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***“SAMBA” THE OPEN SOURCE SOUTH
A MERICAN MODEL BASE:
A BRAZILIAN PERSPECTIVE ON LONG TERM POWER
SYSTEMS INVESTMENT AND INTEGRATION***

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“SAMBA” The Open Source South American Model Base: A Brazilian Perspective on Long Term Power System Integration.

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Abstract

South American countries have diverse and abundant energy resources ranging from oil, natural gas and coal to considerable potentials of other renewable sources, such as biomass large hydro. These resources are not evenly distributed. This asymmetry provides an interesting starting point to examine important energy exchanges in the region. The inclusion, for example, of synergies such as hydro-wind power production and balancing. To date, an open source and access, long term model which highlights South America power integration, has not been available. This paper addresses that gap, and develops scenarios of power plant investments considering different perspectives of integration. OSeMOSYS, a cost-optimization tool used for long-term energy planning, is used to develop least cost supply system configurations. The electricity supply systems of thirteen countries are modelled individually and linked together via trade links to form SAMBA (South America Model Base). A scenario comparison of the generation mix evolution in each country up to 2058 shows that an enhanced grid network and strategic large hydropower plants can alter South America's overall generation mix and result in a reduced electricity generation cost. The insights have important investment, trade and policy implications.

Keywords: OSeMOSYS; South America electricity supply; electricity trade; cost-optimization; scenario comparison.

1. Introduction

In 2012, electricity generation from renewable sources in South America represented 69% of the total, which is significantly higher than the global average of 21% [1][2]. However, due to structural reforms in the electricity sectors in the 1990s the continent is becoming increasingly dependent on thermal generation [3]. This is particularly true in Brazil, the largest producer (51%) and consumer (56%) of electricity on the continent, where there has been a steady increase in the installed capacity of thermal power plants since 2003 [1]. The share of conventional installed thermoelectric capacity is 27% of the total, but conventional thermal generation represented only 16% of the total production in 2012 [4]. This means that part of the generation normally linked to thermal plants is in fact provided by using the storage capacity of hydroelectric power plants.

This backup generation will, however, not be available in the near future: because Brazil is not building new power plants with multi-year reservoir capacity the flexibility of hydroelectric production in the country is declining. The new run-of-river hydro plants aim to reduce environmental impacts in the Amazon region, where the largest remaining potential can be found. Thus, the existing reservoirs are being used in excess, compromising the flexibility they provide. In addition, the long-term planning of the Brazilian electricity sector – carried out by the state owned company Empresa de Pesquisa Energética – resists to consider more conventional thermal plants operating in a way that they cover the

base of the power demand, such as natural gas combined cycle thermal plants, which could reduce the declining flexibility of reservoirs.

Thus, Brazil loses storage capacity each year as the production of hydroelectric power plants with large reservoirs capacity to remain constant and energy demand to increase. Still, this storage capacity in reservoirs represents about 4.5 months of average monthly national consumption in 2012 [5]. The flexibility offered by reservoir-based hydroelectric production supports the integration of electricity generation from other renewable sources with higher levels of intermittency, such as thermal biomass, wind, solar thermal and photovoltaic power plants.

Due to the challenges faced by a rapidly increasing electricity demand (3% annual growth rate), the Brazilian government has been interested in funding and developing joint-venture projects in the electricity sectors of neighboring countries, particularly hydropower plants and grid interconnectors. In this sense, the country is leading the early stages of a power systems integration process in the region that does not only involve short-term electricity surplus. There are environmental and feasibility studies being carried out for the construction of power plants and transmission lines with Argentina, Uruguay, Paraguay, Venezuela, Bolivia, Guyana and Peru [6].

Brazil's role in this area will contribute to South America's economic growth and political stability in addition to strengthening Mercosur, the Union of South American Nations (UNASUR) and the institutions required for regional energy integration. These include the Regional Integration Commission (CIER), the Latin American Energy Development Organization (OLADE) and the South American Regional Infrastructure Integration Initiative (IIRSA).

The purpose of this paper is to examine the potential for and relationship between electricity investments and trade between countries in South America. Scenarios are examined to identify the countries with the greatest export potential, as well as those with the largest expected demand for cost-competitive electricity. Beyond the substantial fossil fuel reserves present in specific regions of the continent, there is considerable renewable energy potential [7]. This paper assesses strategic large hydro projects which are being considered by Brazil in neighbouring countries and identifies areas where extensions would be required in the grid network, thus leading to a cost-efficient growth of the South American electricity supply system.

Section 2 presents the methodology and SAMBA model main assumptions. The results from two scenarios are presented in Section 3, with some insights about power integration process. Section 4 presents a summary of the key outcomes and future steps.

2. Methodology

The methodology followed to develop and apply SAMBA, a model of the South American electricity system is described below. The methodology includes the key assumptions, details on the model structure and the modelling tool. OSeMOSYS from source code to data is open source, which allows repeatability and free access.

2.1 - OSeMOSYS

The model discussed in this paper, SAMBA, is developed using the Open Source energy MOdelling SYstem (OSeMOSYS) [8]. OSeMOSYS is a dynamic, bottom-up, multi-year energy system model applying linear optimization techniques. It determines the optimal investment strategy and production mix of technologies and fuels required to satisfy an exogenously defined energy demand. Technical, economic and environmental implications associated with the identified least-cost energy systems can be easily extracted from the model results. OSeMOSYS assumes a power market with

perfect competition and foresight. This tool has been used to assess proposed power infrastructure on the African continent [9].

2.2 - Model Structure

The model structure developed is based on demand projections and a database of power supply technologies and their economic, technical and environmental parameters. It also includes information regarding the remaining life span of current infrastructure. Fuel prices and quantities are defined according to national database. The model is restricted by “constraints” for operational requirements, governmental policies and socio-economic characteristics of each country. All parameters modelled in SAMBA are time dependent, thus, the study period can be adjusted to represent other potential futures.

