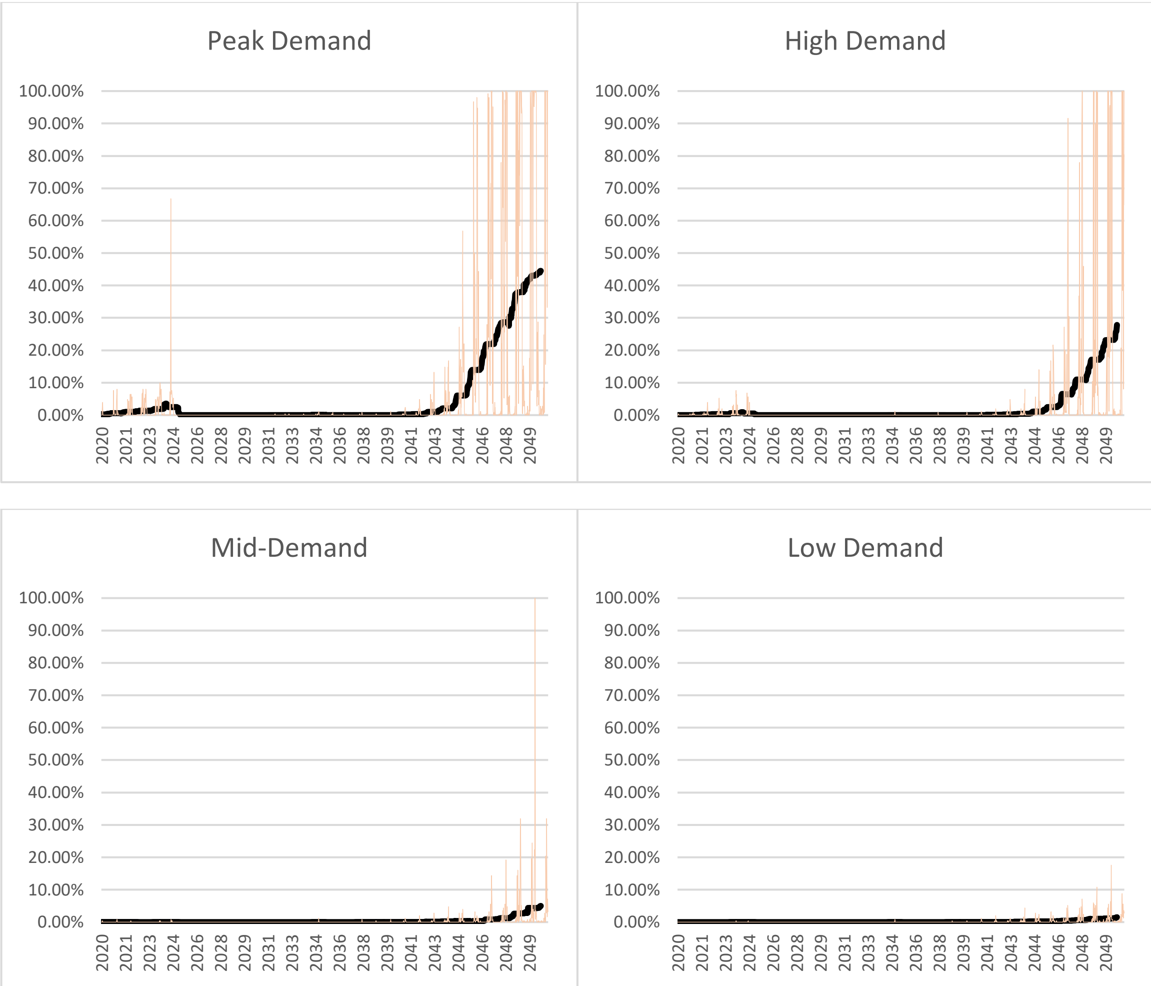


Figure 43: Exports and sinks for the 95th perc. of cumulated not-supplied energy – SC04a Open Market

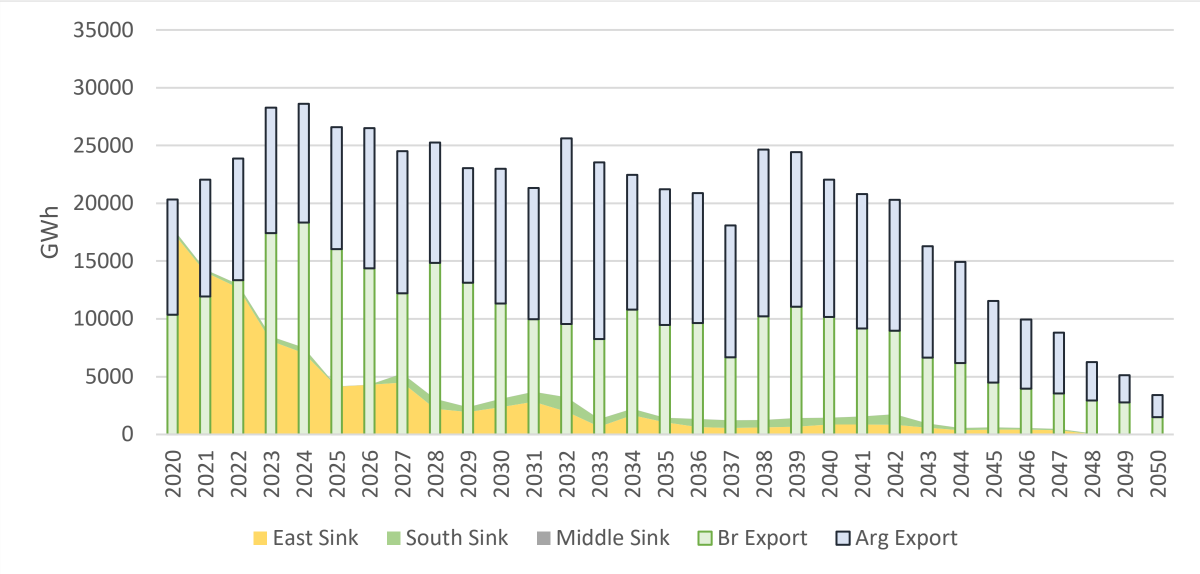


Table 5: Numerical results for key parameters at key years – SC04a Open Market

Component	Unit	2030	2040	2050
Peak Demand	MW	6388	10746	17368
Exports to Brazil	GWh	10763	10786	977
Exports to Argentina	GWh	11535	9474	1559
Imports from Brazil	GWh	88	1202	12720
Imports from Argentina	GWh	33	1672	5259
Sinks (Brazil and Argentina)	GWh	4447	864	26
Not-supplied Energy	GWh	0.00	0.00	1132
Output from Itaipú	GWh	45812	42390	41994
Output from Yacyreta	GWh	12518	11452	11729
Output from Acaray	GWh	949	743	629
Output from Yguazu	GWh	141	130	60
Output from Corpus Christi	GWh	0.00	10604	10642
Output from Itati-Itacora	GWh	0.00	6001	6017
Output from New Small Hydro Plants	GWh	127	2123	2051
Output from Solar	GWh	754	756	755

5.2.4. SC04b – ANDE's Generation Master Plan 2021-2040 + new Binational Hydropower Plants (BHP) and Renewables Energies (with Carbon-neutral Demand)

After harnessing the potential of new BHP, Paraguay would still need to invest in renewables to satisfy its future energy requirements, especially after 2040. To assess this expansion, this scenario simulates the construction Solar PV plants and Batteries according to the schedule shown in **Figure 44.** The parameter driving this expansion is the expected ENS, seeking to reduce it below 3% of total demand for each year, and considering the 95th percentile of ENS from all realizations.

Figure 45 shows the energy balance when new BHP and new Solar PV plants are included. Such a combination makes possible to have an annual firm energy of between 20% and 25% more than each year's demand. As can be seen in Figure 45, ENS starts to growth in 2042, then it oscillates between 1,5% and 2,2%. Figure 46 shows the power balance for the peak demand, where batteries start to play a critical role since 2041, where the peak demand surpass the installed capacity if batteries are not considered. Since then, power demand growth is met with batteries; and moreover, as can be seen in the final years, more than one third of the peak demand is met with batteries.

Next, Figure 47 shows the failure frequencies for the four considered load bands. It is worth to note that the failure frequency for P1 demand is reduced by half in comparison to scenario SC04a, where no investments are included after 2040. In addition, the failure frequencies for the two higher load bands depict a similar timing and pattern, while the lower demand load band is reduced towards the end of the time horizon. Finally, investments in solar PV and batteries make possible to reduce the marginal costs at the border's nodes significantly. Since 2041 however, prices in the neighboring nodes are still lower than in the Paraguayan nodes, as shown in Figure 48 and Figure 49.

Figure 44: Aggregated capacity of Solar PV plants and Batteries – SC04b

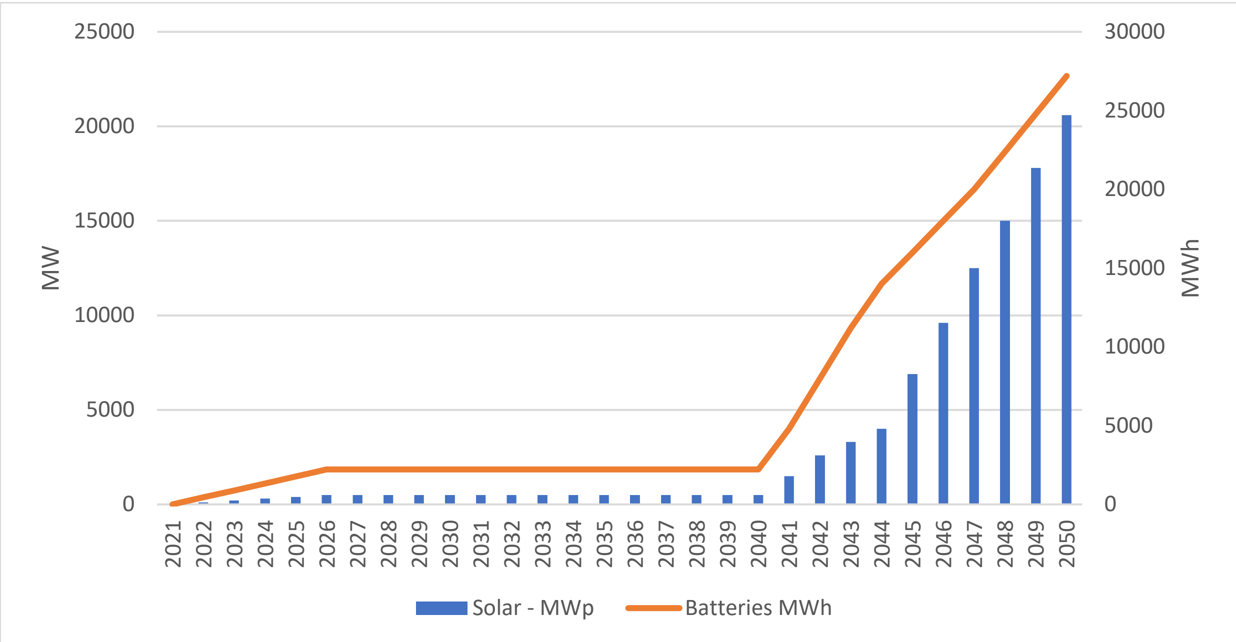


Figure 45: Energy balance for the 95th perc. of cum. not-supplied energy – SC04b Closed Market

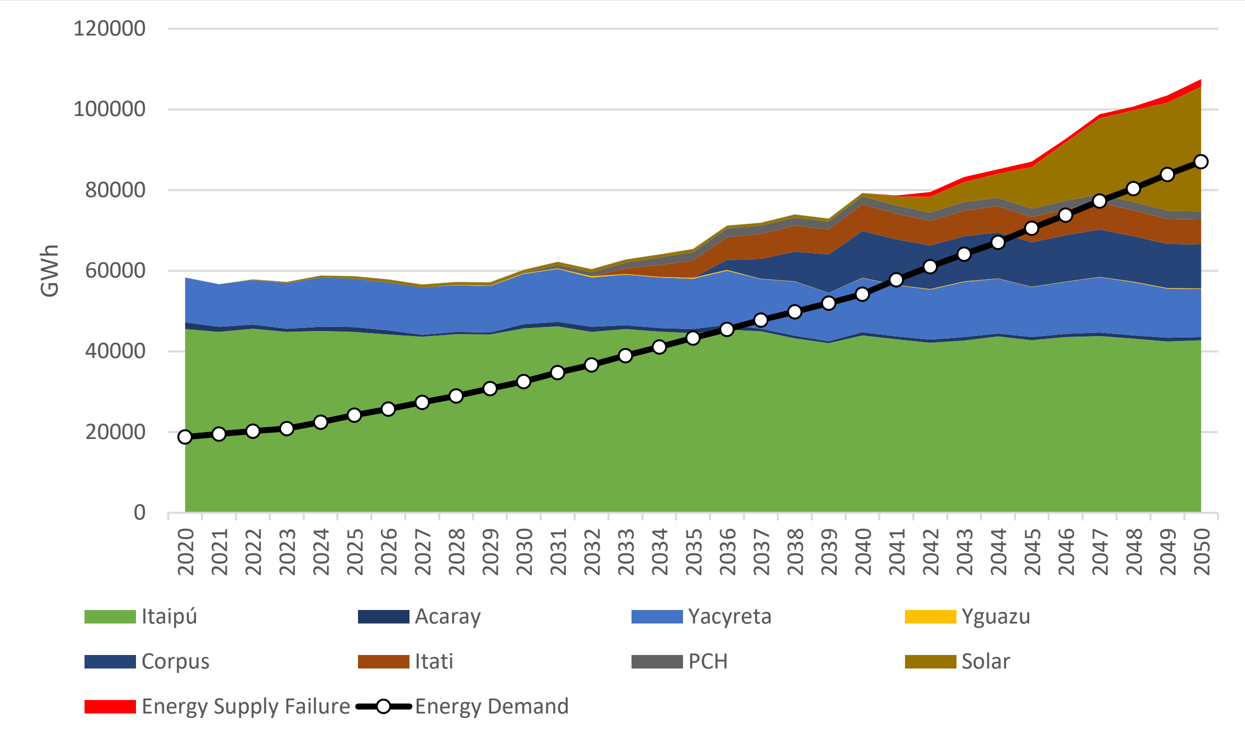


Figure 46: Power bal. for P1 load and 95th perc. of cum. not-supplied energy – SC04b Closed Market

