Seasonal pumped hydropower storage role in responding to climate change impacts on the Brazilian electrical sector

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APPENDIX A – Development: energy production correlations for wind and solar power

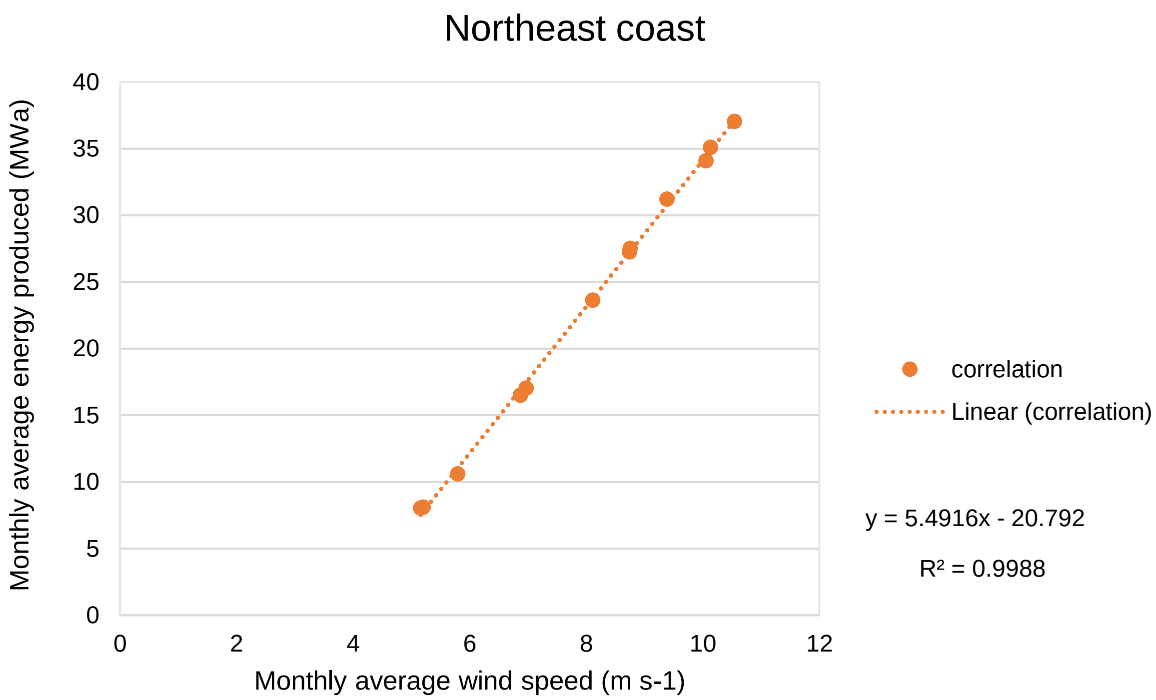


Figure A-1 – Correlation between monthly average wind speed and monthly average energy produced in the Northeast coast spot.

Table A-1 – Capacity factor season average comparison between VWF model results, historical results from ONS, and RCP results from CORDEX data for wind farm spot in the Northeast coast region for the year 2019.

Northeast coast - historical year 2019					
	VWF model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.379	0.387	0.265	0.182	0.183
autumn	0.226	0.183	0.207	0.031	0.026
winter	0.595	0.473	0.776	0.423	0.544
spring	0.706	0.753	0.883	0.818	0.844

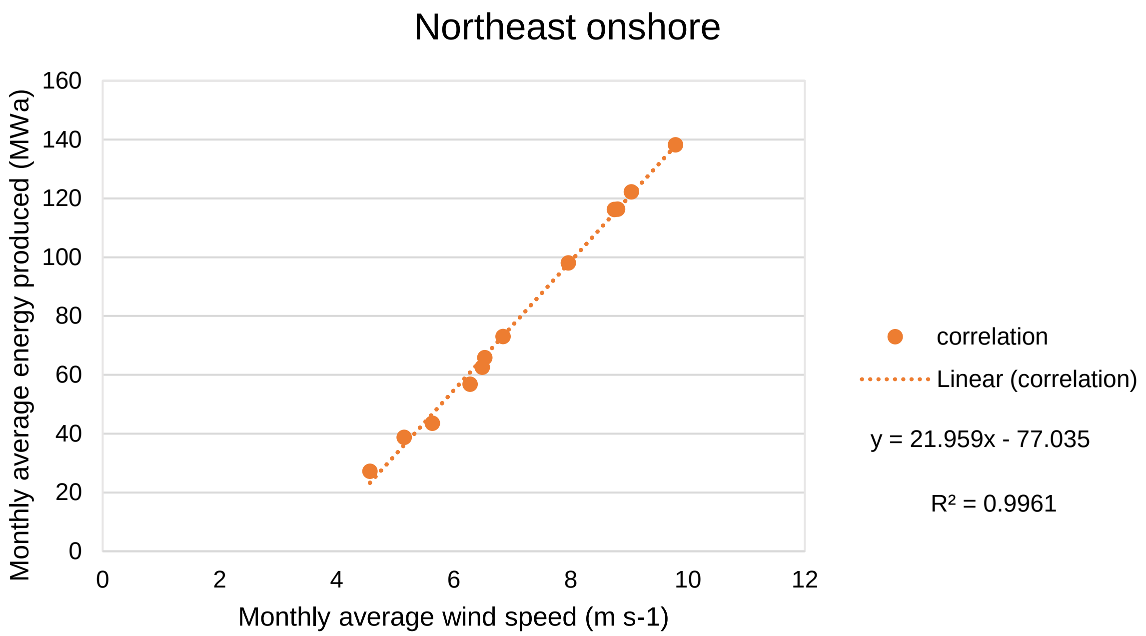


Figure A-2 – Correlation between monthly average wind speed and monthly average energy produced in the Northeast onshore spot.

Table A-2 - Capacity factor season average comparison between VWF model results, historical results from ONS, and RCP results from CORDEX data for wind farm spot in the Northeast onshore region for the year 2019.

Northeast onshore - historical year 2019					
	VWF model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.244	0.300	0.067	0.003	0.008
autumn	0.236	0.373	0.203	0.071	0.102
winter	0.613	0.670	0.610	0.614	0.570
spring	0.467	0.523	0.538	0.452	0.498

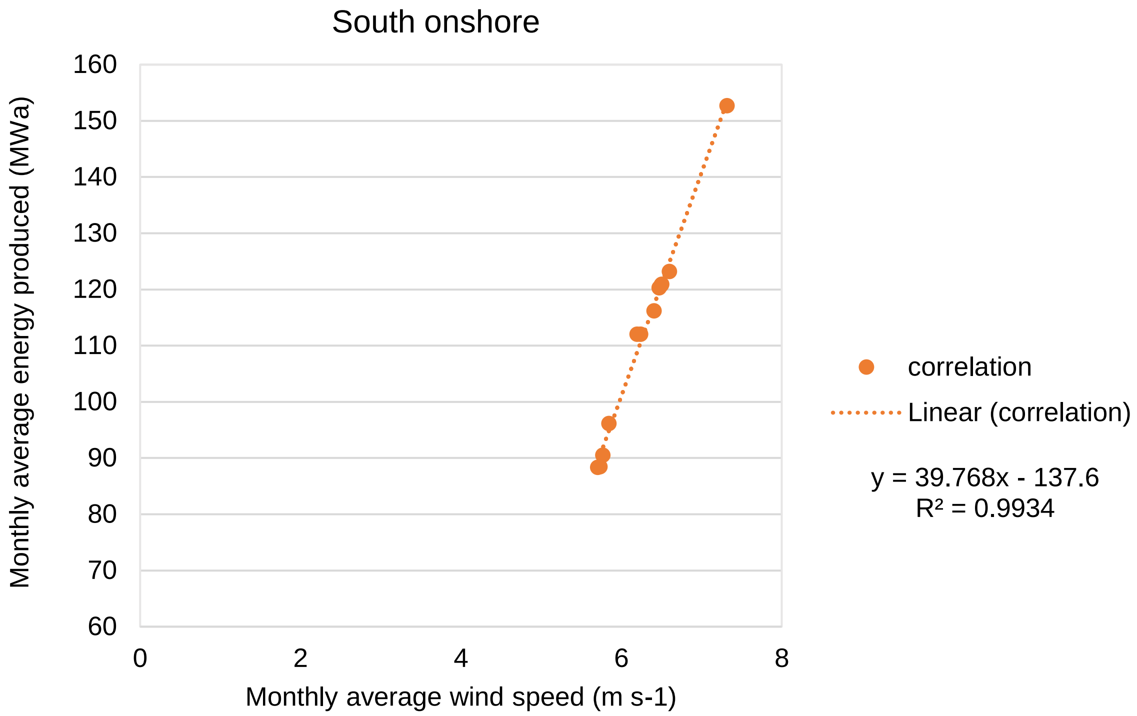


Figure A-3 - Correlation between monthly average wind speed and monthly average energy produced in the South onshore spot.