The key element of this power system optimisation framework is the ‘useful electricity’ demand and each country has a specific demand profile. This parameter has a high impact on the final results. For projecting the demand was considered that all countries will reach an annual consumption per capita of 5.500 kWh by 2058, a similar consumption level of a developed country such as Portugal (4848 kWh), Spain (5530 kWh) and Italy (5515 kWh) in 2012 [10]. Thus, it is important to keep in mind that values of demand in SAMBA model are merely indicative, despite considering national and international macroeconomic parameters.

Table 1 presents countries and regions included in the model to identify the implications of the power integration process in South America. The continent is divided in 13 individual country-level system models. Suriname and French Guyana power systems are not included in these first SAMBA scenarios, despite their trade potential, due to a lack of existing or future grid interconnections. Furthermore, due to the continental size of Brazilian power system it is divided into four subsystems: South, Southeast/Center-West, Northeast and North [11].

Table 1 – Countries and regions included in the model

Argentina	AR
Bolivia	BO
Brazil Southeast/Center-West	BR SE
Brazil South	BR SO
Brazil Northeast	BR NE
Brazil North	BR NO
Chile	CH
Colombia	CO
Ecuador	EC
Guyana	GY
Paraguay	PY
Peru	PE
Uruguay	UR
Venezuela	VE

2.3 - Key assumptions

A certain number of assumptions are fundamental in defining the structure and general context of the modelling effort. The following parameters are maintained constant throughout the analysis:

- The real discount rate applied is 8%.
- The monetary unit is 2013 US\$.
- Carbon electricity intensity reduced in 34% by 2058 [2].
- Natural energy inflow in hydro basins and multi-year reservoir capacities are modelled in Brazil subsystems and in Venezuela [11].
- Subsidies in national fuel prices are eliminated in the long-term converging to international prices.
- Losses in transmission and distribution systems, reduction costs and increasing efficiency of generating technologies are considered.
- Existing oil refining capacity and international pipelines limits the national supply of the countries.
- Countries grouped into three different time zones, improving solar resource availability.
- The reporting horizon of this study spans from 2013 to 2058. Simulations are undertaken on a yearly basis for the entire model period.
- Minimum annual electricity generation for technologies with some inflexibility level.
- The modelling framework is extended between 2053 and 2063 in order to avoid so called 'edge-effect' considerations from affecting the reported results.
- The year is represented by 48 characteristic time periods (12 months with early morning, morning, afternoon and night distinction for one type of day) per year.
- As mentioned above, OSeMOSYS assumes a perfect market with perfect competition and foresight.

2.4 - Scenarios

Currently, grid interconnections in South America correspond mainly to binational large hydro dams such as Itaipu (Brazil and Paraguay) and Yacireta (Argentina and Paraguay), in which Paraguay exports its surplus of electricity. On the other hand, interconnections which are not associated with binational power plants countries are limited, which limits the possibility for electricity trade. However, Brazil is considering some major infrastructure large hydro projects through bilateral power purchase agreements with Peru, Bolivia and Guyana [7], in order to import electricity. The following scenarios are developed:

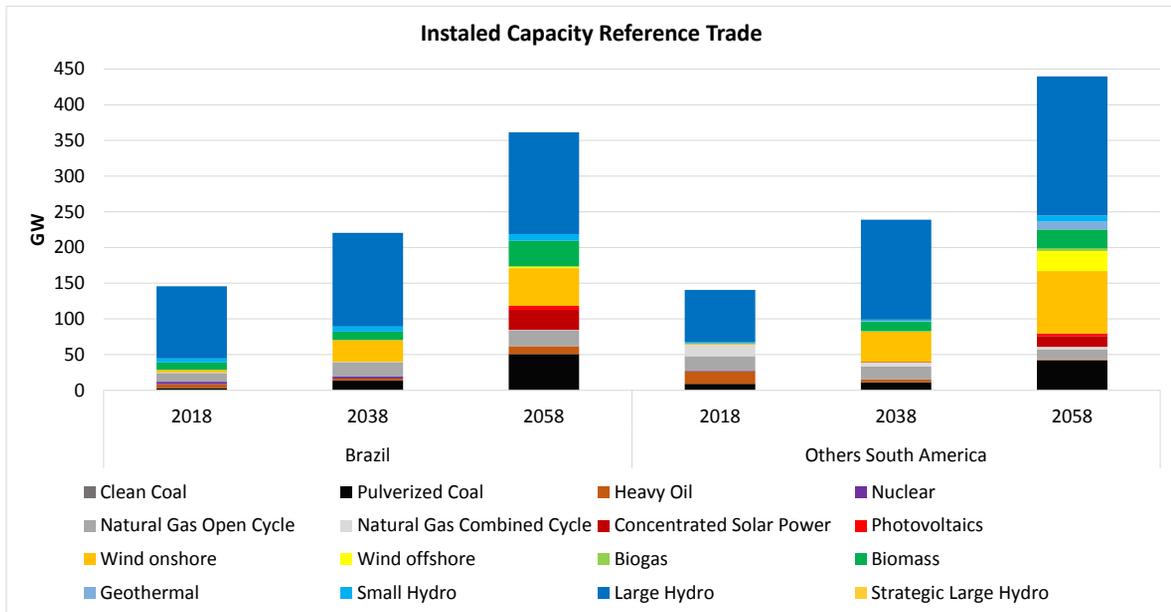
- a) *SAMBA Reference Scenario* – Existing and committed grid interconnections projects are represented in SAMBA. Results show the evolution of trade potential if no further projects are considered on the continental grid network. This scenario indicates future financially-viable power generation infrastructure.
- b) *SAMBA Integration Scenario* – Additional to existing and committed grid interconnections, planned uncommitted projects are also included such as strategic large hydro projects and associated transmission lines considered by Brazil with Peru, Bolivia, Guyana and Argentina, while constraints on transmission lines are relaxed from 2023 onwards, allowing trade to occur between neighbouring countries at cost-optimal levels, as calculated by the model. A comparison with the Reference Scenario can identify which additional grid interconnection projects should be considered on the continent so as to allow further exploitation of cost-competitive energy resources.