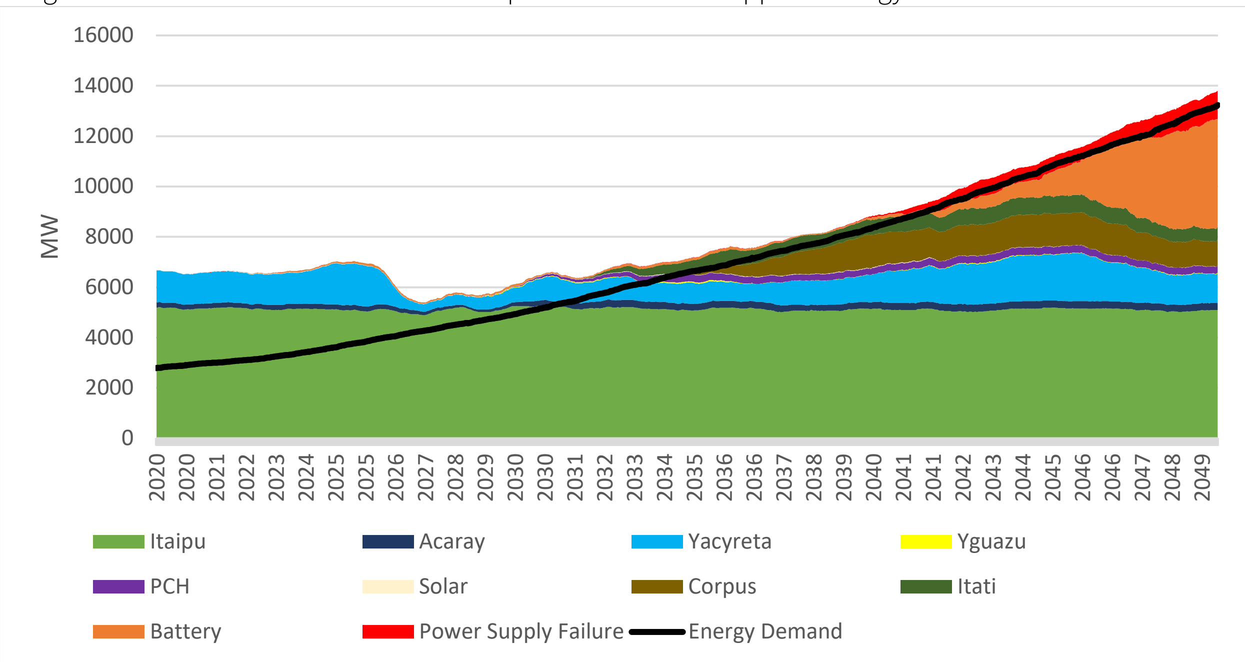


Figure 47: Power Supply Failure Frequency – SC04b Closed Market

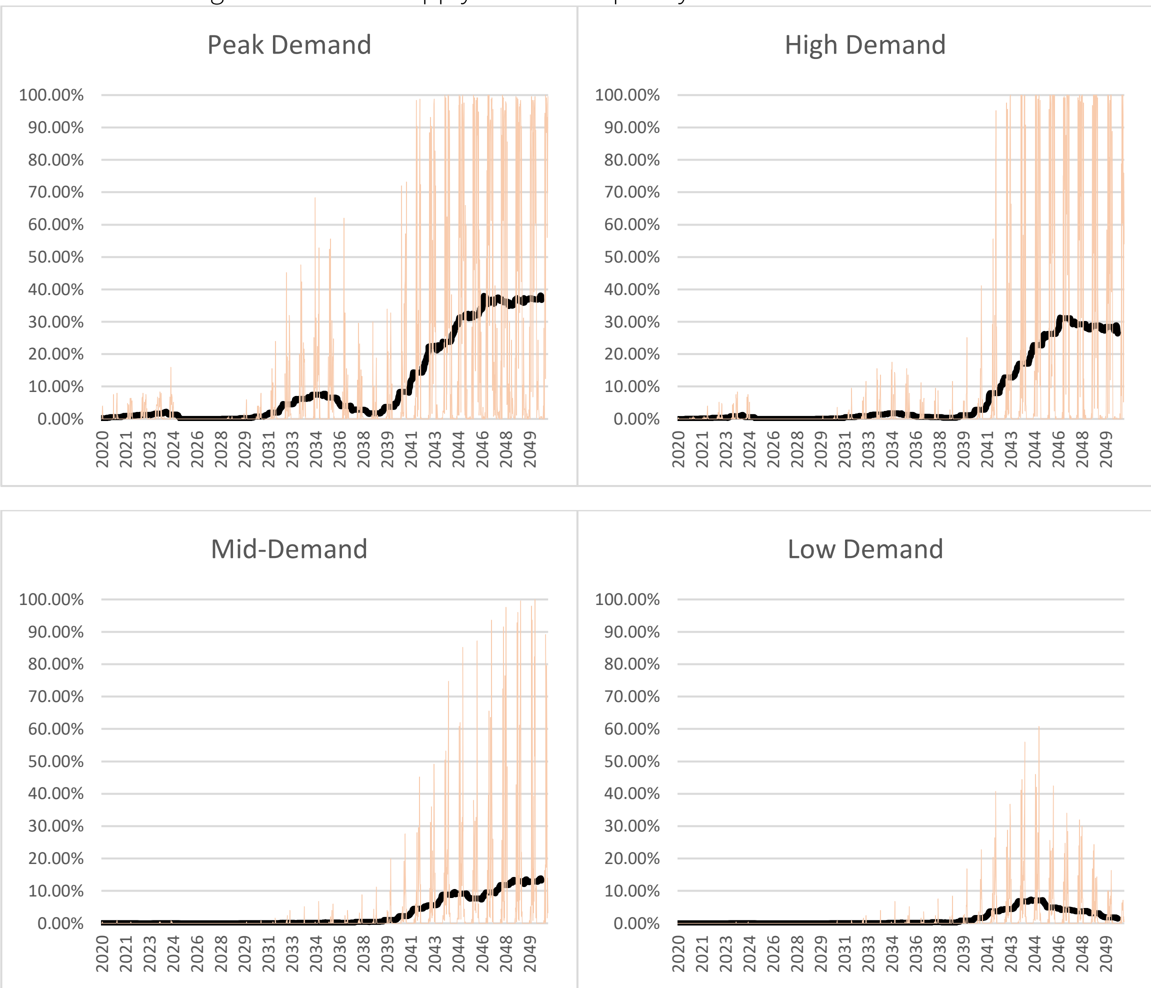


Figure 48: Marginal cost in Paraguay's East and Brazil's South nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC04b Closed Market

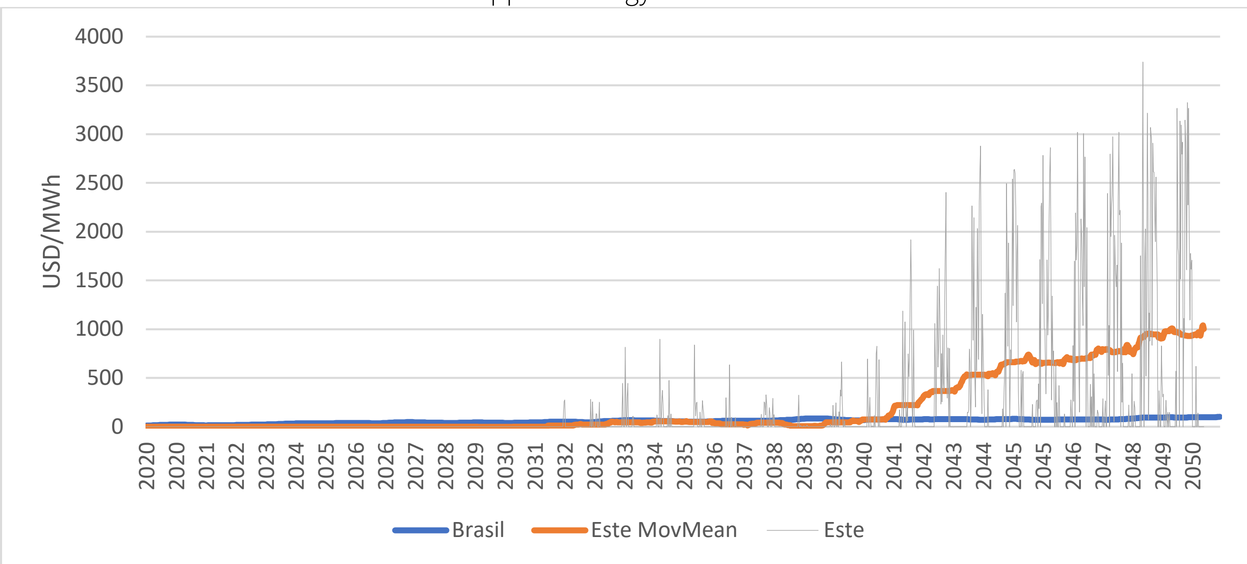


Figure 49: Marginal cost in Paraguay's East and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC04b Closed Market

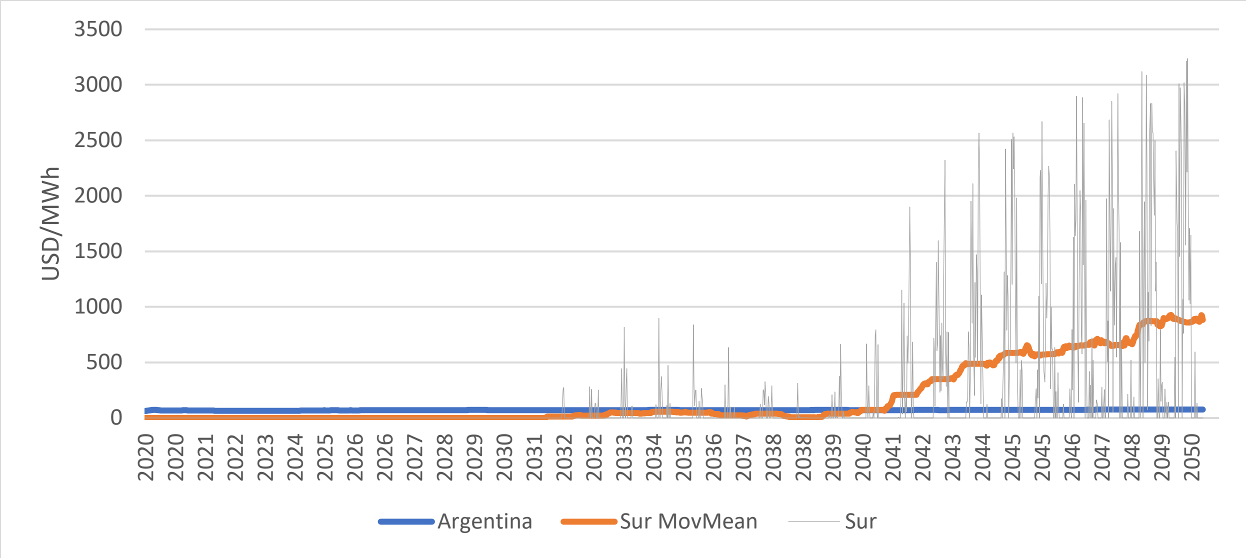


Figure 50 shows the energy balance in the Open Market setting. Here, the ENS is almost negligible, as the excess demand could also be met with imports. The power balance dispatch at peak demand also changes, as can be seen in **Figure 51,** since the possibility of importing power makes the model to dispatch hydropower plants more regularly.

Finally, the failure frequencies, shown in **Figure 52,** are reduced to zero for three of the load bands. For the peak demand, the frequency is reduced from 40% to 10% by 2050.

Figure 50: Energy balance for the 95th perc. of cumulated not-supplied energy – SC04b Open Market

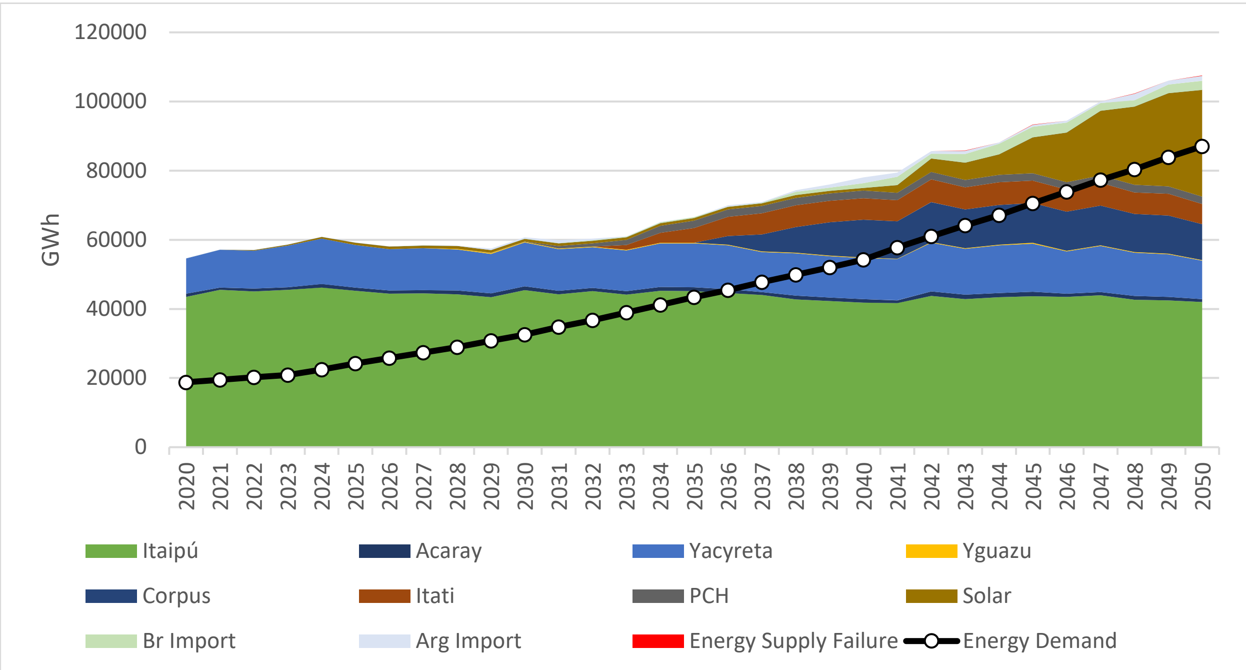


Figure 51: Power bal. for P1 load and 95th perc. of cum. not-supplied energy – SC04b Open Market