Table A-3 - Capacity factor season average comparison between VWF model results, historical results from ONS, and RCP results from CORDEX data for wind farm spot in the South onshore region for the year 2019

South onshore - historical year 2019					
	VWF model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.291	0.270	0.433	0.461	0.360
autumn	0.271	0.207	0.262	0.293	0.320
winter	0.287	0.280	0.316	0.244	0.267
spring	0.342	0.347	0.515	0.438	0.539

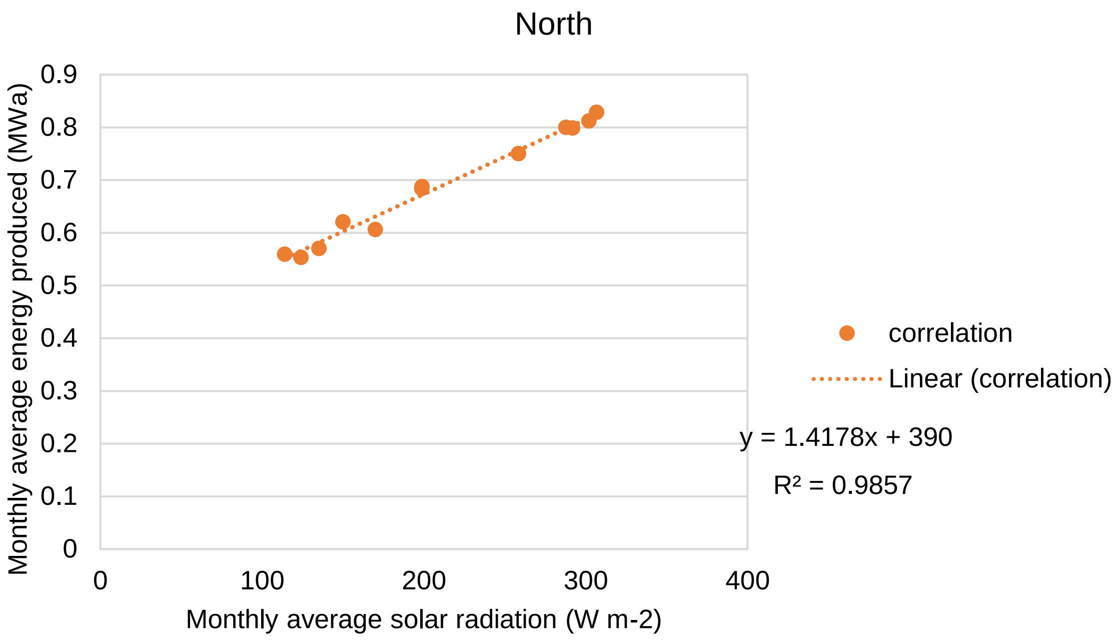


Figure A-4 - Correlation between monthly average solar radiation and monthly average energy produced in the North region spot.

Table A-4 – Capacity factor season average comparison between GSEE model results, and RCP results from CORDEX data for solar power plant spot in the North region for the year 2019.

North - historical year 2019					
	GSEE model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.21	n.a.	0.24	0.24	0.24
autumn	0.19	n.a.	0.23	0.23	0.22
winter	0.23	n.a.	0.24	0.24	0.24
spring	0.26	n.a.	0.25	0.25	0.26

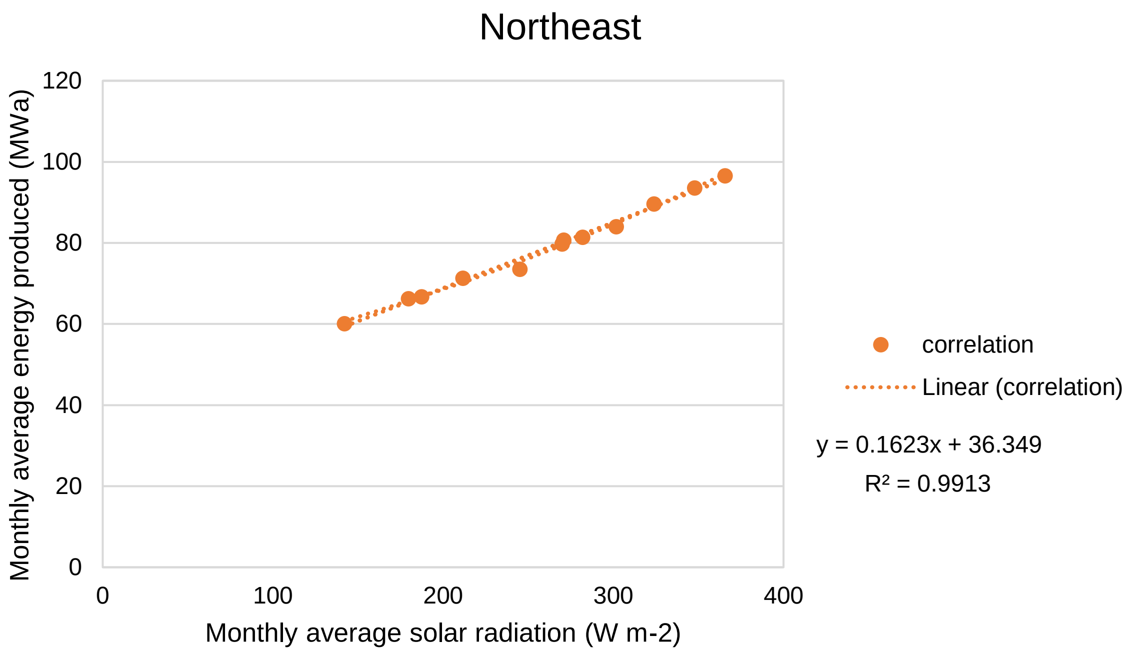


Figure A-5 - Correlation between monthly average solar radiation and monthly average energy produced in the Northeast region spot.

Table A-5 - Capacity factor season average comparison between GSEE model results, historical results from ONS, and RCP results from CORDEX data for solar power plant spot in the Northeast region for the year 2019.

Northeast - historical year 2019					
	GSEE model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.244	0.250	0.239	0.224	0.236
autumn	0.237	0.253	0.251	0.226	0.229
winter	0.296	0.307	0.264	0.260	0.265
spring	0.308	0.293	0.295	0.289	0.296

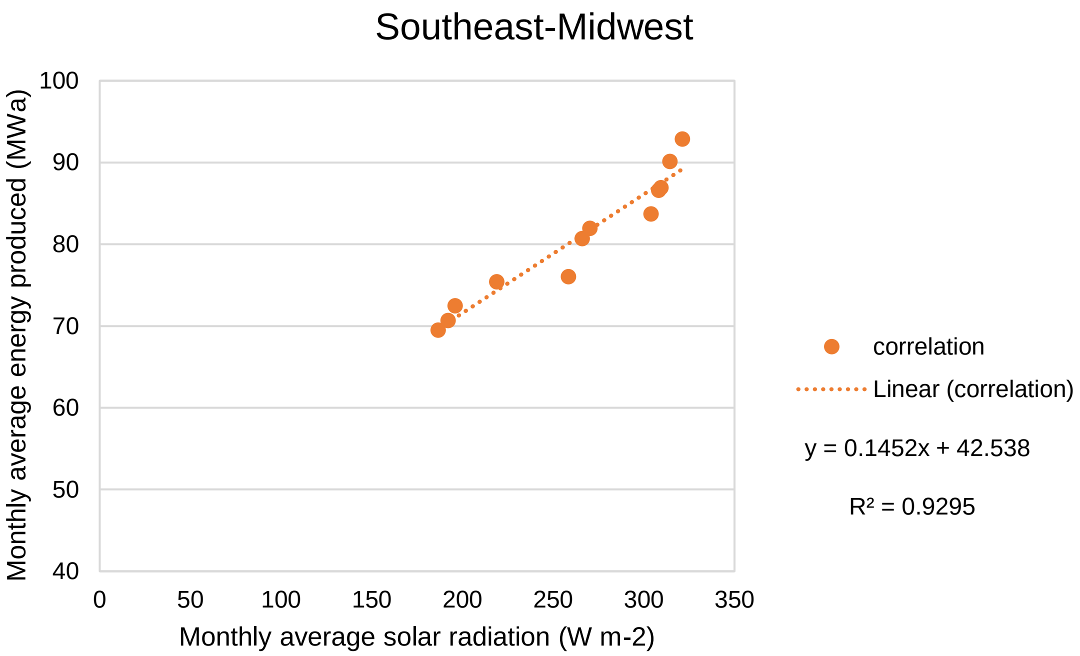


Figure A-6 - Correlation between monthly average solar radiation and monthly average energy produced in the Southeast/Midwest region spot.

Table A-6 - Capacity factor season average comparison between GSEE model results, historical results from ONS, and RCP results from CORDEX data for solar power plant spot in the Southeast/Midwest region for the year 2019.

Southeast/ Midwest - historical year 2019					
	GSEE model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.251	0.287	0.267	0.255	0.255
autumn	0.234	0.245	0.243	0.241	0.235
winter	0.267	0.255	0.233	0.234	0.232
spring	0.252	0.253	0.259	0.255	0.258

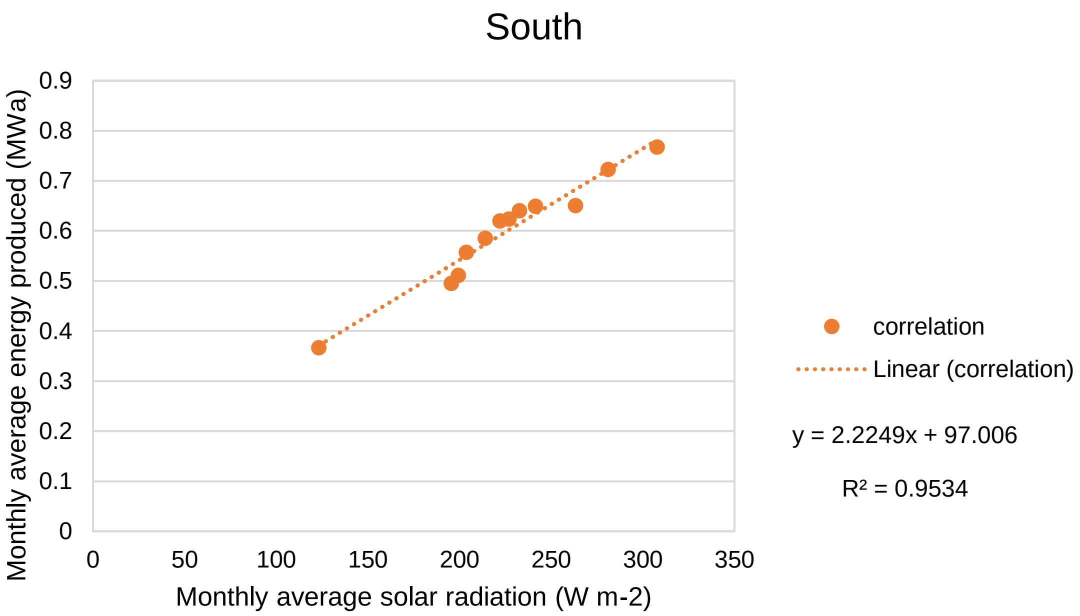


Figure A-7 - Correlation between monthly average solar radiation and monthly average energy produced in the South region spot.