3. Results and discussion

3.1 - Generation Capacity

Due to increased demand in order to achieve the level of electricity consumption per capita in developed countries it will required investments in installed generation capacity. Brazil has the largest installed capacity, equivalent to those of

other countries on the continent added, as shown in Figure 1. The installed capacity in Brazil is expected to increase from 145 GW in 2018 to 361 and 331 GW in 2058, in the Reference and Integration Scenarios, respectively. The lower growth in the second scenario occurs due to expansion investments abroad. The installed capacity in hydroelectric plants in Brazil increase from 100.8 GW in 2018 to 142.7 and 137.9 GW in Reference and Integration Scenarios, respectively. In addition, there is significant increase in on-shore wind installed capacity from 3.7 GW in 2018 to 53 GW and 52.4 GW as well in coal power plants from 3.1 GW in 2018 to 50.7 GW and 56.6 GW in the Reference and Integration scenarios, respectively. There is also an expansion in solar thermal plants to 24.9 GW in 2058.



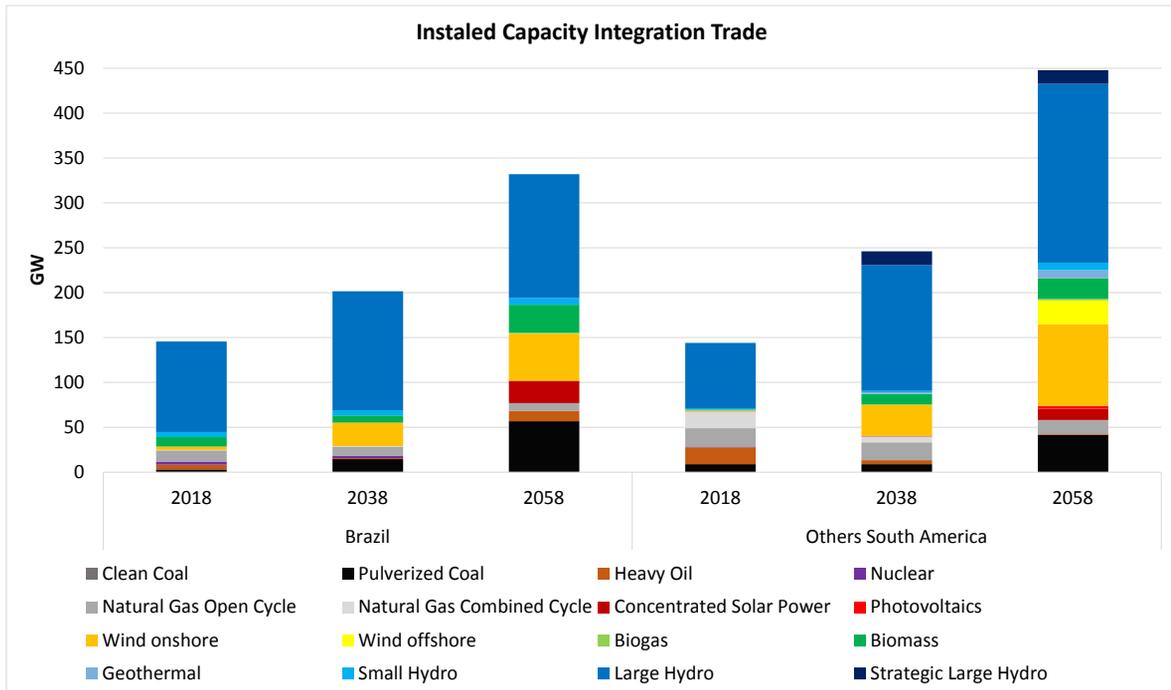


Figure 1 – Evolution of total installed capacity in each power pool in the Reference (top) and Integration (bottom) scenarios.

The installed capacity in Bolivia has the highest relative growth due to low per capita consumption, growing more than elevenfold, from 2.4 GW in 2018 to 27.7 GW and 30.4 GW in Reference and Integration scenarios, respectively. Considering the capacity expansion in other countries of South America, there is great expansion in wind power capacity of 1.1 GW in 2018 to 87.6 GW and 90.9 GW in 2058 in the Reference and Integration scenario, respectively. It also highlights the expansion of geothermal capacity in the Andean countries from 0.2 GW in 2018 to 11 GW and 9 GW in 2058 in the Reference and Integration scenario, respectively. The hydroelectric capacity has the largest absolute increase from 72.6 GW in 2018 to 194.3 and 199.3 GW in 2058 in the Reference and Integration scenario, respectively. In both scenarios the investment mix is diversified, especially in large hydropower plants, on-shore wind, biomass, geothermal and coal.