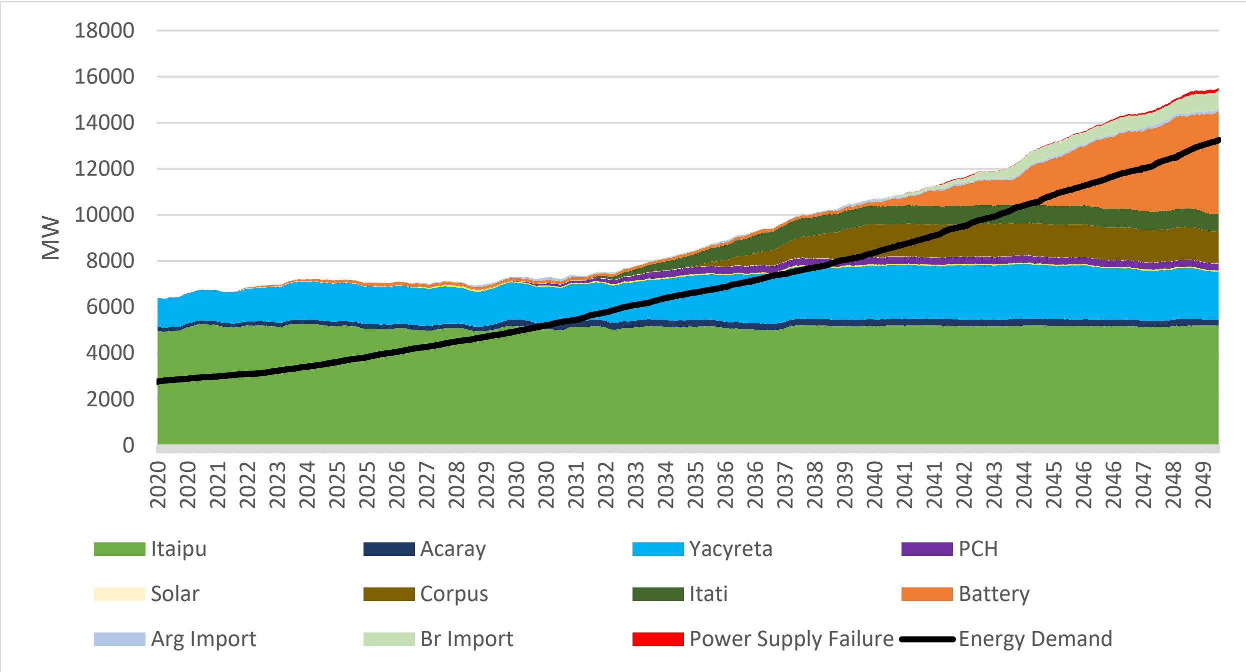
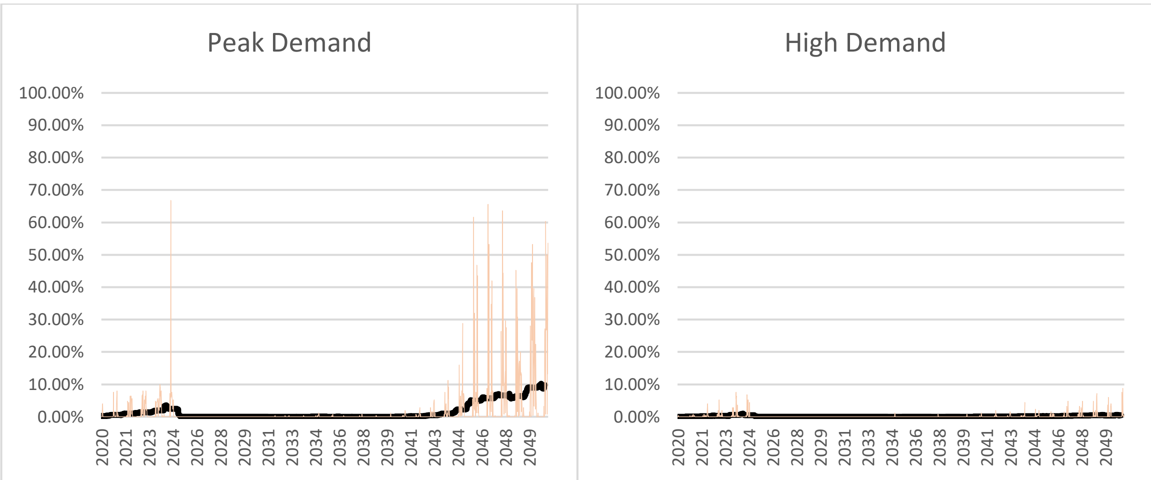
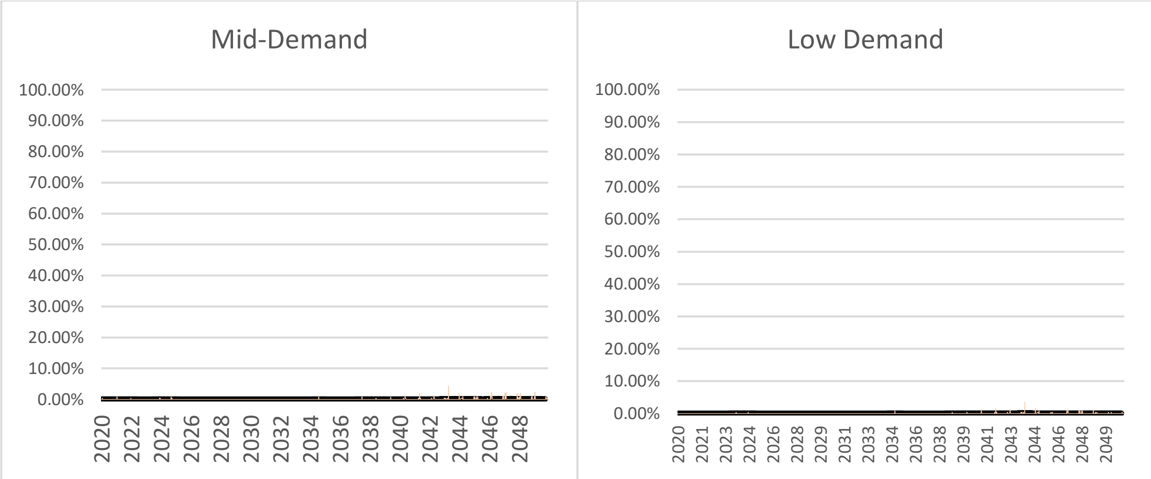


Figure 52: Power Supply Failure Frequency – SC04b Open Market





5.2.5. SC05a – High investment in renewables and batteries

Using the World Bank's results and SDSN suggestions for Wind and Solar development, a portfolio of investment for a scenario with high penetration of non-conventional renewable energies is proposed. A slight difference is that instead of gas turbines, the addition of batteries is considered. This scenario was obtained with an iterative approach. As it was discussed in the technical meetings, performing an optimization of the expansion could have involved an unnecessary commitment of resources and time. Parameters were selected to reduce the price signal to the range of the neighboring countries.

Important key assumptions for the scenario: in comparison to the World Bank Model, the remaining additions are only solar PV, as the limited wind resources from the North-Western region of Paraguay are assumed to be already harnessed in the first iteration; a greater investment in batteries will be required, as the load curve and the solar availability do not follow a similar pattern, *i.e.*, the peak demand of the system is at night, while the peak solar output is at noon. As a result, the cumulative aggregate capacity by technologies can be seen in Figu0re 53.

The model takes into account the aggregated capacity in renewable energy, and the resources (*i.e.*, wind and solar irradiation) to run the simulations. The energy balance for this scenario can be seen in Figure 54. New generation capacity increases the availability of firm energy up to 140,000 GWh. Here, not-supplied energy starts to grow in 2030, as the batteries are installed since 2031. The power dispatch for the 95th percentile of cumulated not-supplied energy is shown in Figure 55. The existence of battery power output above the demand curve is because the surplus from renewables in the low-demand seasons (autumn and winter) is being exported, thus increasing the moving average of the dispatch. Batteries play an important role in reducing the not-supplied energy from the peak demand.

Figure 53: Aggregated capacity of renewables and batteries, and proposed schedule – SC05a

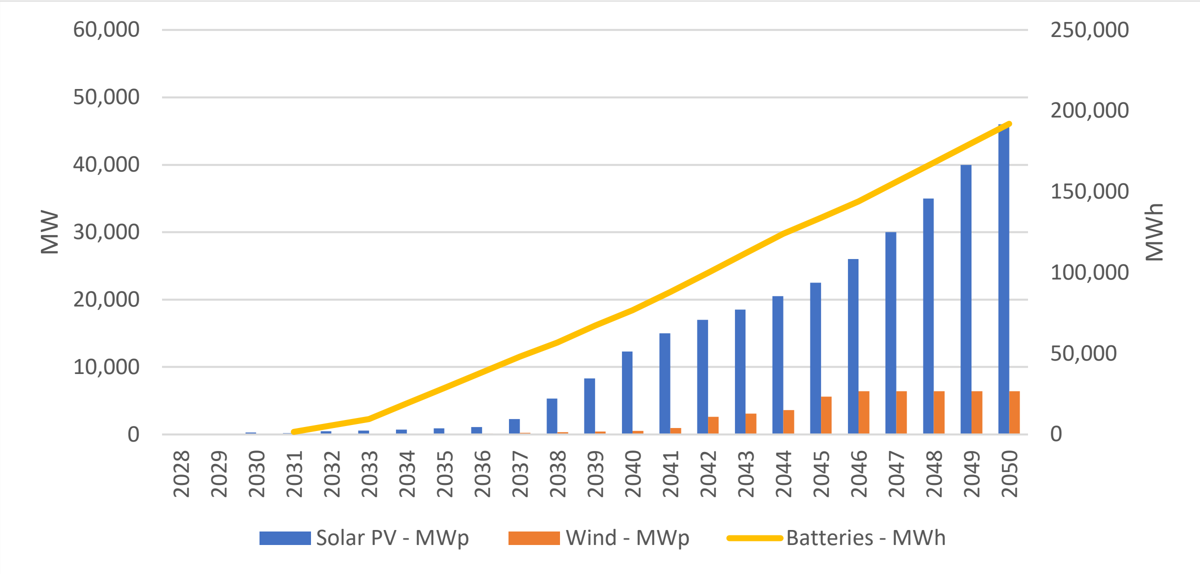
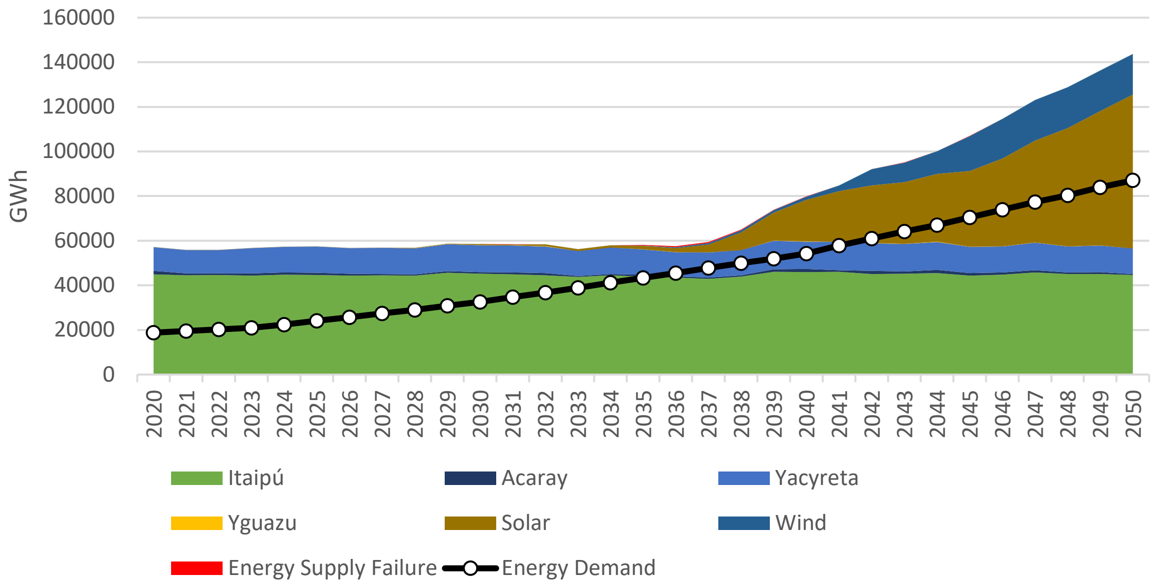


Figure 54: Energy balance for the 95th perc. of cum. not-supplied energy – SC05a Closed Market



As shown also in Figure 56, failures cannot be reduced completely even for the periods where investments are massive. A possible explanation is that the model itself is limited, as it optimizes the power dispatch in a weekly basis. In that sense, it is worth noting that the traditional operation mode of a battery is related to an intra-day optimization, where the operation is optimized by charging the battery in periods of low-demand and supplying the energy storage in peak-demand. In our case, as the level of detail refers to a week, the optimization involves charging the battery in weeks of lower energy demand in order to supply the storage in weeks of higher and peak demand. An optimization throughout our four load bands, *i.e.*, P1, P2, P3, and P4, is not possible, since the battery sizing needs to account the possibility to charge/discharge the battery in all the four load bands of the week. This implies that the battery sizing here is roughly seven times than it would be if the charging/discharging cycles were intra-day. Nevertheless, the sort of “oversizing” that we incur in allows us to estimate the amount of investment and technology mix needed to secure a situation of negligible not-supplied energy and energy surplus, even to export to the neighboring countries, which is the current case.