Table A-7 - Capacity factor season average comparison between GSEE model results, and RCP results from CORDEX data for solar power plant spot in the South region for the year 2019.

South - historical year 2019					
	GSEE model	ONS (historical)	RCP 2.6	RCP 4.5	RCP 8.5
summer	0.262	n.a.	0.269	0.256	0.256
autumn	0.198	n.a.	0.183	0.197	0.189
winter	0.211	n.a.	0.172	0.182	0.177
spring	0.251	n.a.	0.261	0.261	0.245

APPENDIX B - BESMM input data

Figure B-1 presents the installed capacity values added for each technology and subsystem. Southeast/Midwest has 52% of the total installed capacity of Brazil and at the same time 58% of the total electricity demand of Brazil. The other subsystems' demand rate is: 17% in the South region, 16% in the Northeast, and 8% in the North region.

Technology	North [GW]		Northeast [GW]		Southeast/Midwest [GW]		South [GW]	
Hydro	19.8	82%	11.02	34%	63.21	73%	16.99	73%
Termo	3.93	16%	7.33	23%	20.71	24%	4.22	18%
Wind	0.328	1%	12.61	39%	0.03	0%	2.02	9%
Solar	0.05	0%	1.40	4%	0.68	1%	0.04	0%
Nuclear					1.99	2%	-	
Total	24.11	100.0%	32.36	100.0%	86.61	100.0%	23.27	100.0%

Figure B-1 – Installed capacity of each node according to historical values from 2019 [Adapted from EPE, 2020a].

The transmission lines in BESMM were represented in a simplified way as **Error! Reference source not found.** represented them. In this representation there are four transmission lines, one connecting the North node with the Northeast node, one connecting the Northeast with the Southeast/Midwest, on connecting the Southeast/Midwest node with the North node, and one connecting the South node with the Southeast/Midwest node. Transmission line capacities for each node are described in **Error! Reference source not found.**.

Table B-1 - Transmission lines capacity for each node [Adapted from ONS, 2022c].

Node	GW
North ↔ Northeast	44.1
Northeast ↔ Southeast/Midwest	22.1
Southeast/Midwest ↔ North	83.1

South ↔ Southeast/Midwest	48.5

Table B-2 shows the energy generation activity in Brazil in 2019 used as case activity input in BESMM.

Table B-2 – Energy generation activity of each subsystem according historical values from 2019 [Adapted from EPE, 2020a].

	North [GWa]	Northeast [GWa]	Southeast [GWa]	South [GWa]	Total [GWa]
Hydro	7.5	2.5	29.7	8.0	47.7
Termo	1.8	2.1	6.1	1.2	11.2
Wind	0.2	5.5	0.0	0.7	6.4
Solar	0.0	0.4	0.2	0.0	0.6
Nuclear			1.8		1.8
Total	9.5	10.5	37.9	9.9	67.8

Demand projections used the rate of the SSP2-45 for Latin America developed by Huppmann et al., 2019a, for MESSAGE-GLOBIOM 1.0. Overall, an SSP socioeconomic pathway describes the drivers of how the future might unfold in terms of population growth, governance efficiency, inequality across and within countries, socio-economic developments, institutional factors, technology change, and environmental conditions that are influenced by these factors [Riahi et al., 2017]. And, SSP2 outlines a middle-of-the-road approach to mitigating and adapting to climate change [Fricko et al., 2017]. Figure B-2 shows the projections for each node of the BESMM based on the growth rates of SSP2-45 for Latin America. According to this projection, the energy demand in Brazil in 2100 will be 368 GWa, with almost 60% of that demand coming from the Southeast/ Midwest alone.

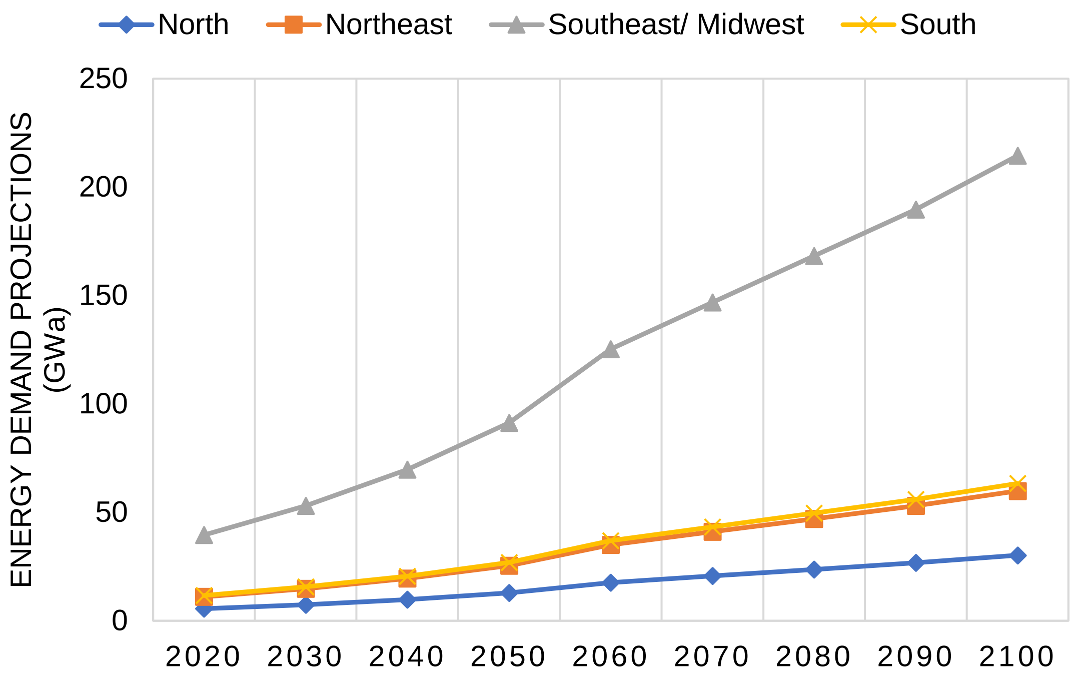


Figure B-2 – Energy demand projections for each node based on SSP2-45 scenario.

Technology prices were based on the PNE 2050 [BRASIL, 2020]. According to Brasil (2020) The investment costs and fix costs, for each source, were obtained from the EPE database, constituted from information on energy purchase auctions and national and international references. Investment costs include all direct costs (civil works, equipment, connection and environment) and indirect costs of the development. The variable cost values reflect the sum of the fixed and variable values, except for dispatchable sources (where the variable O&M is contemplated in the unit variable cost). Table B-3 present all the values used in the BESMM.

Table B-3 - Technologies costs, including investments costs, fix costs and variable costs [Adapted from BRASIL, 2020].

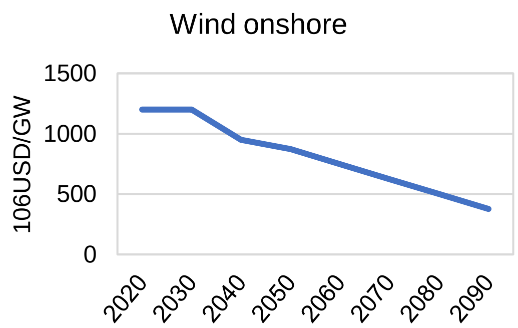
Technology	Investment costs [106USD[1]/GW]	Fix cost [106USD[1]/GW]	Variable cost [106USD[1]/GW]
Hydropower	1352	12.8	
Biomass power plant	1200	23.1	
Natural Gas power plant	900	220.0	25
Coal power plant	2500	100.0	30
Oil power plant	1100	220	35
Nuclear power plant	5000	110	
Wind power	1400	25.6	

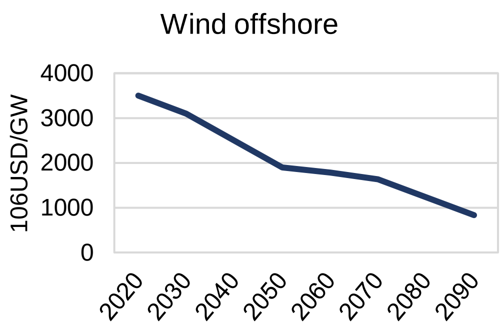
Solar power plant	1100	5.1
SPHS tunnel and plant	600	6.4
SPHS dam and land	*	-
Grid (transmission lines)	1000	36.0

1 Note: Exchange Rate: R$3.90/US$ (monthly average of December 2015).

* The unit in this case is 106USD/m³ based on the costs provided by [Hunt, Julian D. et al., 2020].

With regard to wind and solar power, the investment costs have been adapted to take into account future technological developments. Hence, a linear regression was used to calculate the prices up to 2090 based on the future price trends up to 2050. Figure B-3 shows the future prices defined for wind onshore, wind offshore and solar power based on PNE 2050 [BRASIL, 2020].





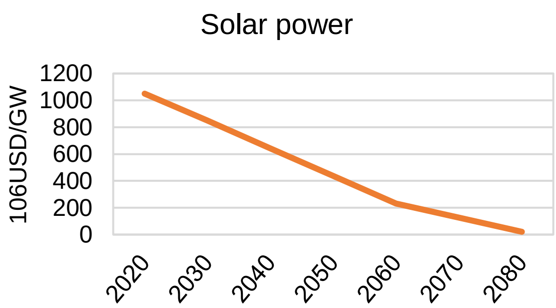


Figure B-3 – Wind power onshore and offshore and solar power defined future prices up to 2099 for the BESMM.