3.2 – Electricity Generation Mix

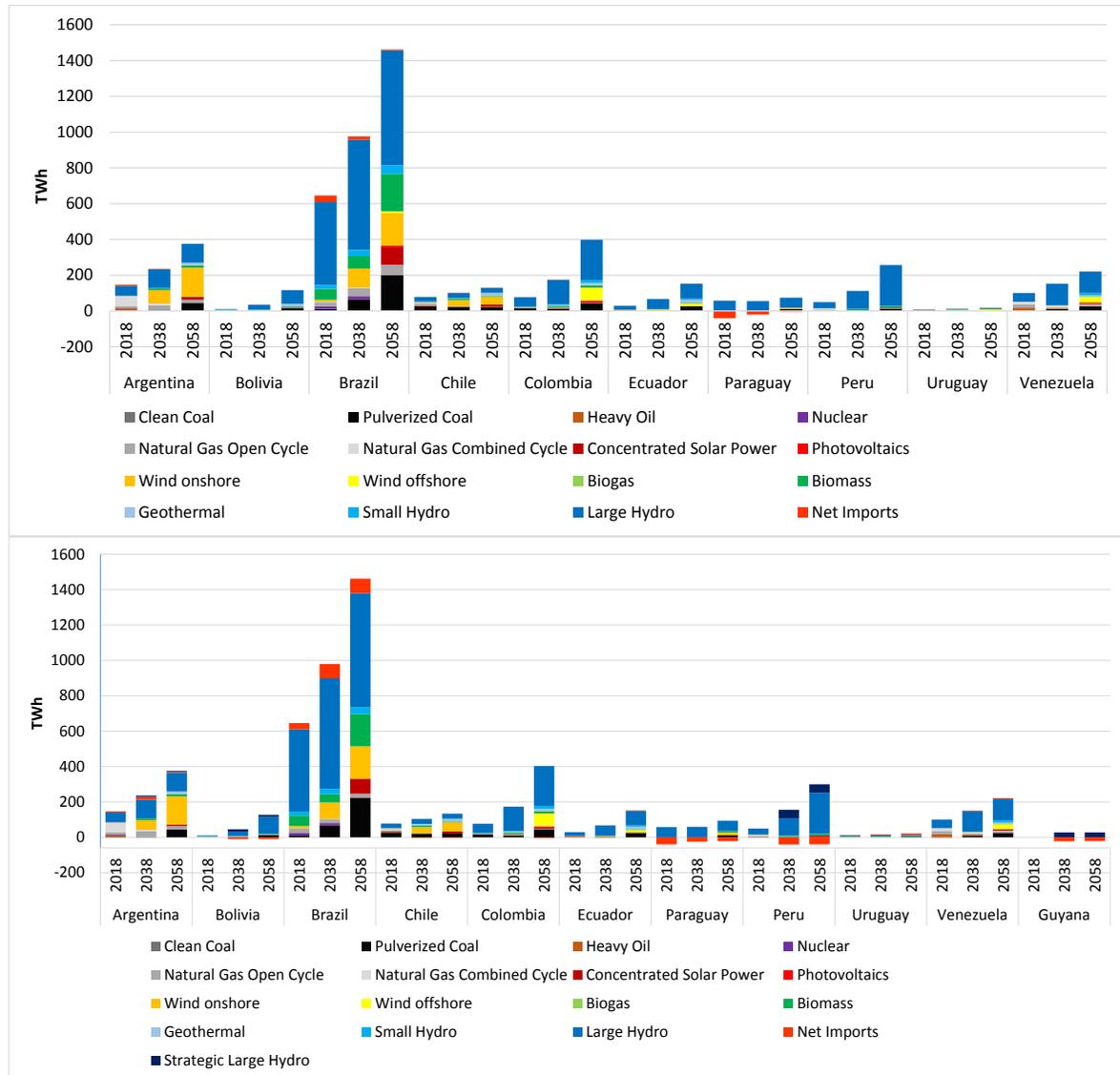


Figure 2 – Evolution of generation mix in each power pool in the Reference (top) and Integration (bottom) scenarios.

In the reference scenario is interesting to note that Paraguay is the major exporter of electricity on the continent, particularly to Brazil and to Argentina, although the export volume decrease significantly from 40.4 TWh in 2018 to 4.8 TWh in 2058. The hydroelectric generation predominates in almost all countries due to the exploitation of the great potential on the continent. There is a expressive increase in hydropower generation in Peru from 32.8 TWh in 2018 to 228.6 TWh in 2058 and in Colombia from 51.1 TWh in 2018 to 224.8 TWh in 2058. Renewable electricity generation, non-hydro, has also strong expansion in geothermal power plants, solar thermal and biomass.

In the Integration Scenario, due to Brazilian investments in large hydropower and associated transmission lines in Peru, Guyana and Bolivia, these countries become electricity exporters with potentials estimated up to 40.5 TWh, 20.7 TWh

and 9.3 TWh in 2058. The electrical system of Guyana was considered only in the Integration Scenario after being connected to Brazilian grid in 2025. The generation from on-shore wind and coal also show significant increases. In both scenarios the nuclear generation is not competitive, which may indicate that the nuclear generation programs in Brazil and Argentina are justified more by political decisions.

Comparing both scenarios (Figure-3), there is a big difference in Brazil and other countries in South America. The increase in hydroelectric production (93 TWh) from strategic projects financed by Brazil abroad reduces the need for expansion of capacity in other countries of South America especially in on-shore wind power and coal. In Brazil the increase in imports reduces the generation of natural gas open cycle plants and biomass, but leads to an increase in coal-fired generation.

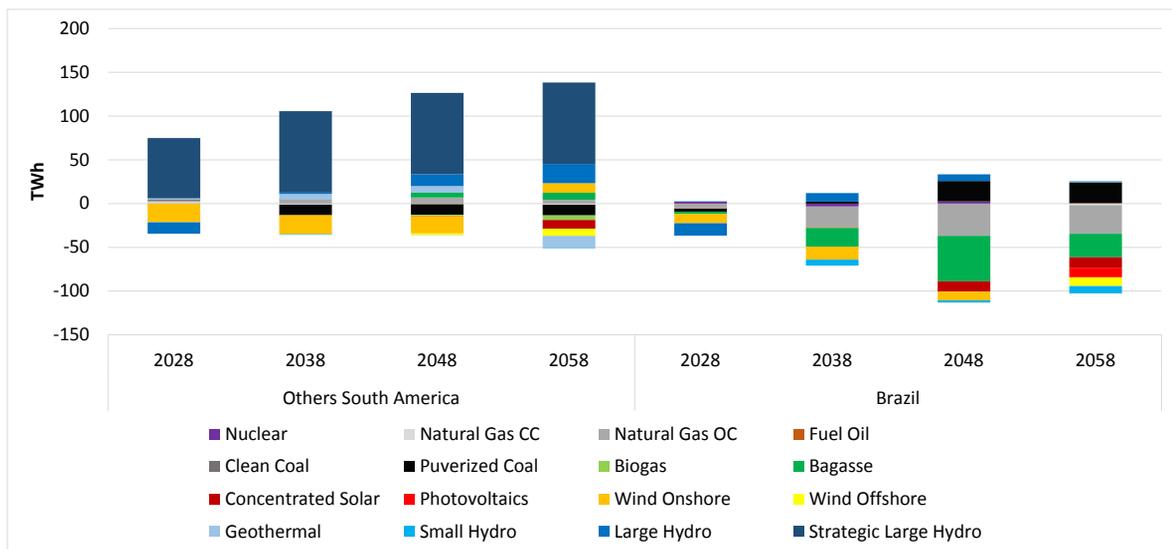


Figure 3 – Differences in generation mix for each country in the two scenarios (Integration minus Reference).