The marginal cost in neighboring nodes for the 95th percentile of cumulated not-supplied energy for the peak demand is shown in Figure 57 and Figure 58. On one hand, these investments are insufficient to reduce the marginal costs for the period 2034-2040. On the other hand, from 2040 to 2050, investments do allow the marginal costs of Paraguay to oscillate around those of the neighboring countries. Here, the marginal operating cost in the Paraguayan-ends of the border is reduced beyond the cost in the neighboring-end for some periods - thus reaching a "desirable" situation with cheap supply and no external dependence. However, it is worth noting that, for reaching this "desirable" situation of cheap domestic supply, we must first invest in the corresponding power plants and batteries. Moreover, two important analysis are: 1) the required capital costs to achieve such a "desirable situation", and 2) by anticipating that the required capital costs will be huge and subject to several externalities (mainly in the case of the new Binational power plants), the trade-off between economics (high domestic investment against low import costs) and politics (energy security against external dependence).

Figure 55: Power balance for P1 load and 95th perc. of cumulated not-supplied energy – SC05a Closed Market

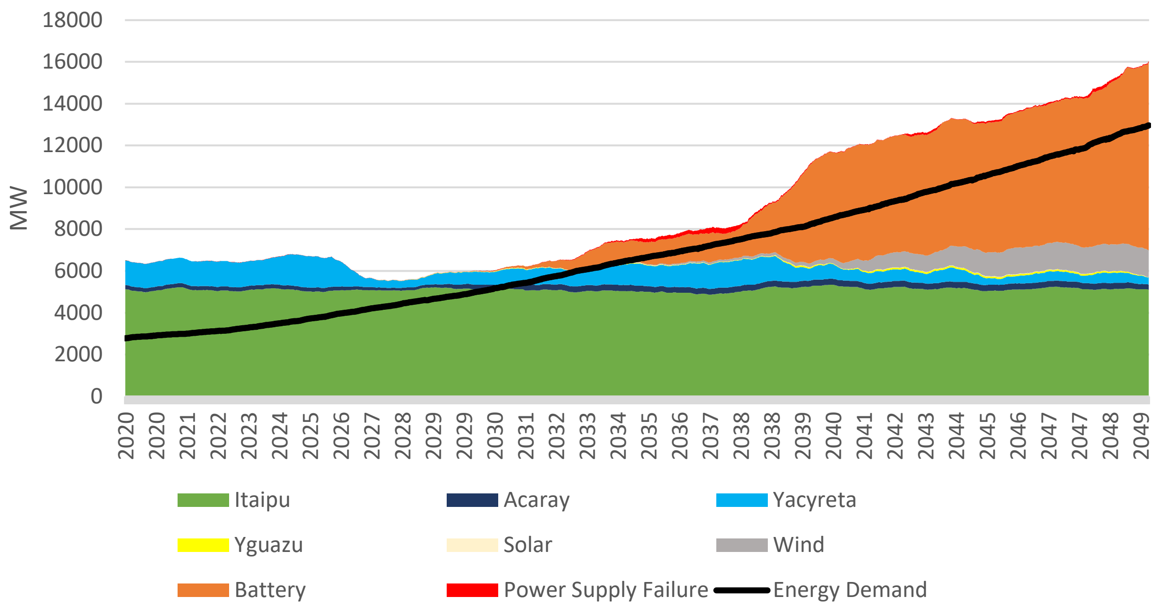


Figure 56: Power Supply Failure Frequency – SC05a Closed Market

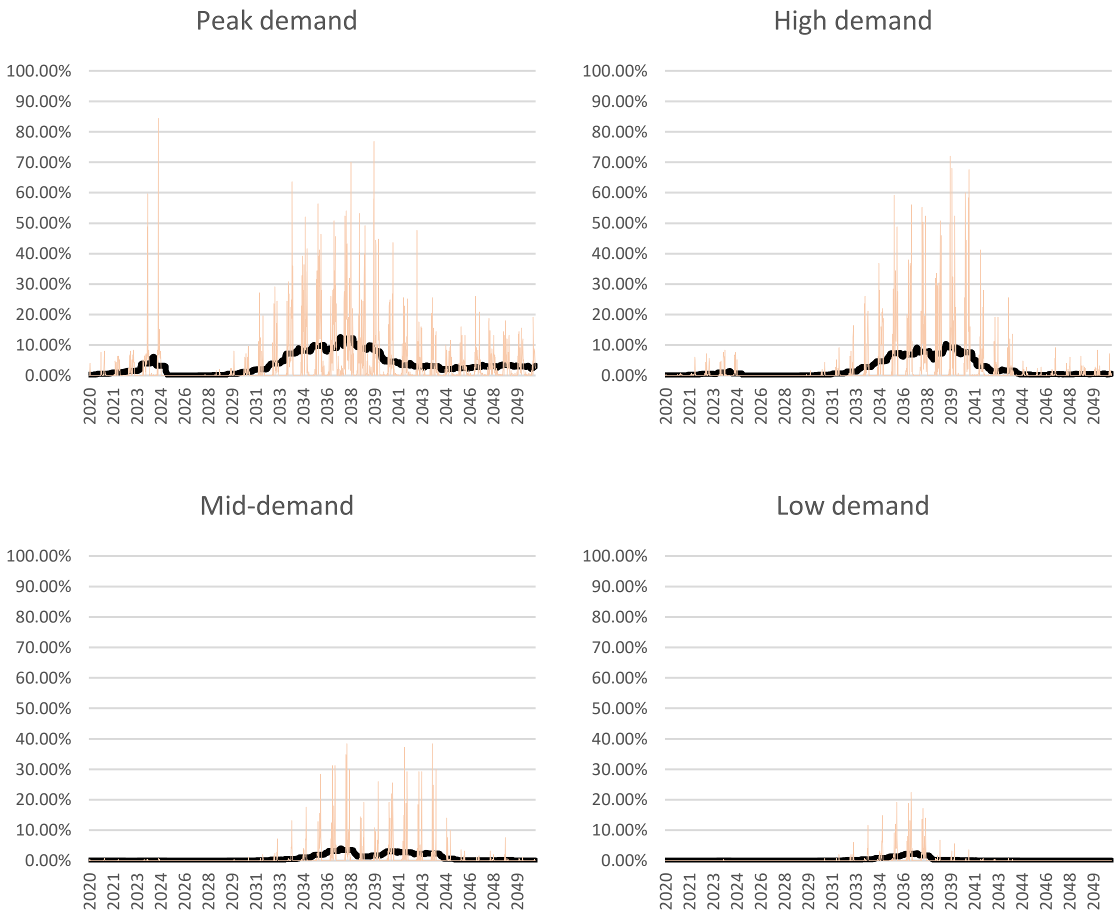


Figure 57: Marginal cost in Paraguay's East and Brazil's South nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC05a Closed Market

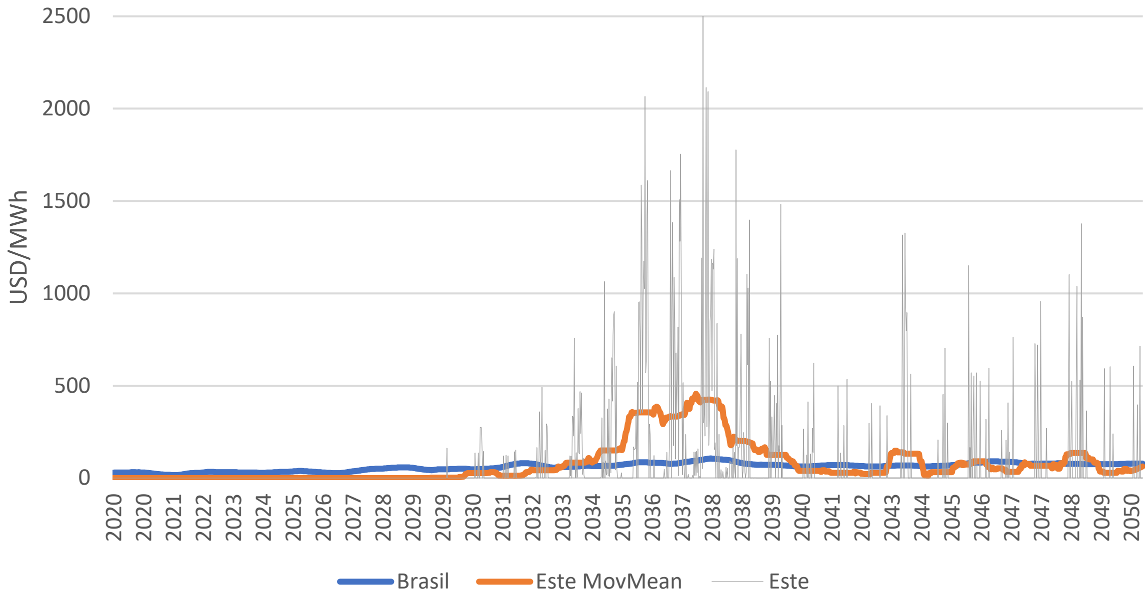


Figure 58: Marginal cost in Paraguay's East and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC05a Closed Market

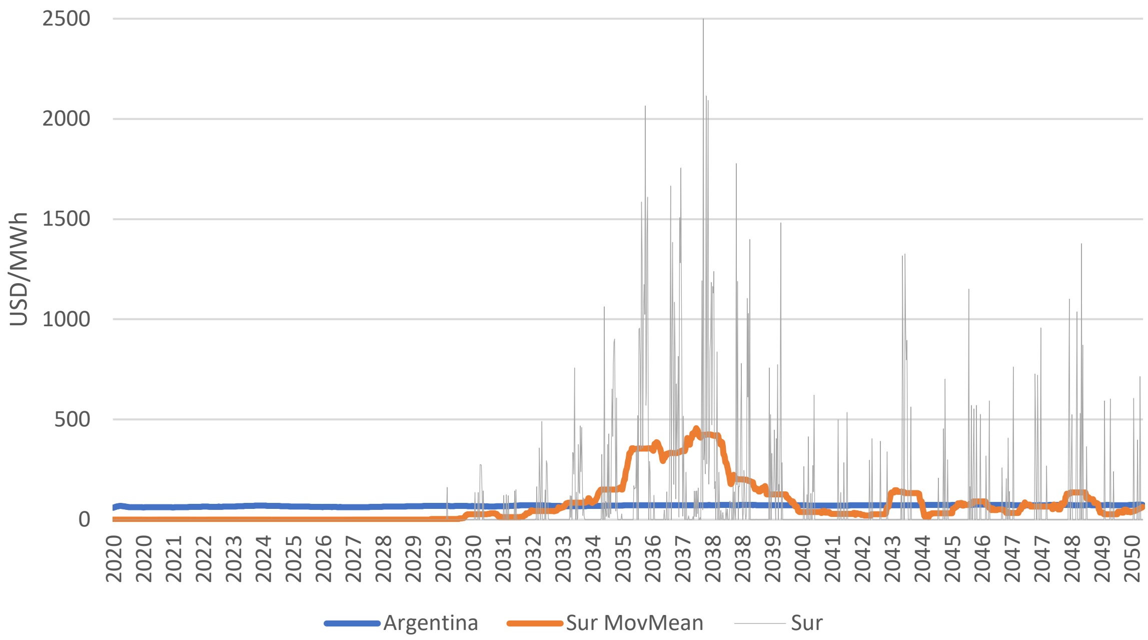


Figure 59 shows the energy balance for the 95th percentile of cumulated not-supplied energy in an Open Market. New investments and open market make possible the further reduction of not-supplied energy, in comparison to the Closed Market configuration. In comparison to previous scenarios, imports do not represent a considerable share, as shown in Figure 59 and Figure 60. However, these

Figure 59: Energy balance for the 95th perc. of cumulated not-supplied energy – SC05a Open Market

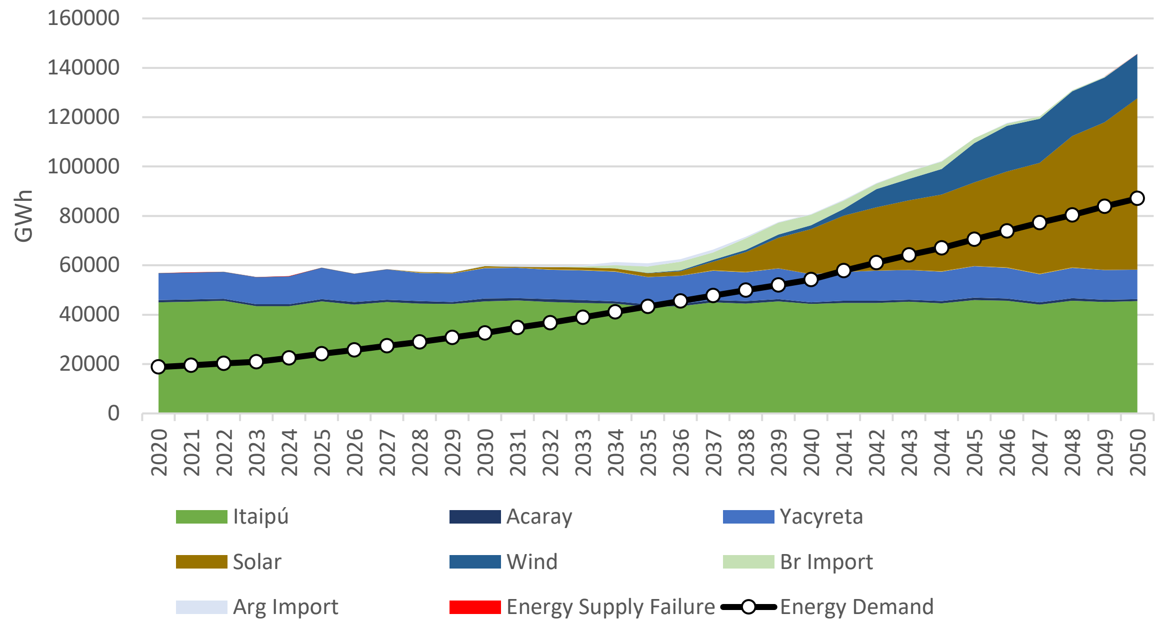


Figure 60: Power bal. for P1 load and 95th perc. of cum. not-supplied energy – SC05a Open Market