Boundaries and constraints were applied to the BESMM to better incorporate the Brazilian electrical system characteristics. For wind and solar power it was applied boundaries on the total installed capacity based on the energy potential of each node [BRASIL, 2020]. For hydropower it was considered no change in the capacities. By keeping the hydropower capacity constant, it will be possible to assess the SPHS's contribution to the BESMM. Based on the difference between the quantity of hydropower generated with and without SPHS, this evaluation will be conducted. The SPHS simulate scenarios will also demonstrate how the BESMM can increase its hydroelectric capacity without having to build additional plants.

The units used in the BESMM model are as follows:

- activities: GWa
- capacity: GW
- cost related to activity, e.g., var_cost: USD2019/GWa = $2019/GWa
- cost related to capacity, e.g., inv_cost: USD2019/GW = $2019/GW
- water inflow: m^3s^{-1}

APPENDIX C - Inflow bias correction. **Error! Reference source not found.**contains all the results for the wind power, solar power, and hydropower updated inputs for the BESMM model. Other technologies were considered to have constant input values. All scenarios with the inclusion of SPHS considered the introduction of SPHS technologies in all EER except in the EER Itaipu. The goal is to assess the role of SPHS in each future climate change scenario. Finally, a comparison was made between RCP scenarios with and without SPHS technologies. Indicators such as the Share of renewable energy endowment, Total SPHS produced, and CO_2 emissions were used to compare the scenarios. **Error! Reference source not found.**, in step 2, illustrates the inputs and outputs of the BESMM schematically.

APPENDIX C – Inflow bias correction

A bias correct was applied to the inflow data generated for future BESMM simulations in order to reduce uncertainties. To bias-correct future data the inflow generated from CORDEX data was compared with historical data from ONS (from years 2006 up to 2021) and a correction factor was applied for each one of the EER. As there is no historical inflow data for EERs in this approach it was compared the inflow from the last reservoir of each EER with the generated inflow of the EER. The assumption made was that no matter how many hydropower units are installed in the EER, the EER's inflow will be the same as the last reservoir. Table C-1 summarizes the last reservoir of each EER. Some EER has more than one last hydropower unit, thus the inflows were summed and in other cases, it was needed to subtract inflow from other river as the inflow is being considered in more than one EER.

Table C-1 – Last reservoir of each EER considered for the comparison with the generated inflow using Cordex data

	EER	**Last reservoir in the EER**
1	Southwest	Ilha dos Pombos
		Mascarenhas
		Itapebi
		Jauru
		Lajeado
		Ponte de Pedra
		Itiquira II
		Manso
2	South	Foz Chapeco
		Quebra queixo
		Dona_Francisca
		14 de Julho
3	Northeast	Xingó
4	North	Tucuruí minus Lajeado
5	Itaipu	Itapu minus Porto Primavera, and Rosana
6	Madeira	Santo Antônio
		Dardanelos
		Rondon II
		Samuel
7	Teles Pires	São Manoel
8	Belo Monte	Pimental
9	Amazonas	Santo Antônio Jari
		Curuá-una

		Balbina
		Fernando Gomes
10	Paraná	Porto Primavera
11	Iguaçu	Baixo Iguaçu
12	Paranapanema	Rosana

Figure C-1 shows the comparison between historical inflow of last reservoir of the EER Southeast and Cordex 2.6 inflow data after the bias correct.

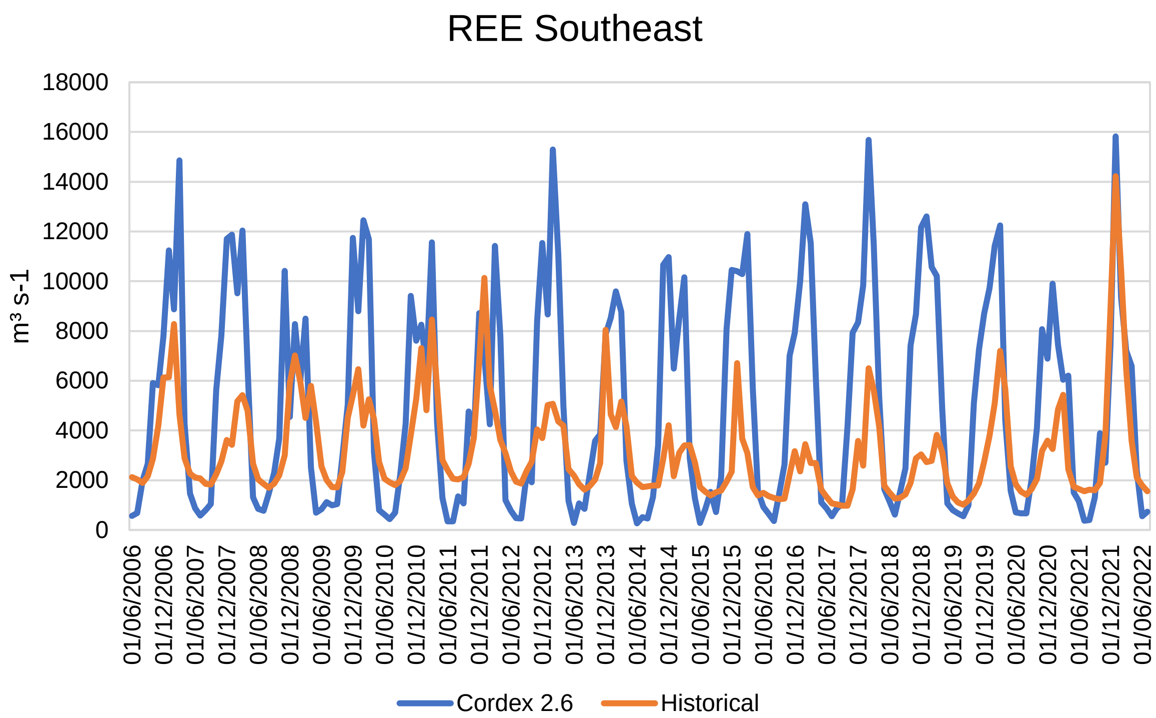


Figure C-1 – Comparison between historical inflow of last rivers in the EER Southeast and Cordex 2.6 inflow data.

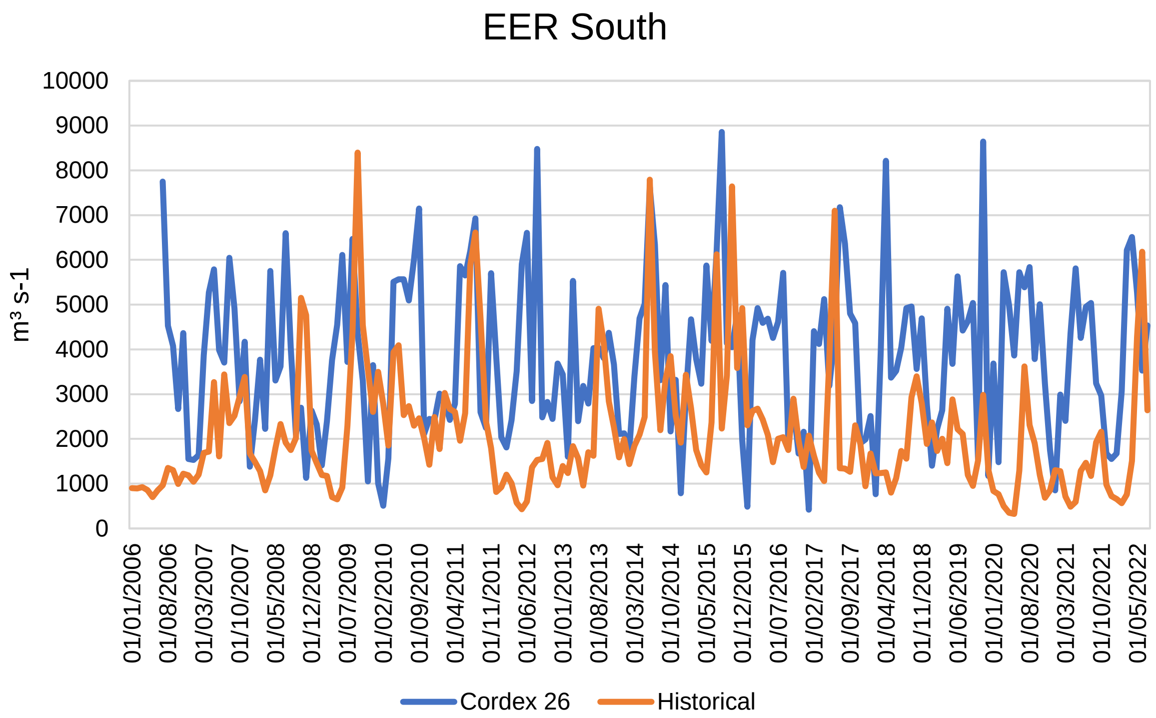


Figure C-2 - Comparison between historical inflow of last rivers in the EER South and Cordex 2.6 inflow data.