Assessing individual results for the countries (Figure 4), there are large differences between the two scenarios. In the Reference Scenario, the external dependence of Brazil is meaningless. Although the country imports 80 TWh in 2058 in the Integration Scenario, it accounts only 5% of the total demand. In Uruguay, the electricity imports in 2058 increase from 8% in the Reference Scenario to 35% in the integration scenario. Chile and Colombia increase exports of electricity to Argentina and Ecuador, respectively. Such trade opportunities may allow improvements in infrastructure of the electrical sectors and generate additional revenue for their economies.

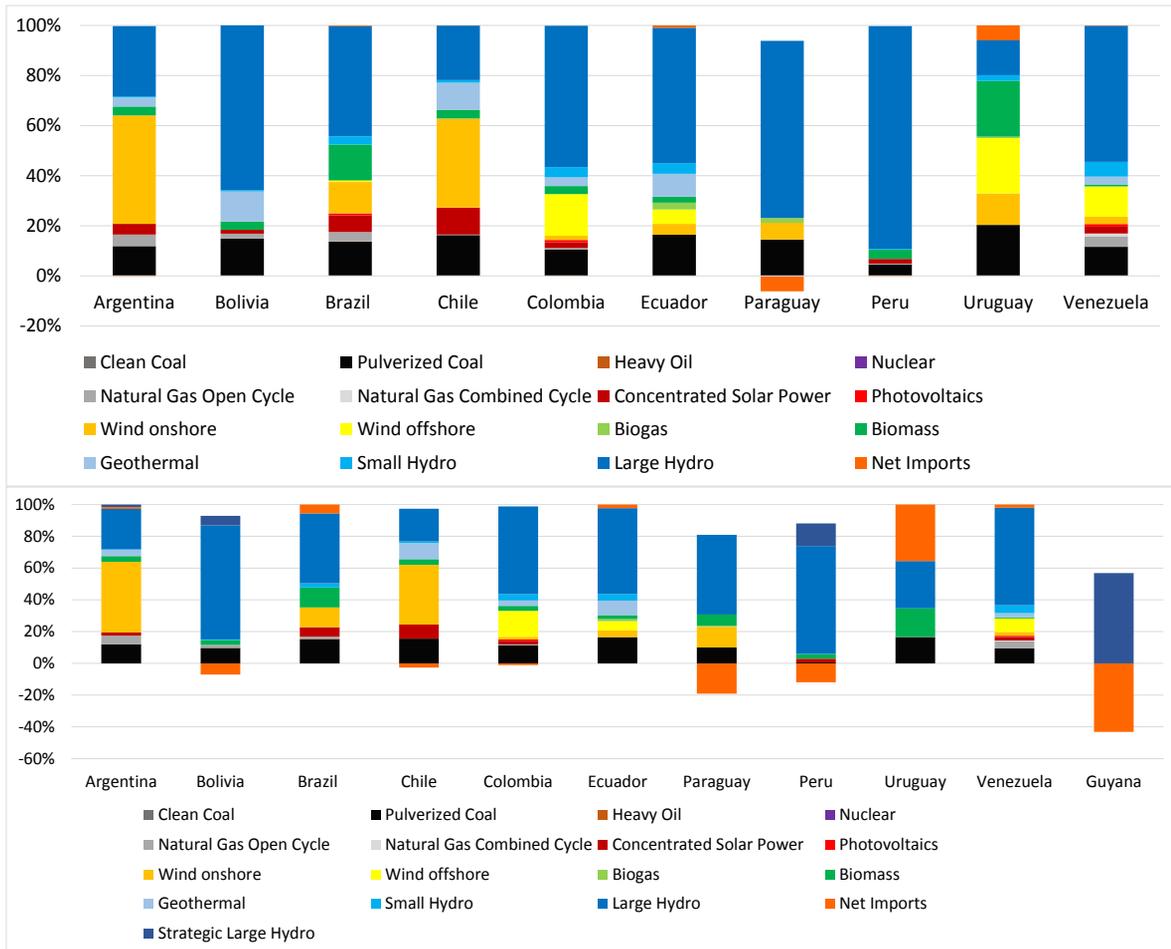


Figure 4 – Evolution of generation mix by country in 2058 for the Reference (top) and Integration (bottom) scenarios.

As shown in Figure 4, Bolivia, Chile, Colombia, Paraguay, Peru and Guyana have potential for becoming net exporters, while Argentina, Brazil, Ecuador, Uruguay and Venezuela net importers. Enhancing the electricity trade will improve energy security, despite reducing the total generation. In this sense, power purchase agreements such as the one reached between Brazil and Peru in 2010 [7] can attract more investments to the electricity sectors.

3.3 – Reservoirs Storage Capacity

Figure 5 illustrates the amount of equivalent electricity available in reservoirs in Brazil and Venezuela, where there are a significant storage capacity. This flexibility supports increasing generation of intermittent sources, such as solar and wind. However, in Brazil this storage capacity is expected to decline by 2030 due to increased hydro generation to prevent the dispatch of thermal plants.