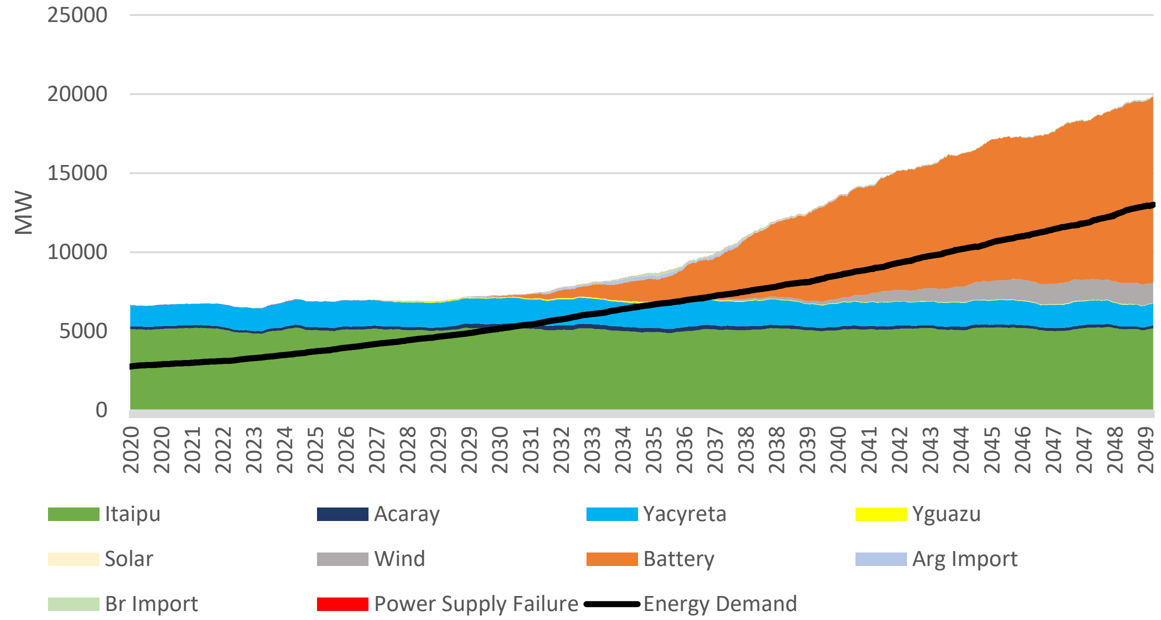
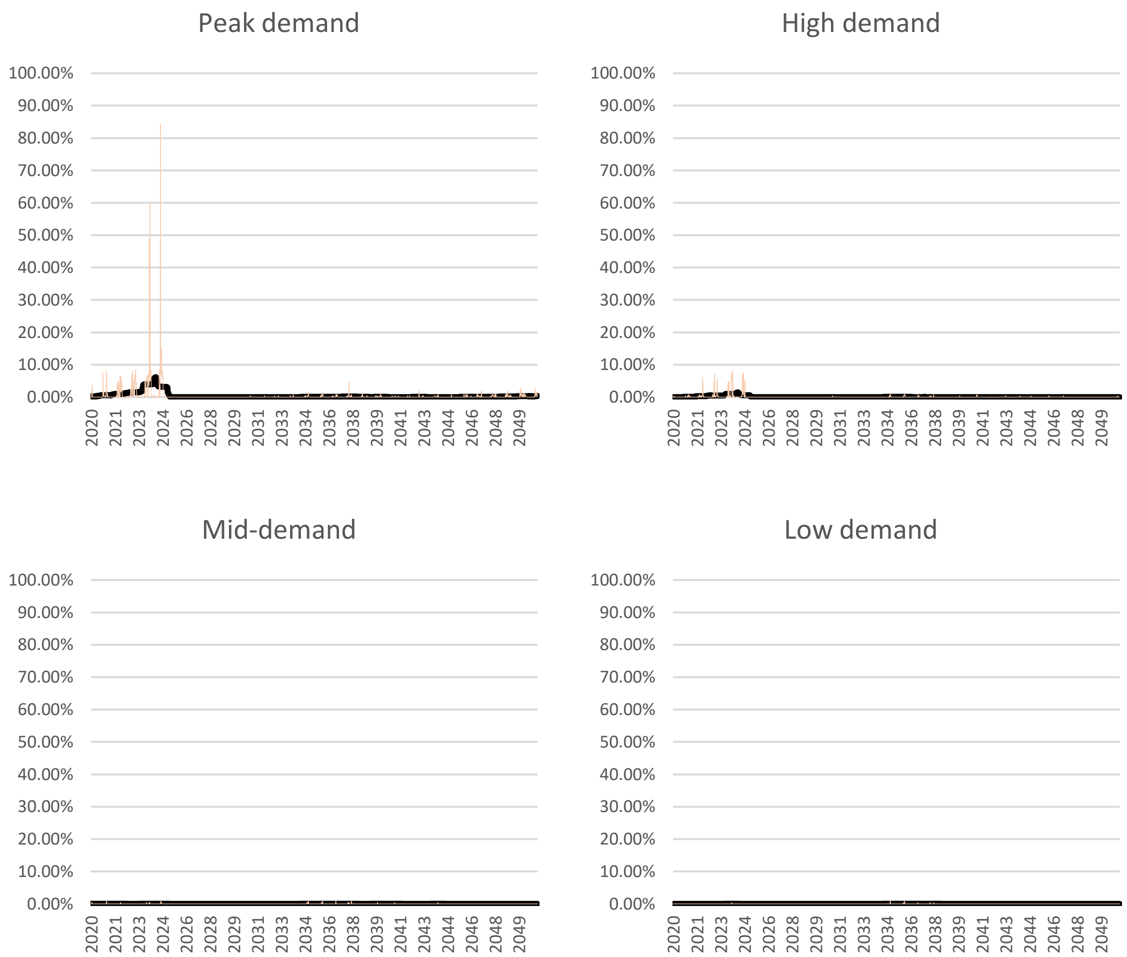


Figure 61: Power Supply Failure Frequency – SC05a Open Market



imports are important to supply load requirements that the investments in renewable are not able to, for instance, due to chronological coincidence. Thus, the not-supplied energy is nearly completely reduced, as can be seen in Figure 61.

Figure 62: Exports and sinks for the 95th perc. of cum. not-supplied energy – SC05a Open Market

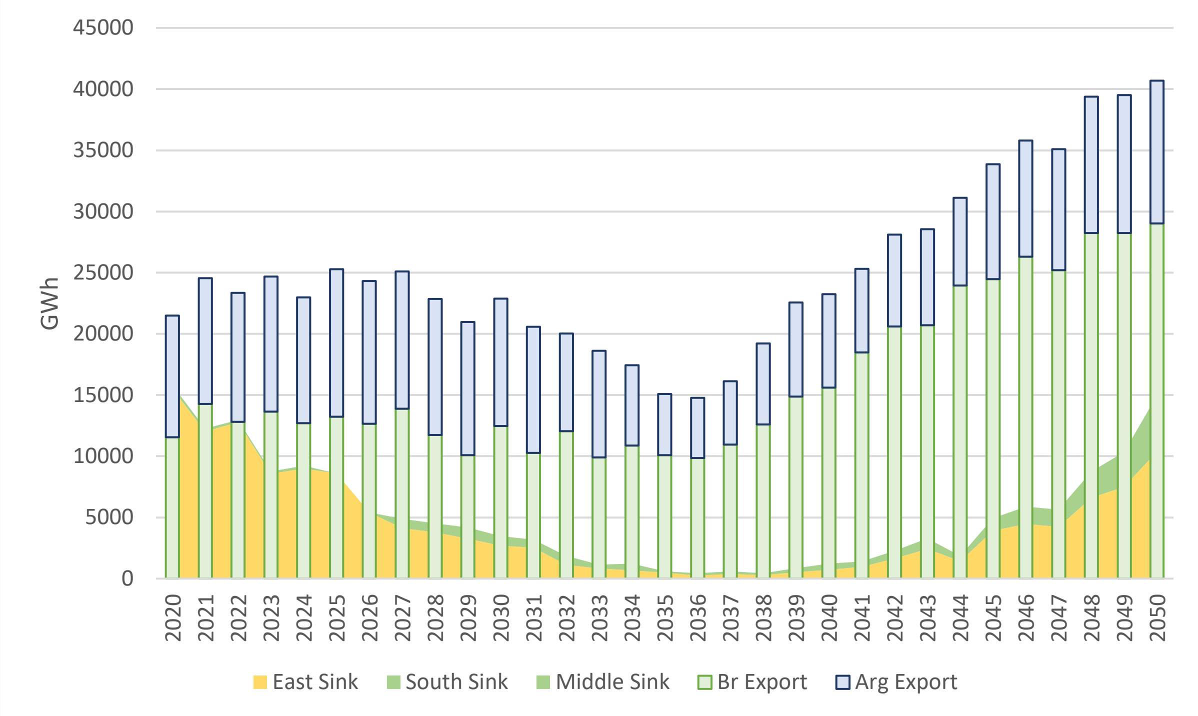


Table 6: Numerical results for key parameters at key years – SC05a Open Market

Component	Unit	2030	2040	2050
Peak Demand	MW	6389	10746	17368
Exports to Brazil	GWh	12476	15617	29016
Exports to Argentina	GWh	10415	7637	11687
Imports from Brazil	GWh	116	4280	14
Imports from Argentina	GWh	269	193.20	5
Sinks (Brazil and Argentina)	GWh	3470	1227	14999
Not-supplied Energy	GWh	0.00	0.00	0.00
Output from Itaipú	GWh	45446	44294	45519
Output from Yacyreta	GWh	12327	11433	11931
Output from Acaray	GWh	1142	653	768
Output from Yguazu	GWh	242	114.03	113
Output from Solar	GWh	448	18187	69359
Output from Wind	GWh	0.00	1549	17913

Results for the transboundary energy exchanges are shown in Figure 62. After 2035, the energy surplus begins to increase once again due to the penetration of renewable energies, and most of them is allocated in the Brazilian and Argentinian markets. In Table 6, numerical results for generation output, imports, exports, and peak demand for 2030, 2040 and 2050 can be observed.

5.2.6. SC05b – Moderate investment in renewables and batteries

Using the not-supplied energy as a parameter, an investment portfolio for a scenario with moderate penetration of non-conventional renewable energies is proposed. The aim of this scenario is to show how much investment is necessary to reduce the expected not-supplied energy, in contrast to the high investment proposal, which mainly seeks to reduce ENS frequencies and marginal costs of operations.

Key assumptions for this scenario are: only investments in solar PV and batteries are considered, since the requirement of investment are moderate, and to serve as a possible complement to ANDE Master Plan 2021-2040 without BHP.

The cumulative aggregate capacity by technologies can be seen in **Figure 63**. To achieve the reduction of ENS, with an expected value under 5% considering the 95th percentile, the investment up to 2050 are 35,000 MWp of Solar PV and 55,000 MWh of batteries, 10,000 MWp less of solar PV and almost four times less investments in batteries than the high investments situation.

The energy balance for this scenario can be seen in **Figure 64**. Here, the maximum expected not-supplied energy is 3%, by 2050. Furthermore, the new generation capacity increases the availability of annual firm energy up to 110,000 GWh. The investment in generation supply is roughly 25% higher than each year's energy demand. Then, the power dispatch for the 95th percentile of cumulated not-supplied energy is shown in **Figure 65**.

Figure 63: Aggregated capacity of renewables and batteries, and proposed schedule – SC05b