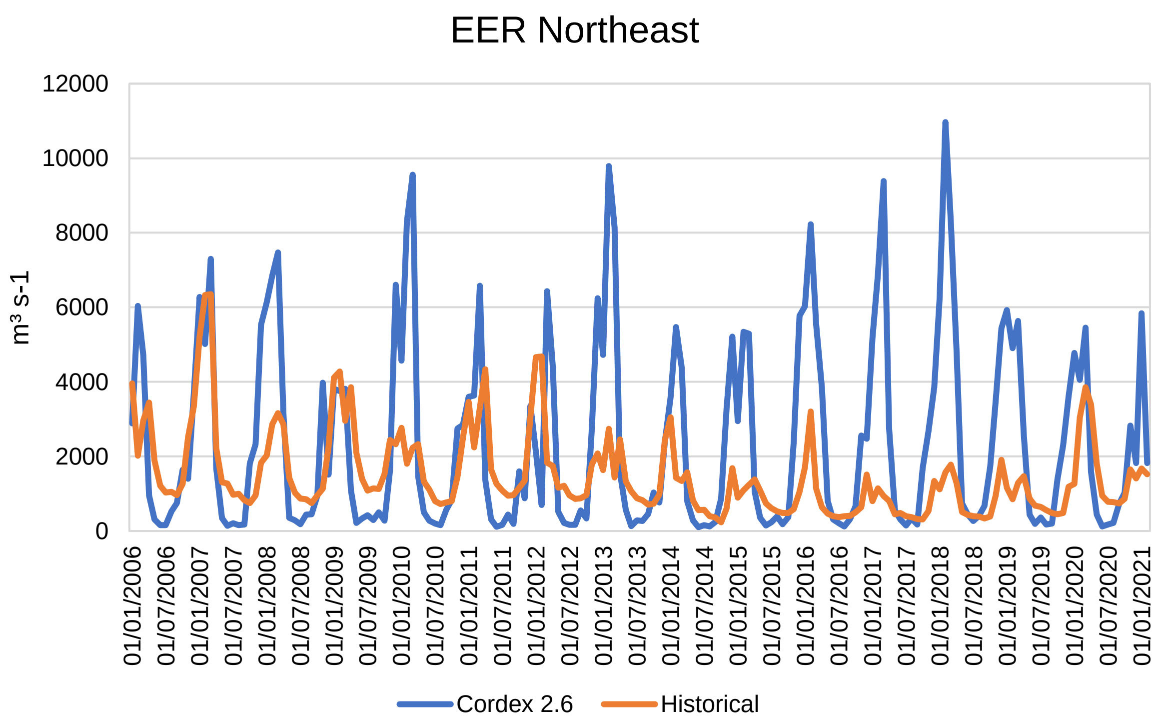


Figure C-3 - Comparison between historical inflow of last rivers in the EER Northeast and Cordex 2.6 inflow data.

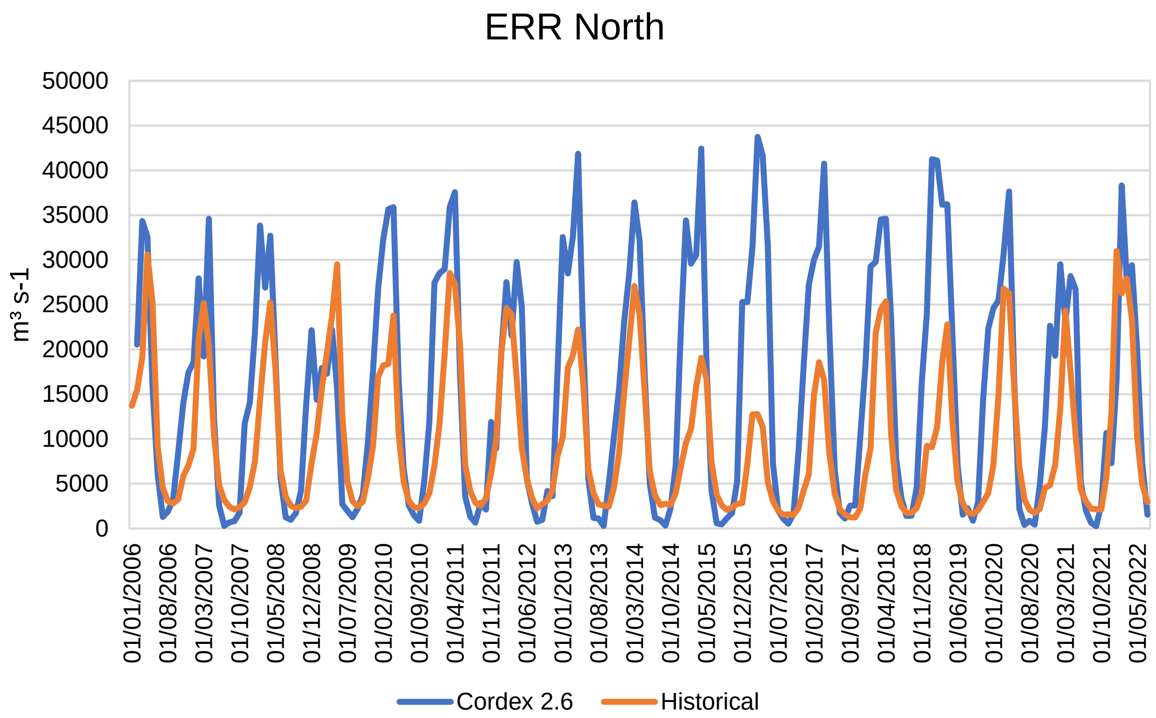


Figure C-4 - Comparison between historical inflow of last rivers in the EER North and Cordex 2.6 inflow data.

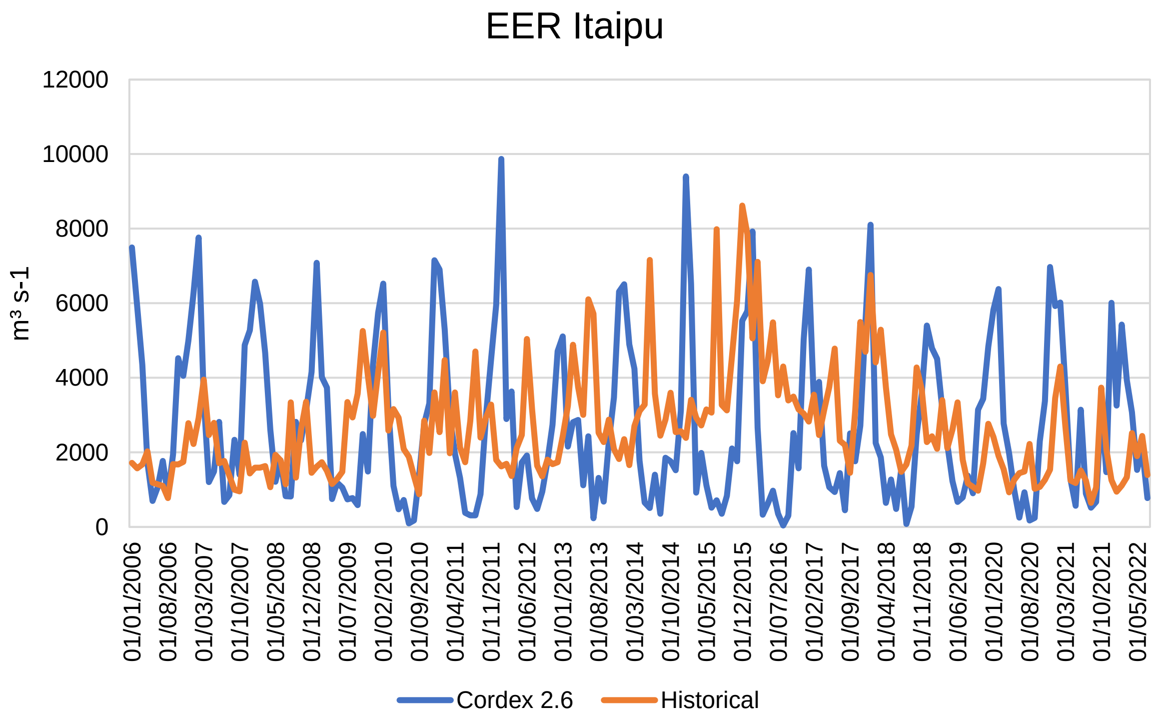


Figure C-5 - Comparison between historical inflow of last rivers in the EER Itaipu and Cordex 2.6 inflow data.

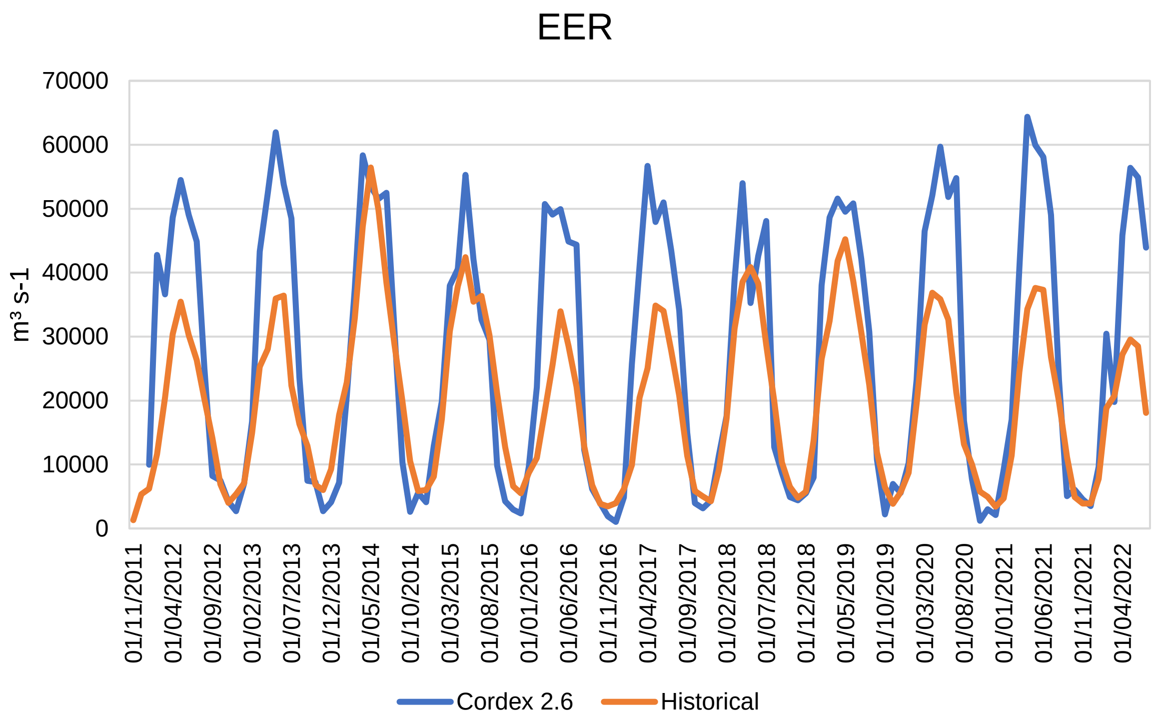


Figure C-6 - Comparison between historical inflow of last rivers in the EER Madeira and Cordex 2.6 inflow data.