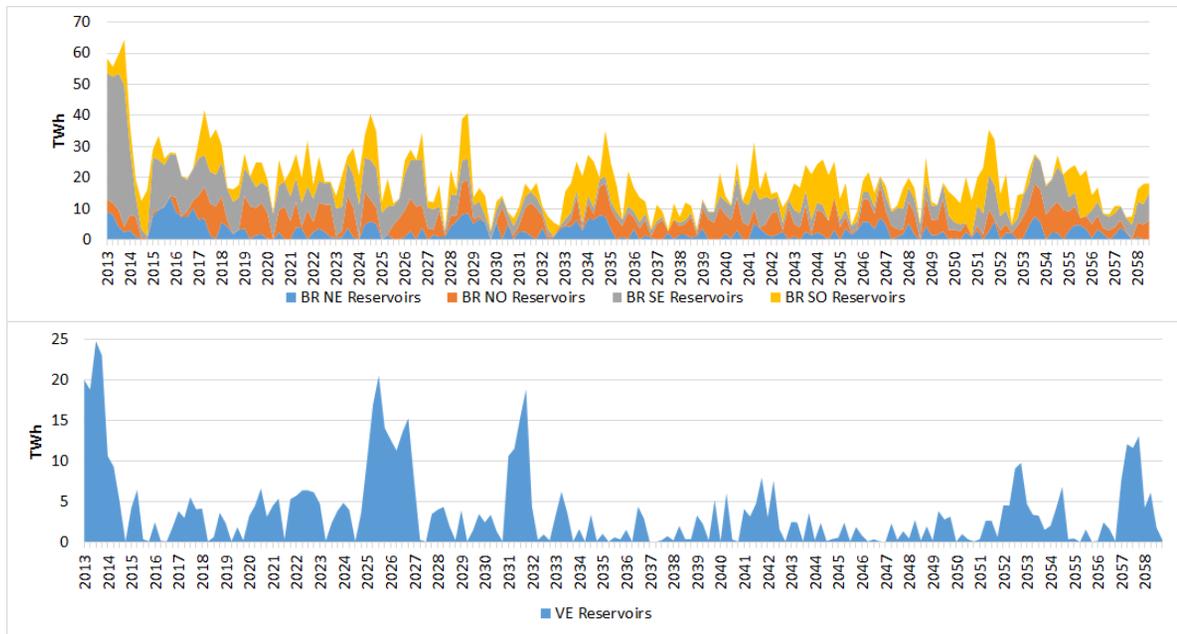


Figure 5 – Equivalent electricity available in reservoirs in Brazil and Venezuela

3.4 - Cross-border electricity trade

Figure 6 illustrates electricity trade flows between countries in the Integration Scenario considering the total potential trade from 2013 to 2058; All modelled countries are involved in electricity exchanges. As indicated by the figure, the largest net exporters are Paraguay (1356 TWh), Peru (1232 TWh), Guyana (854 TWh) and Bolivia (301 TWh). Brazil is also a great exporter (439 TWh) despite being a net importer (3591 TWh). Argentina, Uruguay and Venezuela are net importers.

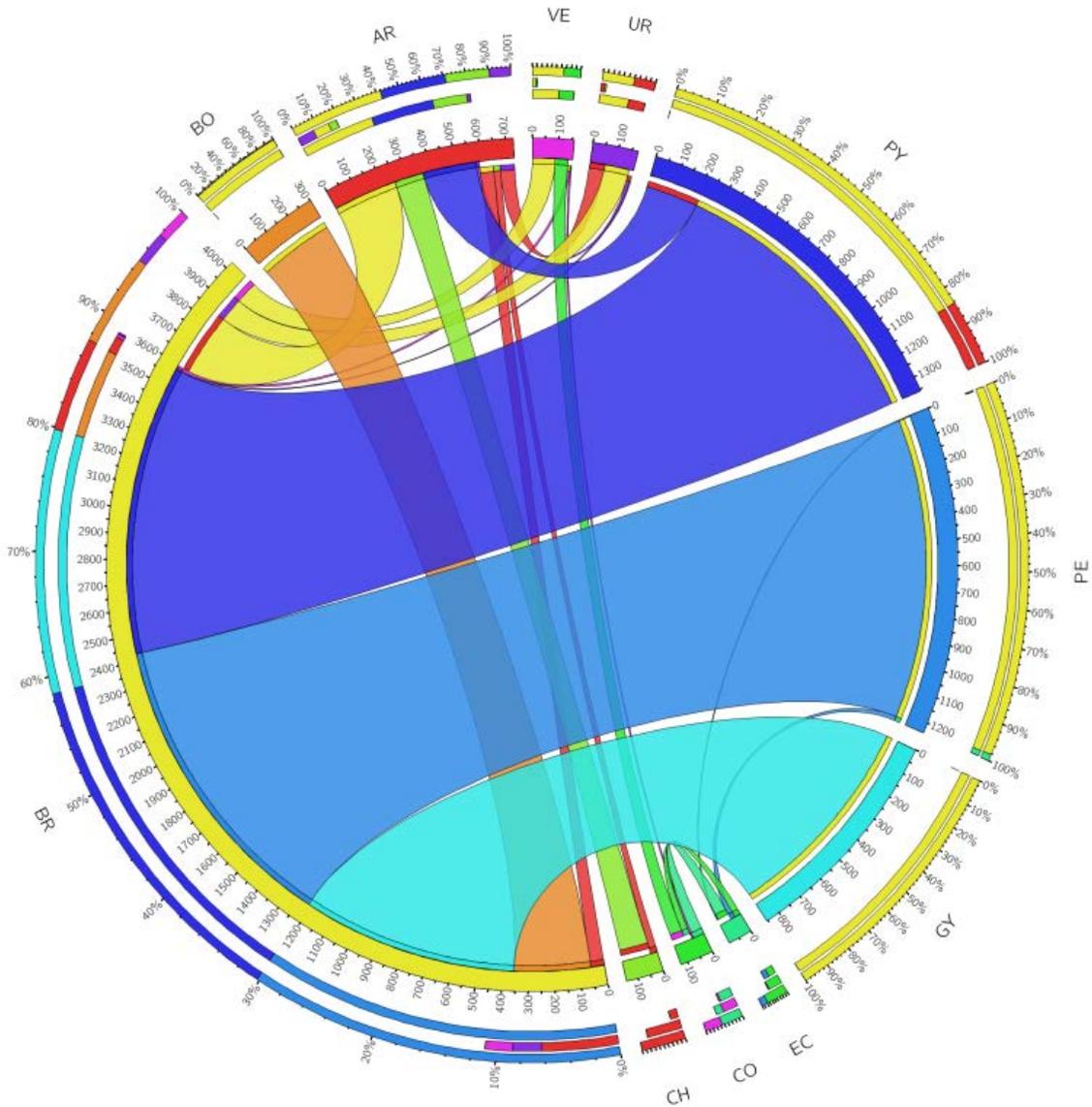


Figure 6 – Electricity trade potential across the continent from 2013 to 2058 (TWh) in the Integration scenario (country code is given in Table A.1 in Appendix A).