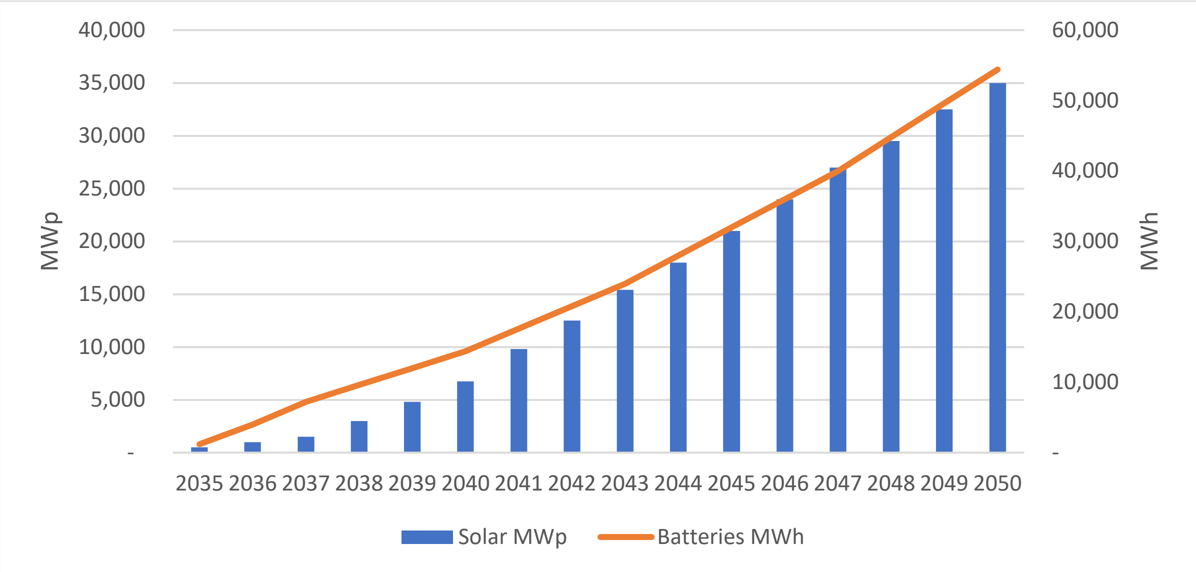
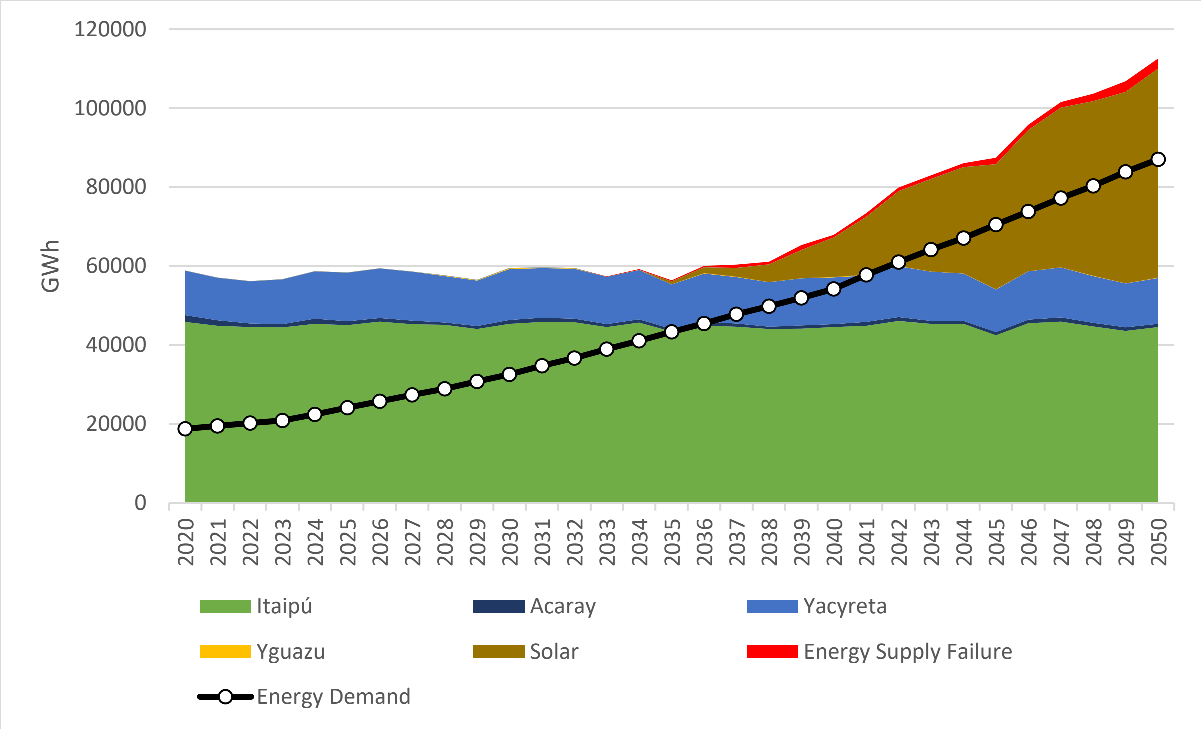


Figure 64: Energy balance for the 95th perc. of cum. not-supplied energy – SC05b Closed Market



Failure frequencies are still high, however, energy related to these failures is low, with a maximum value of 3%, as aforementioned. Another interesting comparison is with SC04b, which accounts for similar values of not-supplied energy and failure frequencies. Nevertheless, SCB04b requires less generation's margin, which represent a reduction of 15,000 MW in solar PV, while new hydropower dams allow the reduction of battery investment by half.

Figure 65: Power bal. for P1 load and 95th perc. of cum. not-supplied energy – SC05b Closed Market

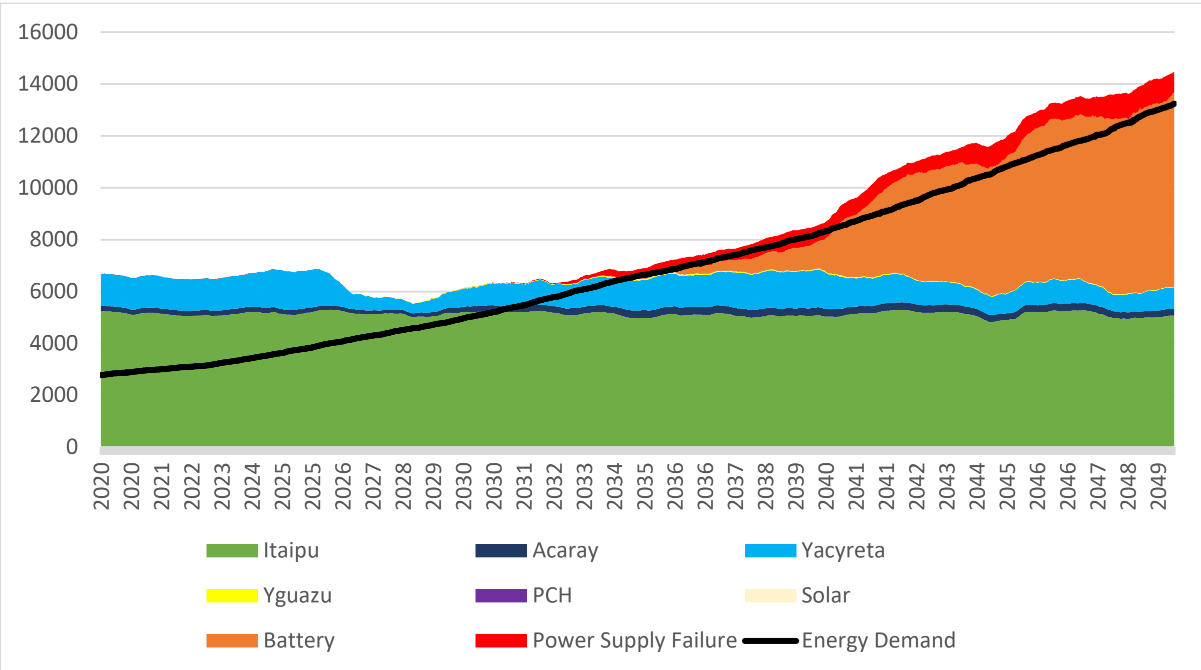


Figure 66: Power Supply Failure Frequency – SC05 Closed Market

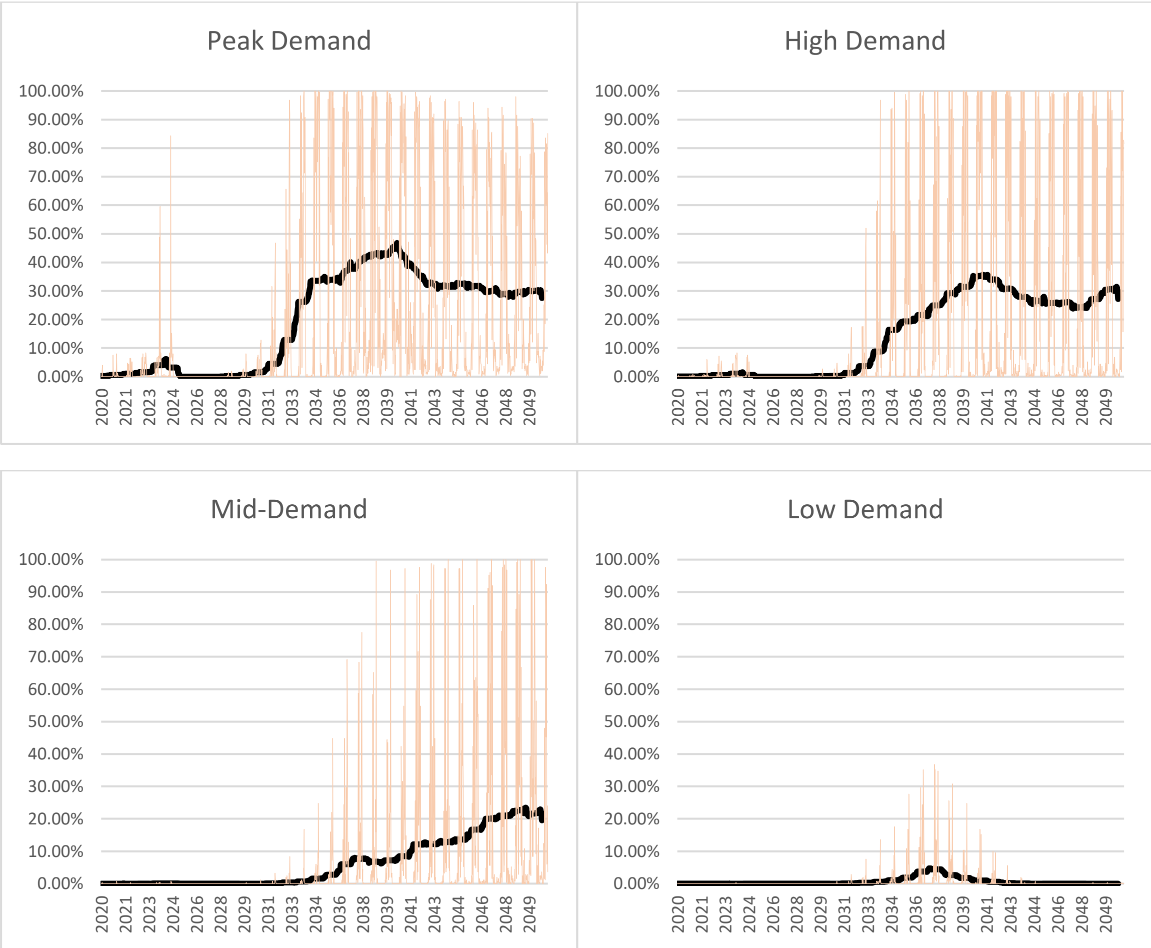


Figure 67: Marginal cost in Paraguay's East and Brazil's South nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC05b Closed Market

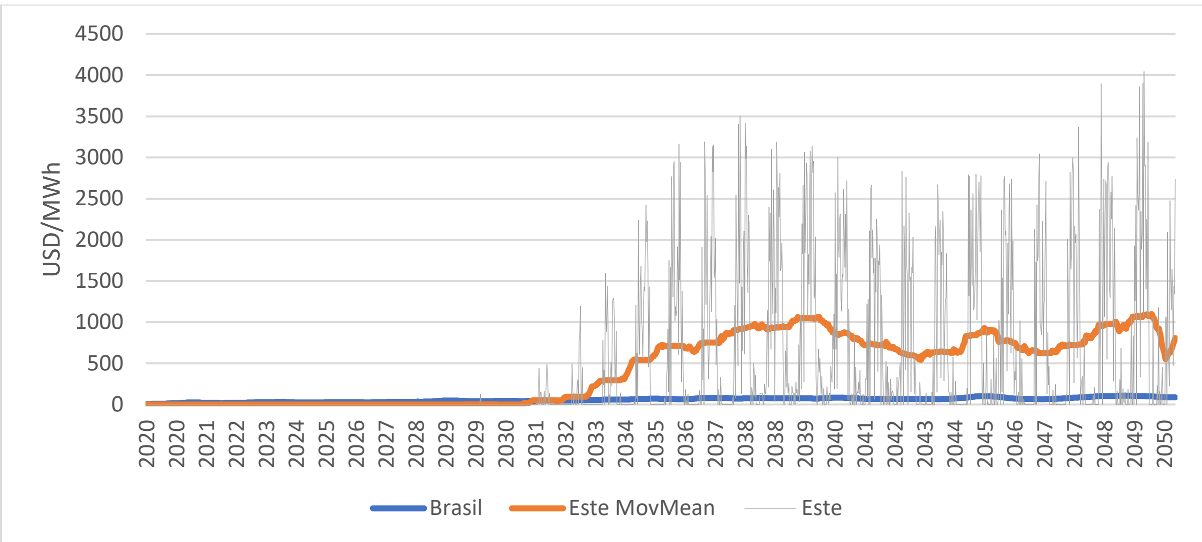


Figure 68: Marginal cost in Paraguay's East and Argentina's nodes for P1 load and 95th perc. of cumulated not-supplied energy – SC05b Closed Market

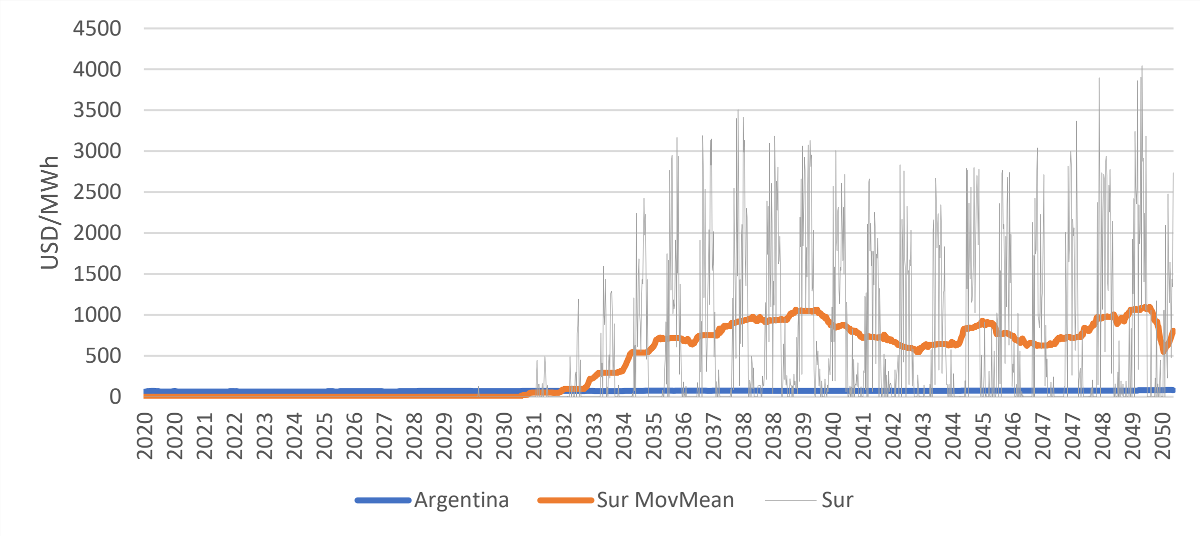


Figure 69: Energy balance for the 95th perc. of cumulated not-supplied energy – SC05b Open Market