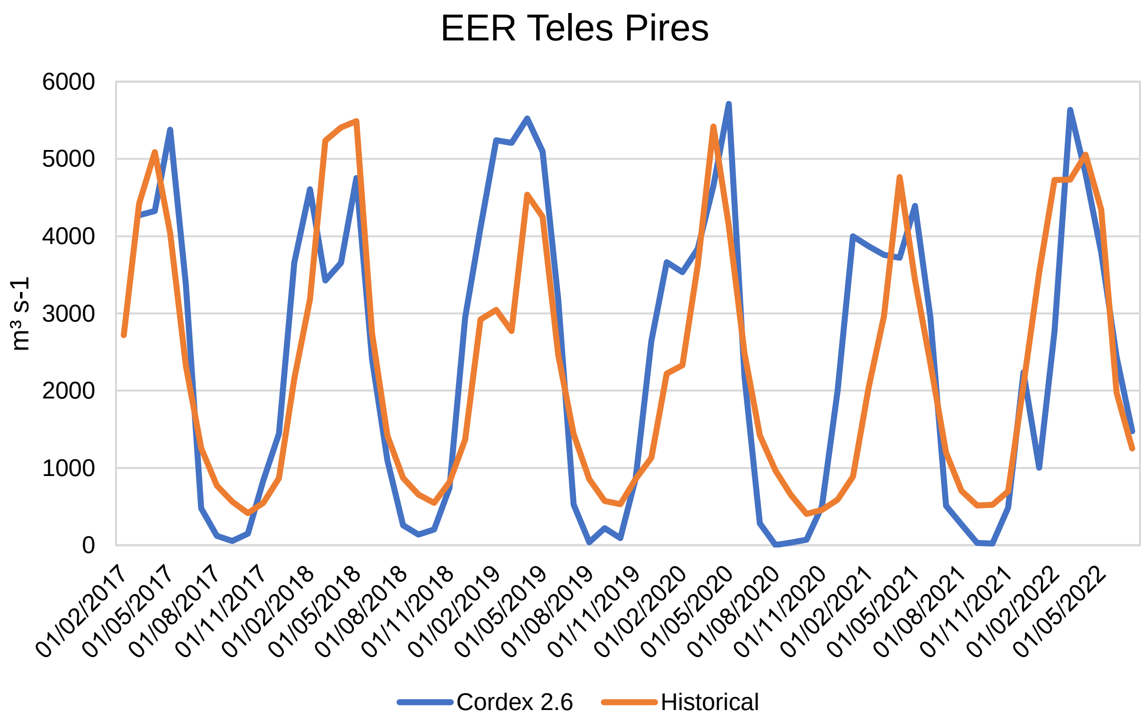


Figure C-7 - Comparison between historical inflow of last rivers in the EER Teles Pires and Cordex 2.6 inflow data.

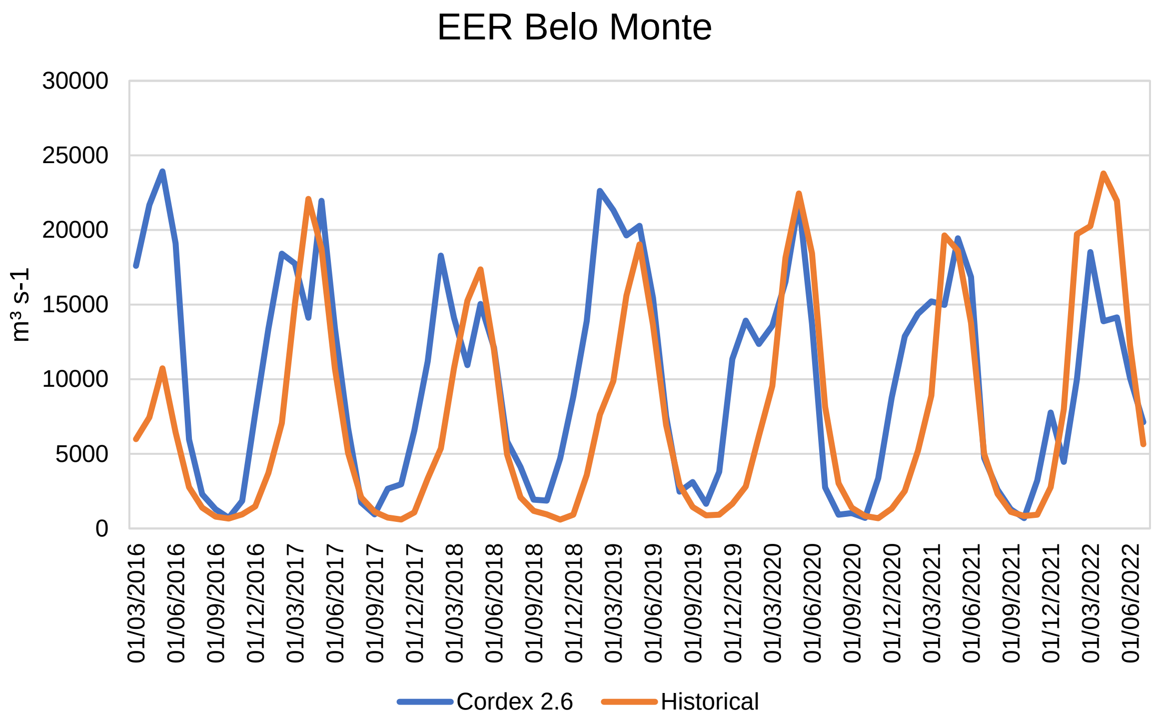


Figure C-8 - Comparison between historical inflow of last rivers in the EER Belo Monte and Cordex 2.6 inflow data.

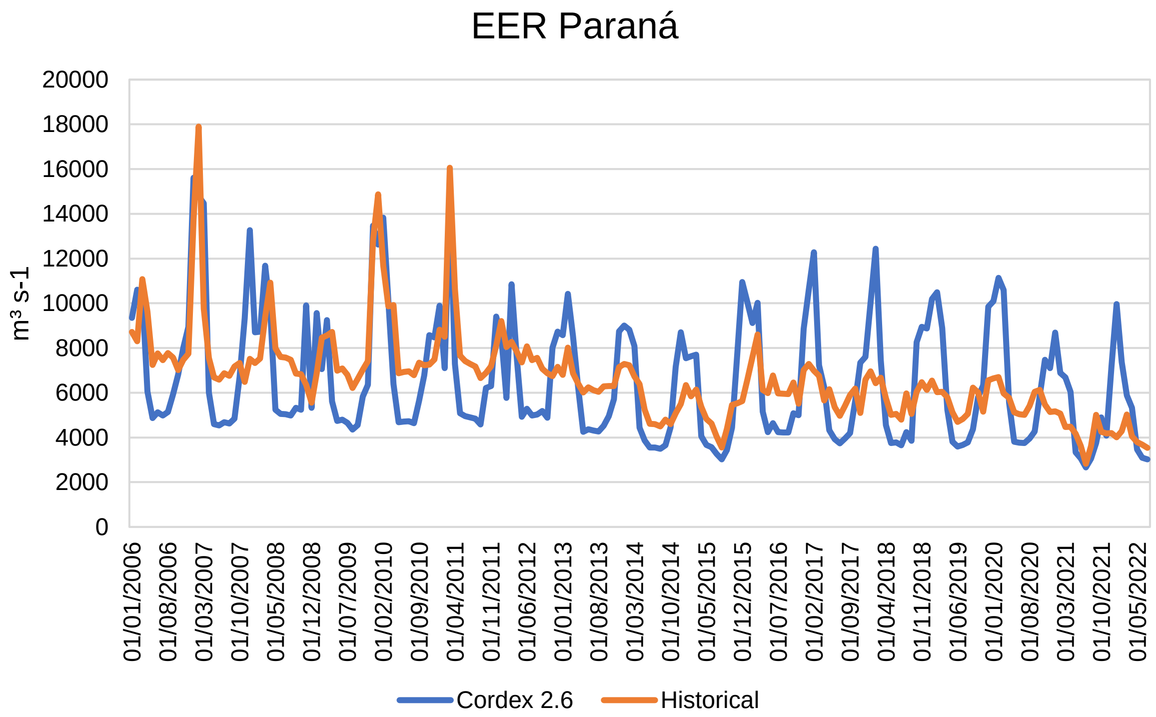


Figure C-9 - Comparison between historical inflow of last rivers in the EER Paraná and Cordex 2.6 inflow data.