3.5 – Financial requirements

As shown in Figure 7, the investment level is similar in both scenarios, but the fuel costs decreases in the integration scenario as the large hydro, wind generation and trade increases. During 2019-2058, annual total system cost savings would range between 0.3-3 billion USD. Brazil is the largest economy on the continent and has a higher capability of funding capital-intensity projects, such as large hydropower plants and transmission lines. Countries with large hydro potential although limited financial capacity, such as Bolivia and Guyana, could improve their power infrastructure

through trade agreements with Brazil, increase national budgets due to electricity trade and reduce spending in fossil fuel generation.

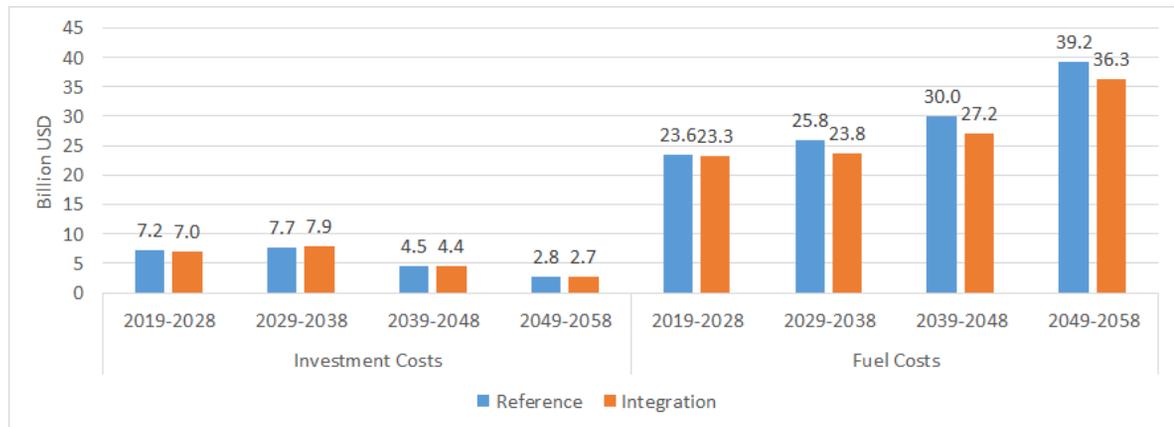


Figure 7 – Comparison of total investment cost and fuel costs in the two scenarios.

4. Conclusions

Major investments in power infrastructure will be needed in South American countries in the coming decades due to the increasing demand for electricity. Power systems integration between countries might allow the exploitation of synergies not only related to the uneven resources distribution and renewable energy potential, but also by differences in the load demand in the countries.

There is a potential for investment in renewable electricity generation on the continent of about 450 GW. Despite some countries showing opportunities for renewable generation, they have not financial capacity to exploit it. As a result, some countries subsidize fossil fuels. There are significant economic asymmetries among countries on the continent, and to overcome this issue, political decisions are needed to promote the development.

Brazil's interest in power systems integration process is driven mainly by maintaining an electric matrix with low operating costs. The investments in strategic large hydropower projects abroad can reduce Brazil's installed capacity in 30 GW in 2058. There is still an 80 GW hydroelectric potential in the Brazilian Amazon, but the environmental impacts and costs associated with mitigation measures of these projects are increasingly criticized by Brazilian society. From the Brazilian perspective, the reward for moving towards a greater power systems integration with neighboring countries will be keeping a renewable electric matrix with low operating costs and carbon emissions.

SAMBA model scenarios might contribute to a better understanding of the whole power sector evolution on the continent, highlighting the trade power potential of each country. With greater knowledge of the possibilities in the long term, policy makers responsible for long term expansion planning will take better informed decisions on which regulation is suitable for each integration agreement. Transparency and solid regulation are key issues to attract investments in capital intensive projects.

The model from source code of the programming language to the data input is open source. This is important as it provides for repeatability and open access. It is potentially helpful not only from an academic point of view, but also helpful in terms of providing a starting point for national, investment and policy focused scenario generation. Future work will provide more detail about the methodology and assumptions used to build the model. More integration

scenarios using SAMBA model might allow to understand the perspectives of each country in the integration process and thus the development of the power sector in South America.

Acknowledgements

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Appendix A – Final Electricity Demand Projections