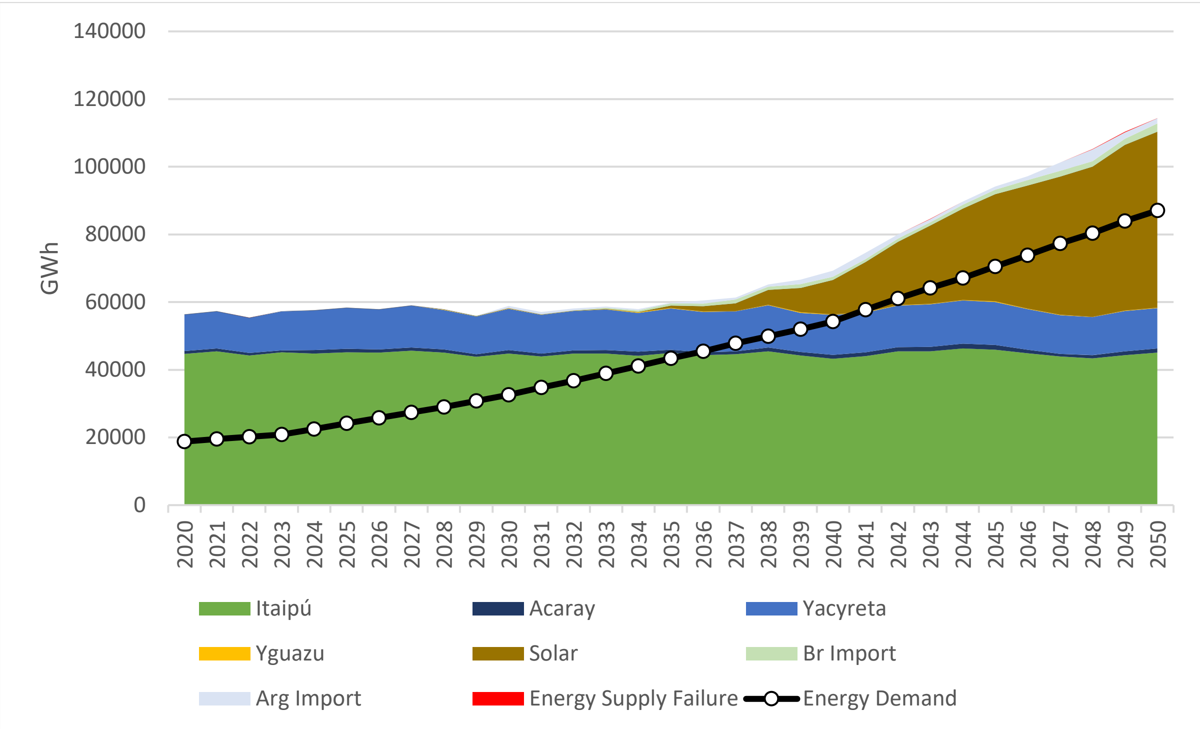


Figure 69 shows the energy balance for this scenario, where the ENS is reduced considerably. Then, Figure 70 shows the energy balance for the 95th percentile of cumulated not-supplied energy in an Open Market. Moderate investments here make possible the further reduction of not-supplied energy, in comparison to the Closed Market configuration. In comparison to previous scenarios,

Figure 70: Power bal. for P1 load and 95th perc. of cum. not-supplied energy – SC05b Open Market

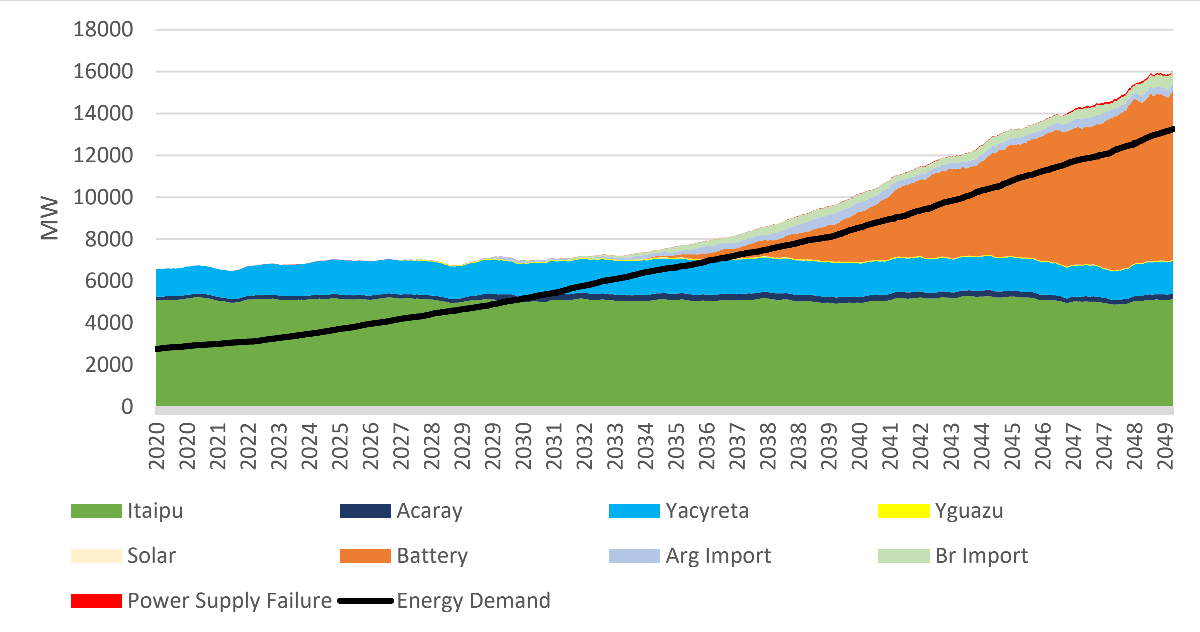
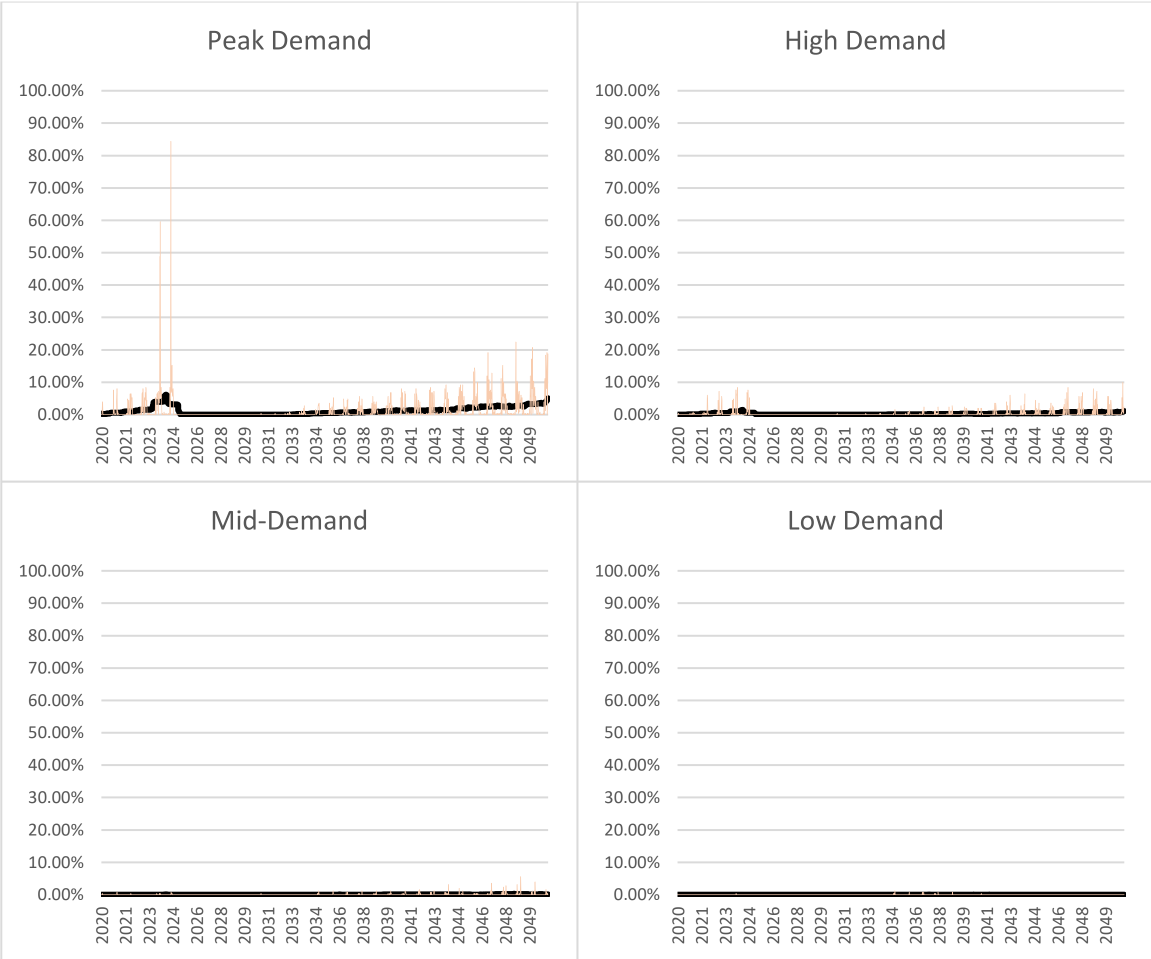


Figure 71: Power Supply Failure Frequency – SC05b Open Market



imports do not represent a considerable share, as shown in Figure 69 and Figure 70. However, as with the previous scenario, imports are important to supply load requirements that the investments in renewable are not able to, for instance, due to chronological coincidence, solar irradiation or water inflow, the model's stochastic variables. Thus, the frequency of not-supplied energy is nearly completely reduced, as can be seen in Figure 71.

5.2.7. Comparison among scenarios

Several charts to compare the scenario's results are shown below. Figure 72 shows the percentage of not-supplied energy in comparison to each year's energy demand, considering the energy balance for the 95th percentile of cumulated not-supplied energy in a Closed Market setting. For SC03 (ANDE's Master Plan), the value is below 3% up to 2040, with lower values than other scenarios thanks to the early investments. But from 2040, it increases rapidly, reaching 31.2% in 2050.

For SC04a, the value remains under 3% until 2043; then, further investments in solar PV and batteries (SC04b) help to maintain it around 2%. For the latter, the energy reserve margin is roughly 20%. If it is decreased to 15%, *i.e.,* 20,600 MW to 17,500 MW of installed solar PV by 2050, the amount of expected not-supplied energy could duplicate, from 2.2% to 4.5%. In contrast, a variation in batteries investment could have less influence.

Moreover, SC05a&b show that to reduce not-supply energy and power only with renewables and batteries would involve huge investments. Results from SC03 are like those from SC05b up to 2039, with expected not-supplied energy of 1.3% and 2.3%, respectively. Then in 2040, SC05b includes an important amount of batteries and solar PV. Nevertheless, two points should be mentioned regarding investments and results: first, SC03 includes several SHP that are equivalent in energy to 1620 MWp of solar PV and help with flexibility that non-conventional renewable energies do not have, in other words, they also replace batteries; second, the results of expected not-supplied energy percentage in SC03 and SC05b now are 3.0% and 1.3%, respectively.

Figure 72: Comparison of ENS percentage for several scenarios

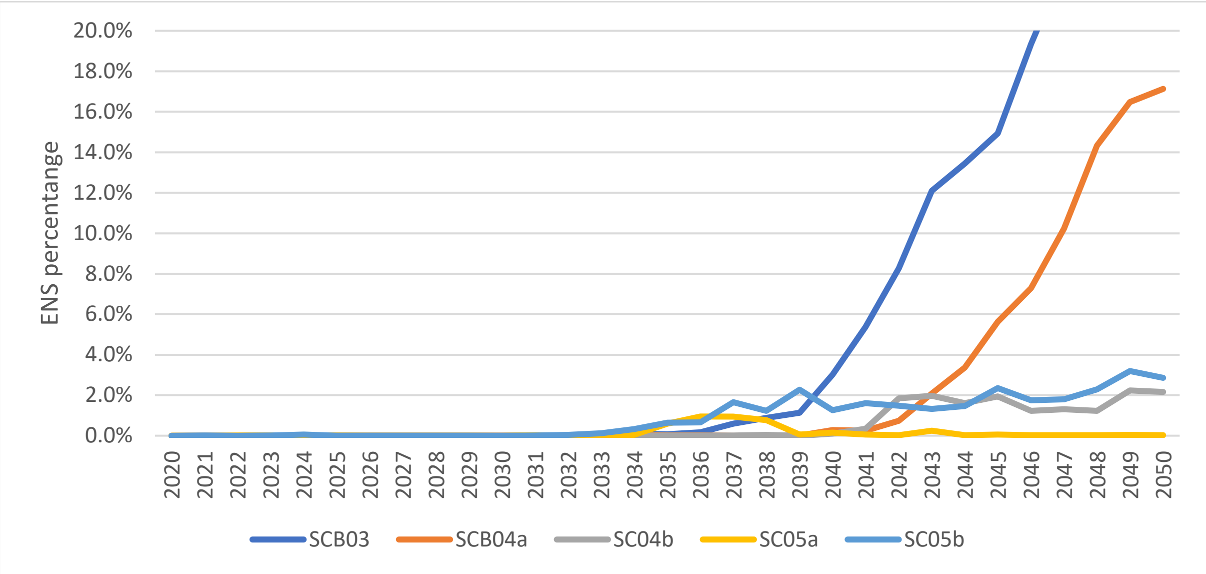


Figure 73 shows the failure frequencies for peak demand of the different scenarios. It is noticeable the behavior of SC04b and SC05b regarding not-supplied energy and power. Although the frequency failure is higher in SC04b, the related energy is less than in SC05b, meaning that each failure in SC05b is related to more energy. Something reasonable as SC05b rely more in solar PV and for the model all the solar plants are in the Central node. Therefore, a week with low solar irradiation will produce a great reduction in energy offer.