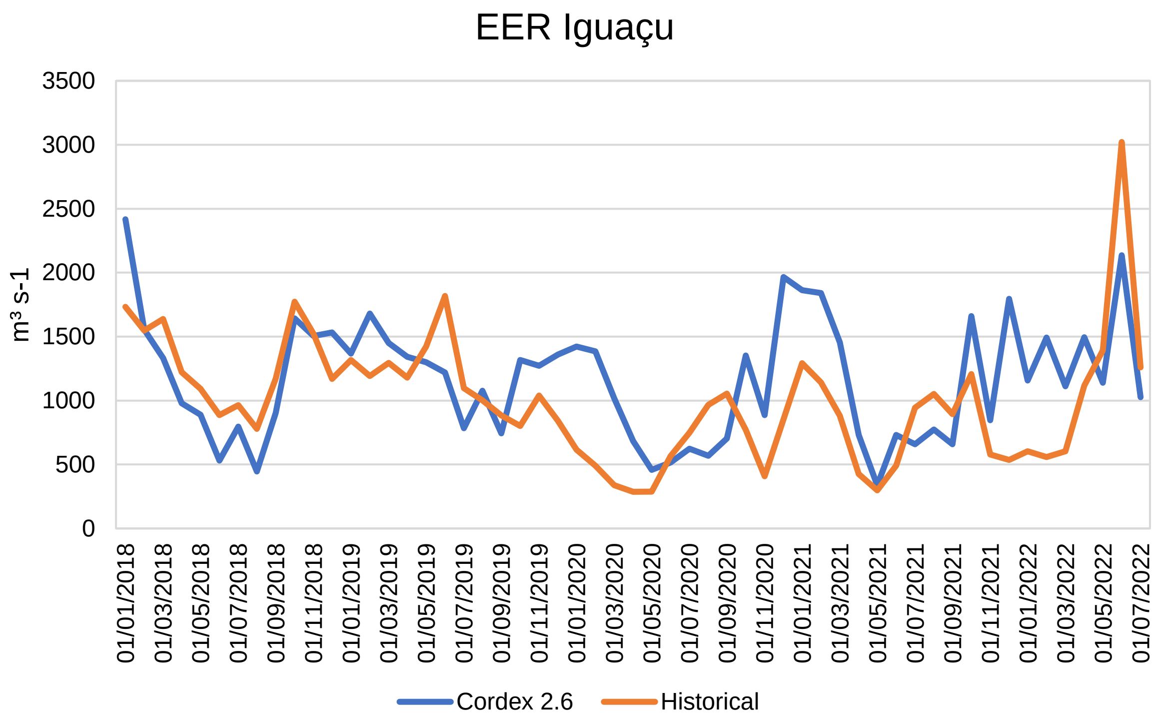


Figure C-10 - Comparison between historical inflow of last rivers in the EER Iguaçu and Cordex 2.6 inflow data.

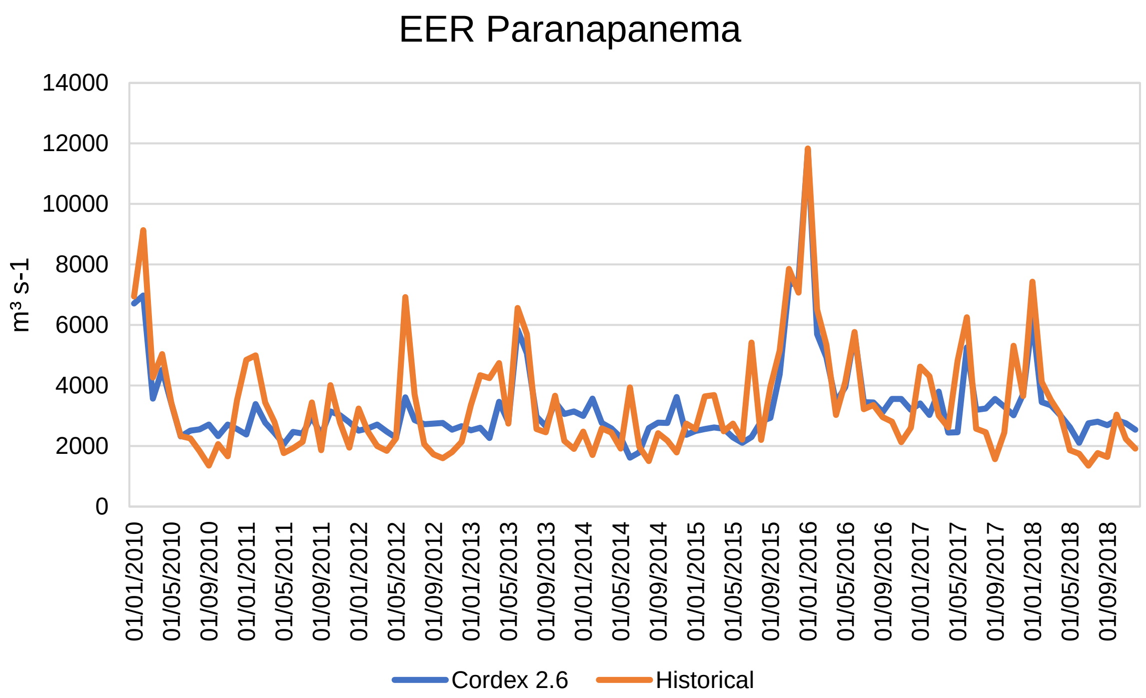


Figure C-11 - Comparison between historical inflow of last rivers in the EER Paranapanema and Cordex 2.6 inflow data.

APPENDIX D - BESMM updated inputs for each RCP scenario

RCP 2.6

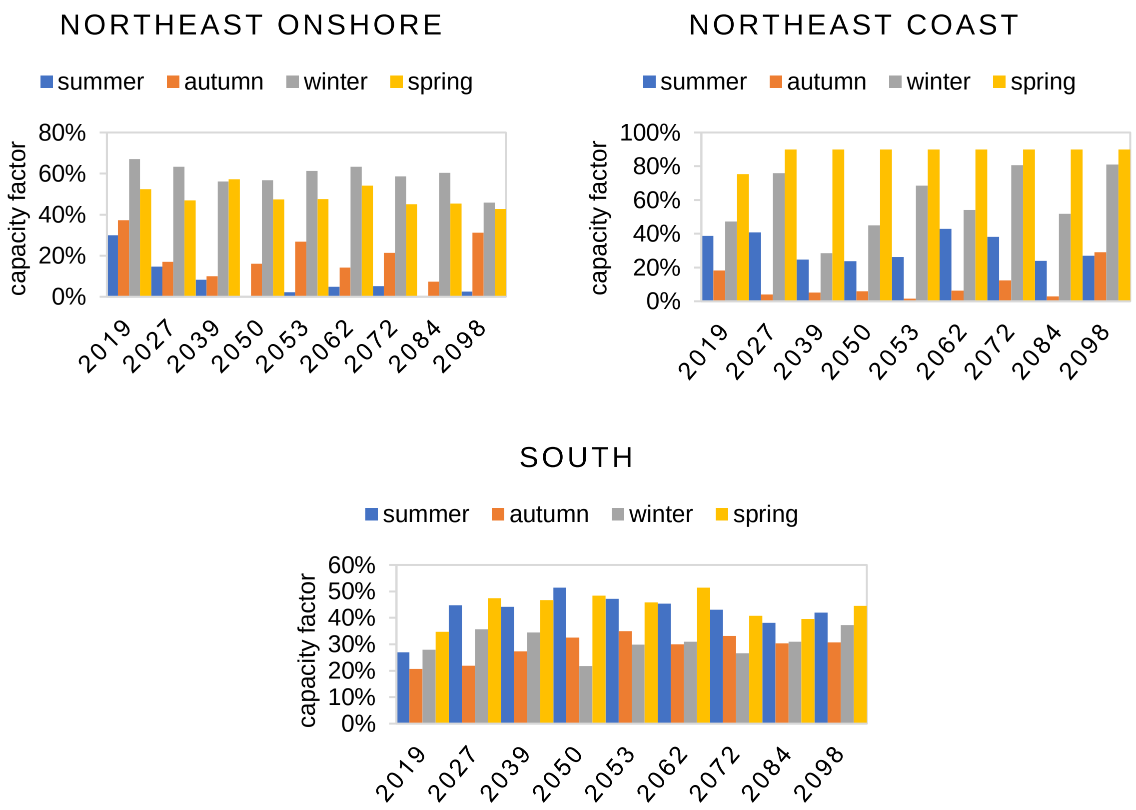
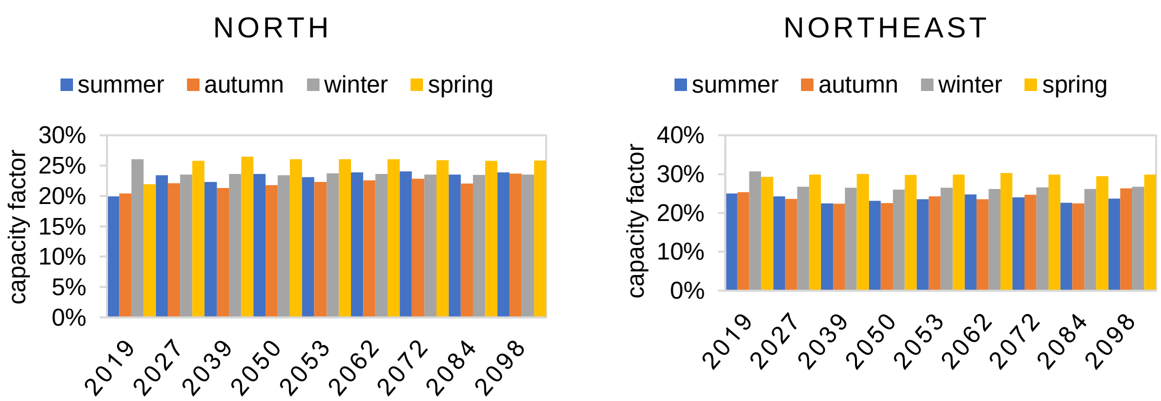
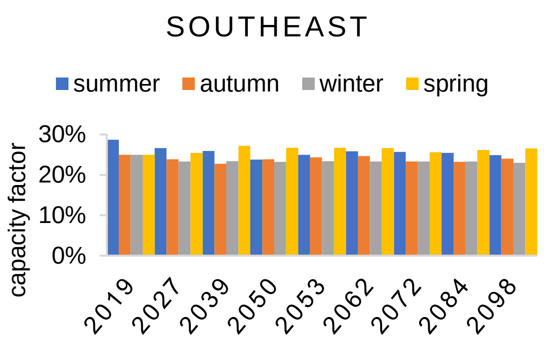


Figure D-1 – Wind power historical capacity factor (2019) and new capacity factors of solar power for selected locations and for selected years for scenario RCP 2.6.