Figure A.1 – Final Electricity Demand across South America

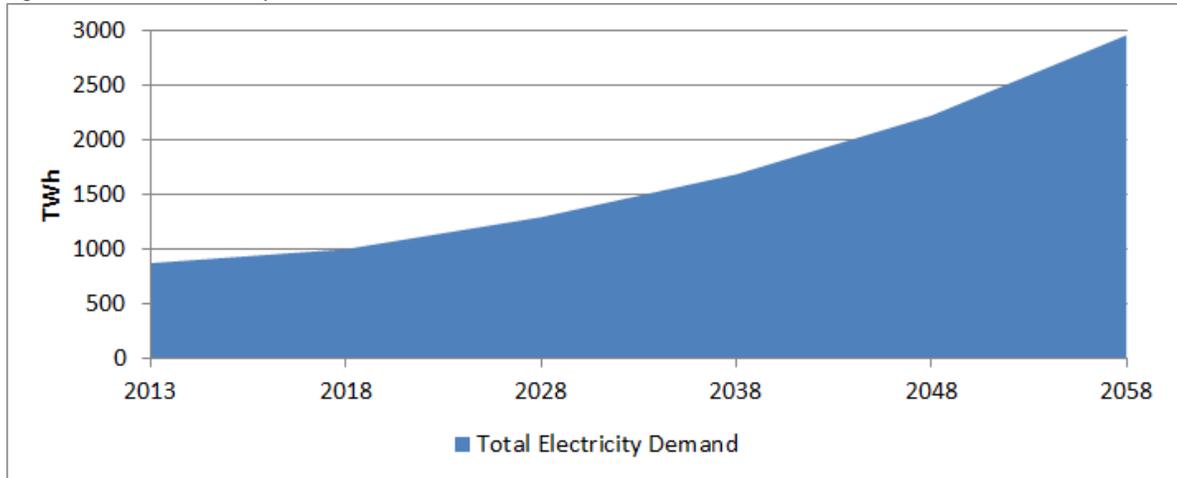


Figure A.2 – Final Electricity Demand across countries

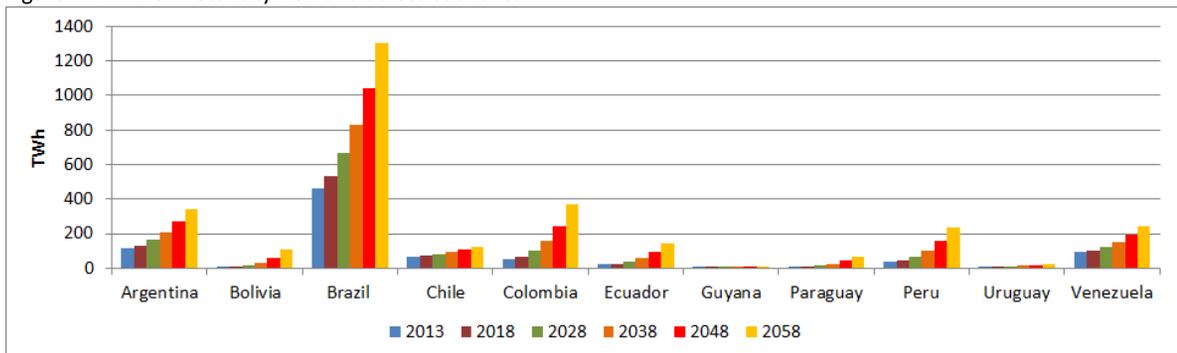


Table A.1 – Final Electricity Demands in each country (TWh).

Country	Code	Final Electricity Demands (TWh)					
		2013	2018	2028	2038	2048	2058
Argentina	AR	113.0	127.9	163.8	210.0	269.0	344.7
Bolivia	BO	6.3	8.7	16.3	30.5	57.3	107.5
Brazil Southeast/Center-West	BR SE	273.0	305.6	382.8	479.7	601.0	752.9
Brazil South	BR SO	81.0	90.7	113.6	142.3	178.3	223.4
Brazil Northeast	BR NE	79.9	89.4	112.0	140.4	175.9	220.4
Brazil North	BR NO	30.2	44.9	56.3	70.5	88.4	110.7
Chile	CH	66.8	71.3	81.3	92.7	105.7	120.5
Colombia	CO	54.5	67.3	103.1	157.9	241.7	370.0
Ecuador	EC	20.9	25.9	39.6	60.7	92.9	142.2
Guyana	GY	0.5	0.6	1.0	1.6	2.7	4.5
Paraguay	PY	9.0	11.2	17.3	26.7	41.2	63.4
Peru	PE	35.8	44.2	67.3	102.6	156.3	238.1
Uruguay	UR	8.6	9.4	11.3	13.6	16.8	20.1
Venezuela	VE	91.1	101.2	124.8	153.9	194.0	239.3

Appendix B – Techno-economic parameters

Table B.1 - Technical Parameters for Power Generating Technologies

Technology	Capital Cost	Fixed Cost	Variable Cost	Efficiency	Lifetime	Load Factor	Construction time
	US\$ / KW	US\$ / KW	US\$ / GJ				
Wind on-shore	1750	114	0.0	N/A	25	42	2
Wind off-shore	4432	36	0.0	N/A	30	31	2
Solar Photovoltaics	1944	40	0.0	25	25	25	1
Concentrated Solar Power	5732	65	0.7	35	40	40	3
Nuclear PWR	7776	115	2.7	35	40	85	6
Nuclear CANDU	7776	115	2.7	35	40	85	6
Natural Gas Combined Cycle	1260	20	1.1	57	30	85	3
Natural Gas Open Cycle	583	10	1.1	38	30	85	2
Clean coal	6530	102	0.9	40	40	85	4
Pulverized Coal	3129	44	0.9	45	40	85	4
Biomass Incineration	1633	13	0.5	35	25	66	2
Biogas	2100	50	1.6	40	25	85	2
Fuel Oil	1512	25	1.6	35	25	85	3
Geothermal	4283	120	0.0	11	20	85	3
Large Hydro	2333	35	0.5	N/A	60	N/A	2
Small Hydro	3499	45	0.5	N/A	60	N/A	2
Strategic Hydro	2177	26	0.5	N/A	60	N/A	4

Note: Load factor for large, small and strategic large hydro varies across the year during wet and dry seasons in each country.

Appendix C – Fuel Prices

Table C.1 – National and International Fuel Prices

Fuel - USD/GJ	International	Argentina	Bolivia	Brazil	Chile	Colombia	Ecuador	Guyana	Paraguay	Peru	Uruguay	Venezuela
Coal	2.78	6.51	2.78*	1.76	3.20	2.03	2.78*	2.78*	2.78*	3.20	1.78	3.20
Natural Gas	3.77	2.45	1.23	7.55	8.83	3.77*	2.59	3.77*	3.77*	1.51	3.77*	1.23
Liquefied Natural Gas	15.09	15.09*	N/A	15.09*	15.09*	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Uranium UO2	2.50	2.50*	2.50*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Uranium U3O8	2.50	2.50*	2.50*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Heavy Fuel Oil	19.11	13.30	4.49	13.47	20.98	11.32	3.49	19.11*	19.11*	17.46	19.95	2.49
Bagass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biogas	37.41	37.41*	37.41*	37.41*	37.41*	37.41*	37.41*	37.41*	37.41*	37.41*	37.41*	37.41*

* Same as international price