Figure 73: Power Supply Failure Frequency for Peak demand

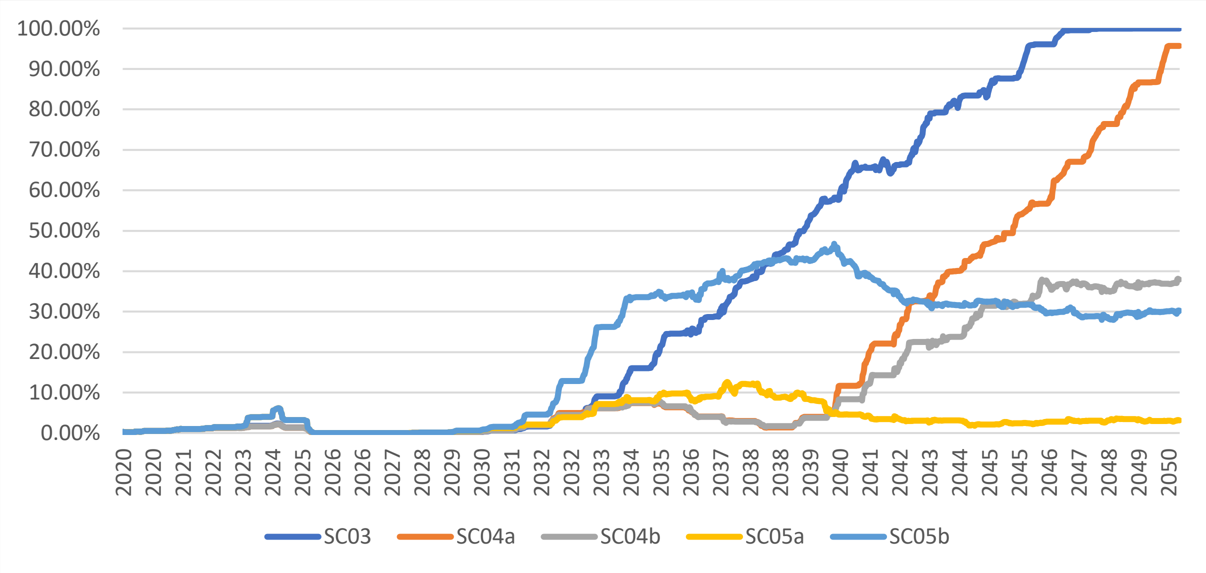
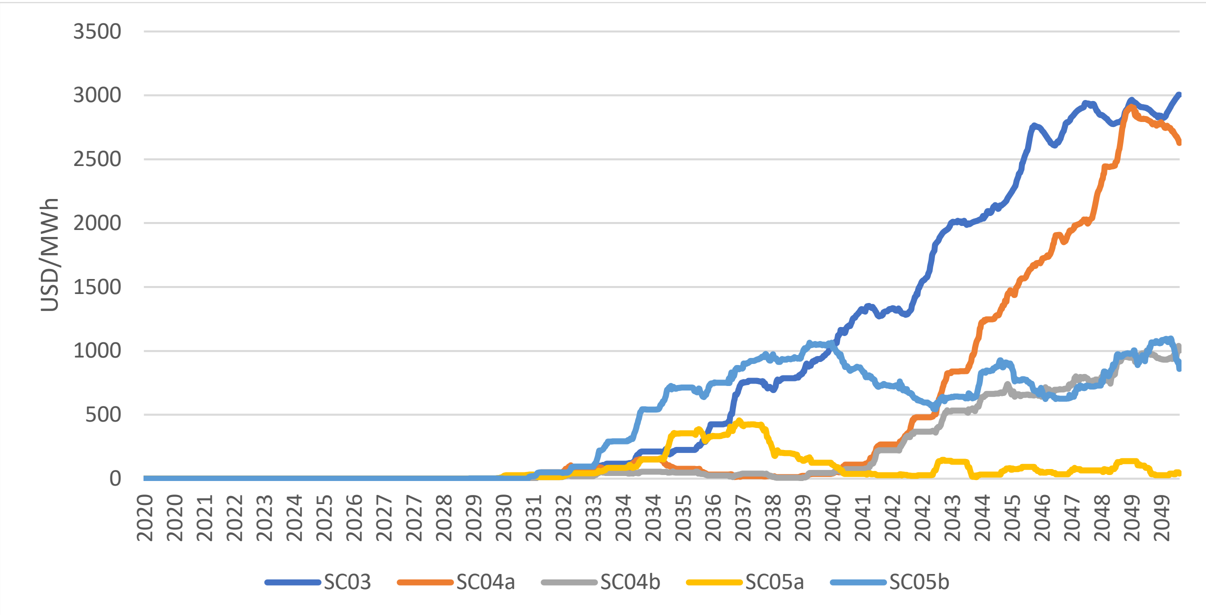


Figure 74: Marginal cost in PY East node for P1 load and 95th perc. of cum. not-supplied energy



Next, the marginal cost for the 95th percentile of cumulated not-supplied energy for the peak demand are shown in Figures 74 and Figure 75. The marginal cost of operation is given by the cost of supply an additional unit of power, when failure occurs, the cost is given by the cost of lost load, which value depend on how severe or deep is the load shed. That is why the costs for the SC04b and SC05b are similar. Finally, Table 7 shows the estimated investments in MMUSD for each scenario, and it is disaggregated by technology.

Figure 75: Marginal cost in PY Southern for P1 load and 95th perc. of cum. not-supplied energy

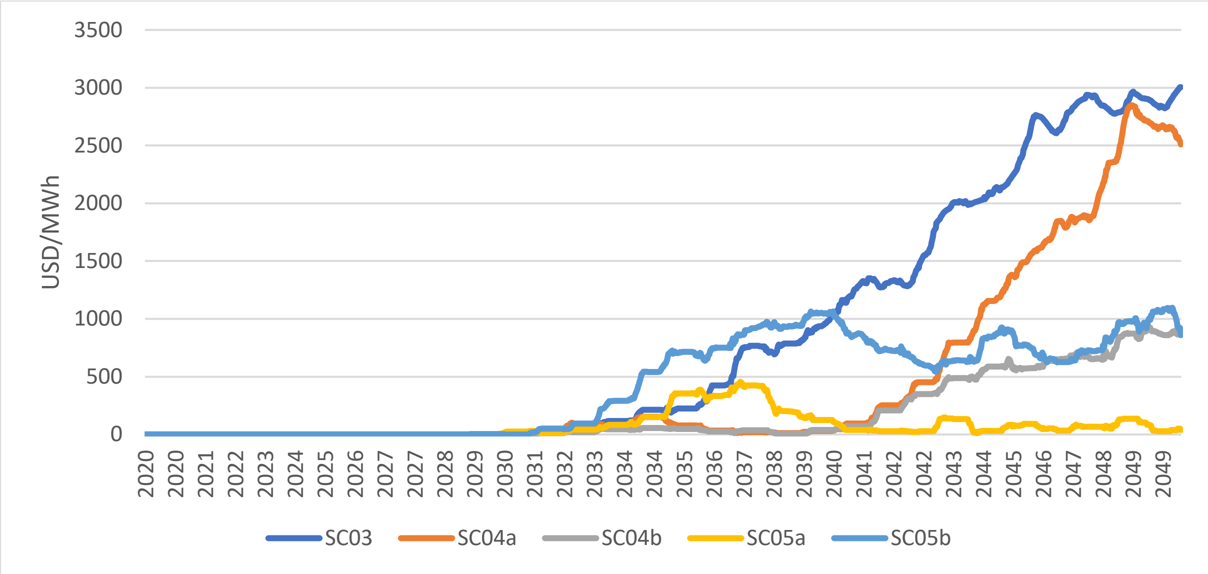


Table 7: Investments by scenario

Scenario	Technology	Cumulative Investments in key years - MMUSD		
		2030	2040	2050
SC03	Batteries	429	1,374	1,374
	Solar	344	1,099	1,099
	SHP	380	1,078	1,078
	Total	**1,153**	**3,551**	**3,551**
SC04a	Batteries	429	429	429
	Solar	344	344	344
	SHP	294	1,078	1,078
	BHP	495	9,150	9,150
	Total	**1,562**	**11,001**	**11,001**
SC04b	Batteries	429	429	5,425
	Solar	344	344	12,404
	SHP	294	1,078	1,078
	BHP	495	9,150	9,150
	Total	**1,562**	**11,001**	**28,057**
SC05a	Batteries	-	15,360	38,400
	Solar	180	7,380	27,600
	Wind	-	688	8,000
	Total	**180**	**23,428**	**74,000**
SC05b	Batteries	-	2,880	10,880
	Solar	-	4,050	21,000
	Total	**-**	**6,930**	**31,880**

Concluding remarks

This study assesses the future electricity system of Paraguay taking into account possible changes in several factors, namely: electricity demand, national and binational investment in generation, and the possibility of international exchanges with different prices in the markets of neighboring countries. Considering each of the proposed scenarios, the major insights are presented in the following:

- The Base Scenario assumes a demand projection based on a deterministic growth rate of 5.46 %/year. By using an exponential growth model with this parameter, 2020's demand would double by 2033, triple by 2039, quadruple by 2046, and quintupled by 2050.
- In the Base Scenario, considering only the existing generation and a Closed Market, not-supplied energy would represent 0.04% of demand by 2033 and would start to increase rapidly ever since, reaching 4,7% of demand by 2040. With an Open Market, not-supplied energy would reach 0.06% and 3.2% of demand by 2040 and 2050, respectively, involving imports of 3200 GWh and 34,000 GWh, respectively.
- The Alternative Scenario considers a demand projection resulting from a bottom-up analysis of energy transition towards electricity and efficiency gains. However, this so-called Carbon-neutral Scenario accounts for similar absolute values of demand (in GWh) with respect to the Base Scenario. Here, demand would be 3-times higher than the base-year demand by 2041, and nearly 5-times higher by 2050.
- In the Alternative Scenario, 100%-probability of insufficient generation dispatch with a Closed Market setting should be expected by 2043, 2045, 2048 and 2050, for peak-, high-, mid- and low-demand levels, respectively. As a result of the inadequate supply resources, marginal costs in the Paraguayan interconnection nodes would be almost 30-times higher than in the neighboring nodes, nearly reaching 3,000 $/MWh. Now, with available transboundary transmission links (Open Market setting), th%, in average, by 2050.
- The application of ANDE's Generation Master Plan 2021-2040 would represent further 550 MW of domestic hydropower plants, 1600 MW of solar PV units, and 7100 MWh of storage systems. In a Closed Market setting, these investments would help dropping the expected not-supplied energy to less than 0.01% of demand in 2033, and to 3% in 2040, considering the percentile 95th of the cumulative ENS by realization.
- Now, according to the scope of the Master Plan, it is logical to expect supply issues after 2040. In that sense, 100%-probability of insufficient generation dispatch would be reached by 2047 for the peak-demand level, a delay of only 4 years in comparison to results obtained from the Base Scenario. It is worth to note, however, that the scope of such master plan extends only up to 2040. Considering the possibility of international exchanges, not-supplied energy by 2040 and 2050 would be 0.02% and 2.0% of demand, respectively.
- In addition to the application of ANDE's Generation Master Plan, the construction of Binational Hydropower Plants is considered. These new hydropower plants would represent an additional 3000 MW for Paraguay. In a Closed Market setting, not-supply energy would be 0.03% of demand by 2040, rising to 15% by 2050. These additional investments would have a more substantial impact for reducing power dispatch failure than in the previous scenarios. Failure probability would still be high tough, reaching to roughly 95% by 2050, for the peak-demand level. Now, considering an Open

Market, not-supply energy by 2040 would be much less than 0.01% of demand, while by 2050 would be 1.0%, with net imports of 14,000 GWh.

- A scenario of high investment in renewables and batteries is finally explored. As the amount of investment is chosen deliberately, the probability of dispatch failure is somewhat controlled, reaching to a maximum of 10%, in average, over the entire simulation period in the Closed Market configuration. A 0%-probability of dispatch failure could not be achieved for several factors, for instance, due to the discrepancy between the peak hours of solar generation output and demand, and limitations of the model to account for intra-day dispatch of the energy storage systems.

Further study

The weekly resolution of the model represents a serious limitation when dealing with energy storage systems, which have the sole purpose of seizing intra-day discrepancies of peak power output, i.e., solar, at noon, and demand, at night. Therefore, a further study to reduce the model's time resolution, ideally achieving an hourly level of detail, has merit.

From a financial viewpoint, the question emerges: what to prioritize: new investments or imports? By means of this work, we can define an "opportunity cost" and thus assess the alternative of investing in new power plants in Paraguay or importing energy from neighboring countries when demand surpasses supply in the long run. In each scenario, we plotted the marginal costs of supply at both ends of the existing transboundary links. By doing so, we can compare how much does it cost to supply 1 extra MWh of energy after the supply/demand balance is achieved in each node. The most-critical situations are obtained with the Base and Alternative Scenarios, without adequation in the supply side whatsoever. In a Closed Market setting, the marginal costs at the Paraguayan end by 2050 would be of the order of 3,000 USD/MWh, nearly 30-times higher than costs at each of the opposite ends. This means that the installation of any power plant, or the availability of imports, with operational costs below 3,000 USD/MWh would have economic dispatch merit and would help reducing overall costs and not-supplied energy. Precisely, when dealing with the same Scenarios but in the Open Market setting, the lack of supply is almost entirely covered with imports accounting for lower operational costs. Moreover, when assessing scenarios of investment, even if they involve Closed Market settings, new power plants help covering the initial not-supplied energy, thus reducing the marginal costs observed in the first two scenarios. Therefore, we can show by how much the Paraguayan costs decrease thanks to the investment in new power plants. This decrease in marginal costs, however, does not come for free, as the investment costs of these new power plants should be considered.

The shape pattern of demand is assumed to remain equal to that from 2019 over the entire simulation period. It is worth to note that this pattern is associated to spikes occurring in only 5 hours within a week. A load management strategy seeking to mitigate these spikes could offer an alternative to the construction of new power plants or to the import of energy when the supply failure becomes critical.

In summary, Paraguay would need to increase the power capacity to meet demand from 2030 on. In order to meet future demand, the introduction of new generation resources should be complemented with improvements in the system's load factor, new binational hydropower plants, and/or a strong regional market that supports imports/exports. Otherwise, large investment in storage systems would be required to promote energy security and reduce external dependence.

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