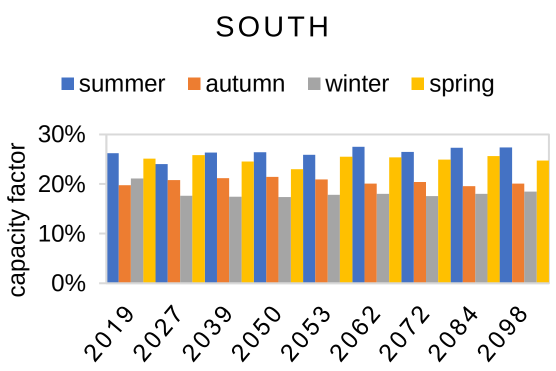


Figure D-2 – Solar power historical capacity factor (2019) and new capacity factors for selected locations and for selected years for scenario RCP 2.6.

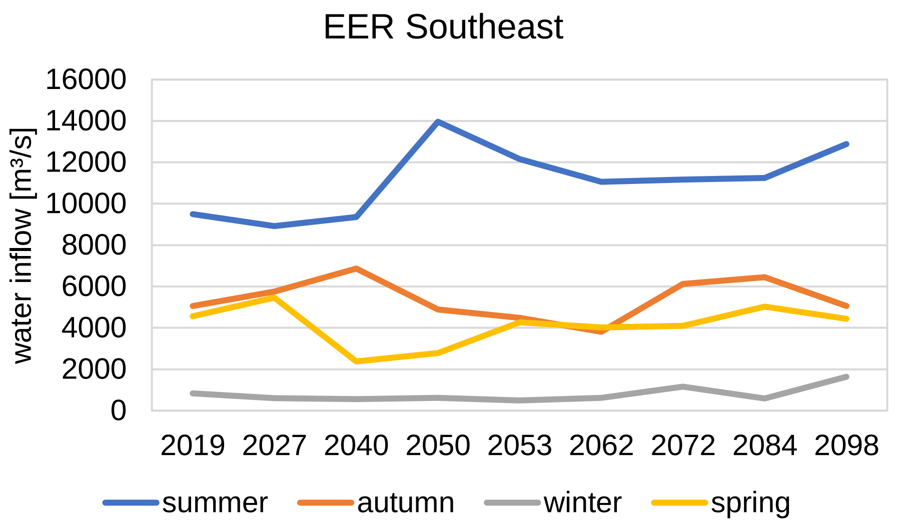


Figure D-3 – EER Southeast historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

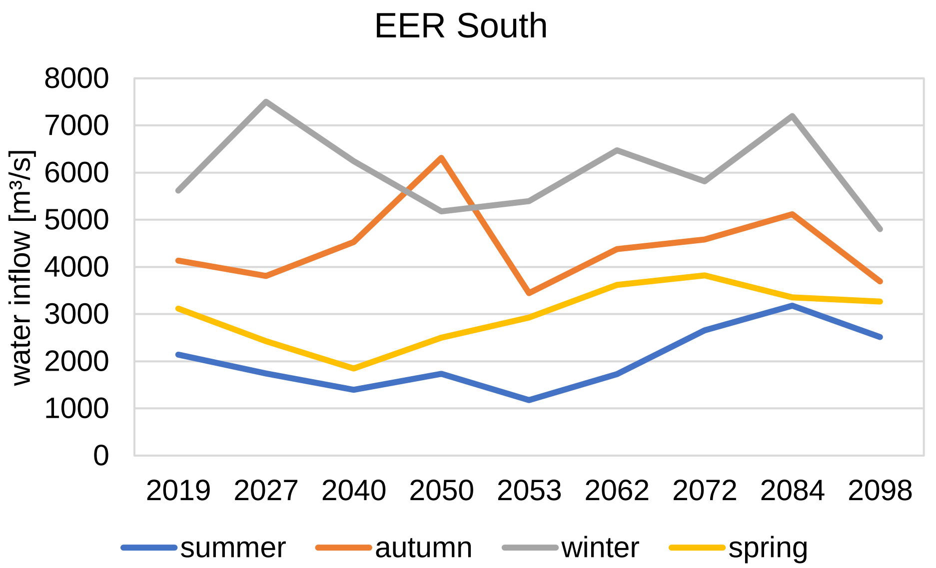


Figure D-4 - EER South historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

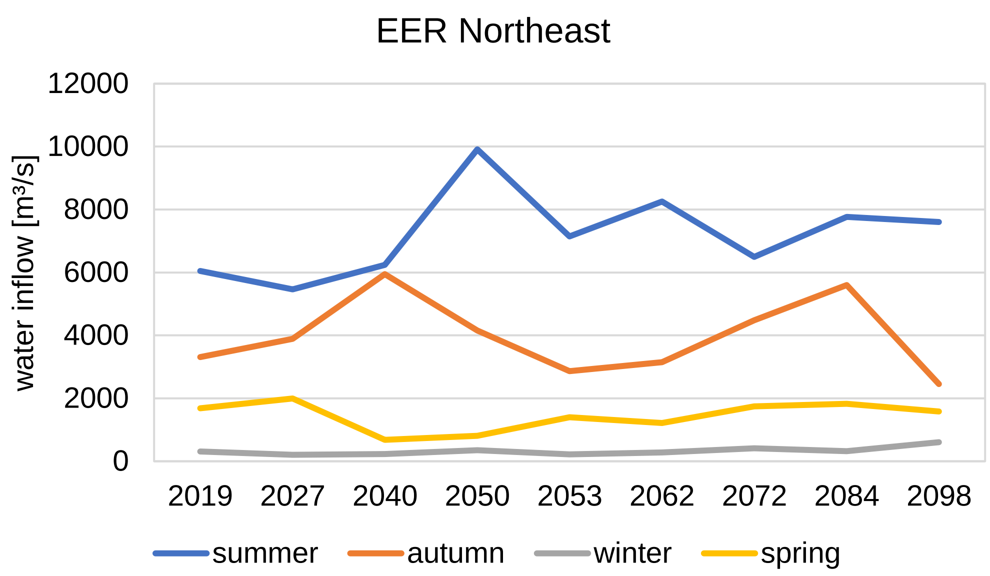


Figure *D*-5 - EER Northeast historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

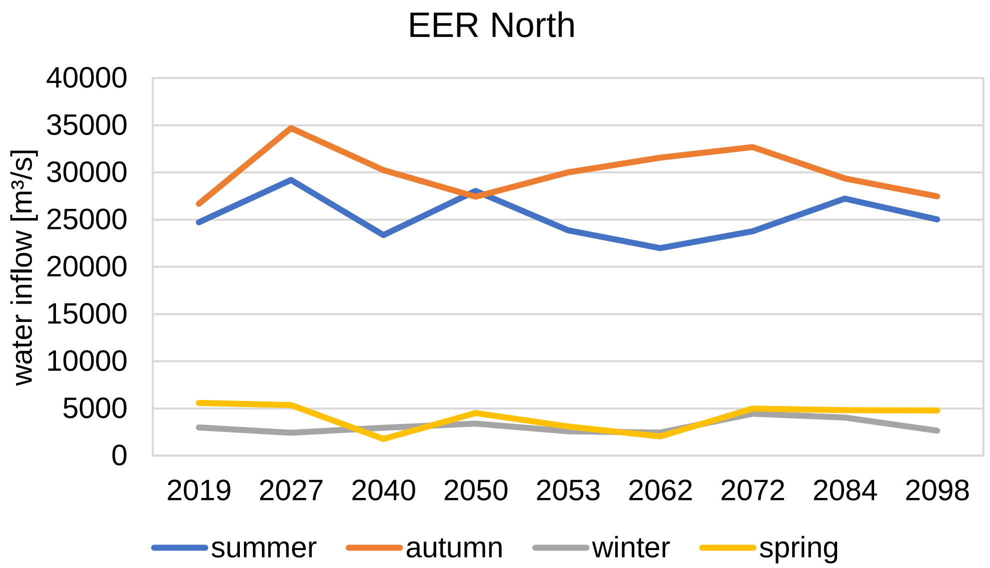


Figure D-6 - EER North historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

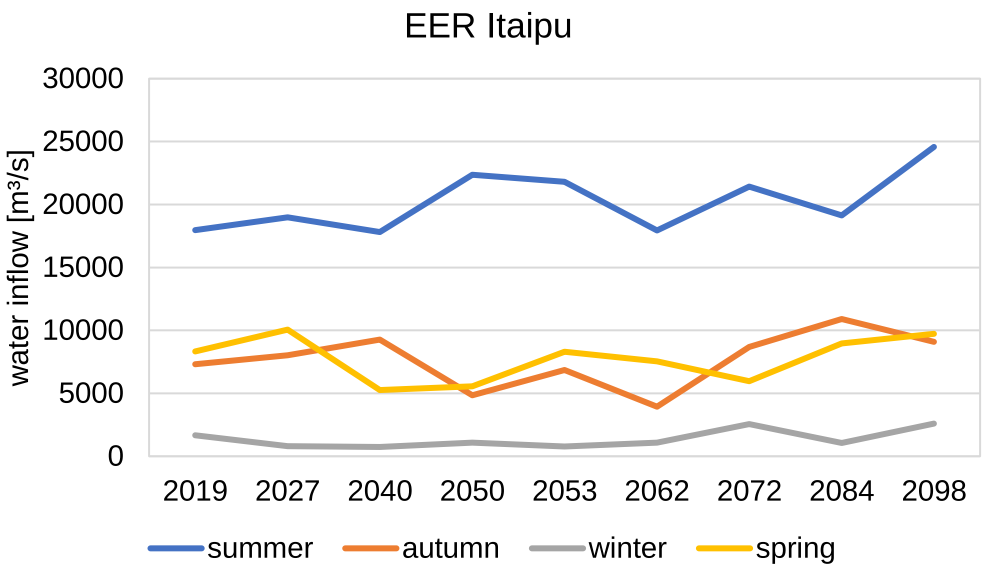


Figure *D*-7 - EER Itaipu historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

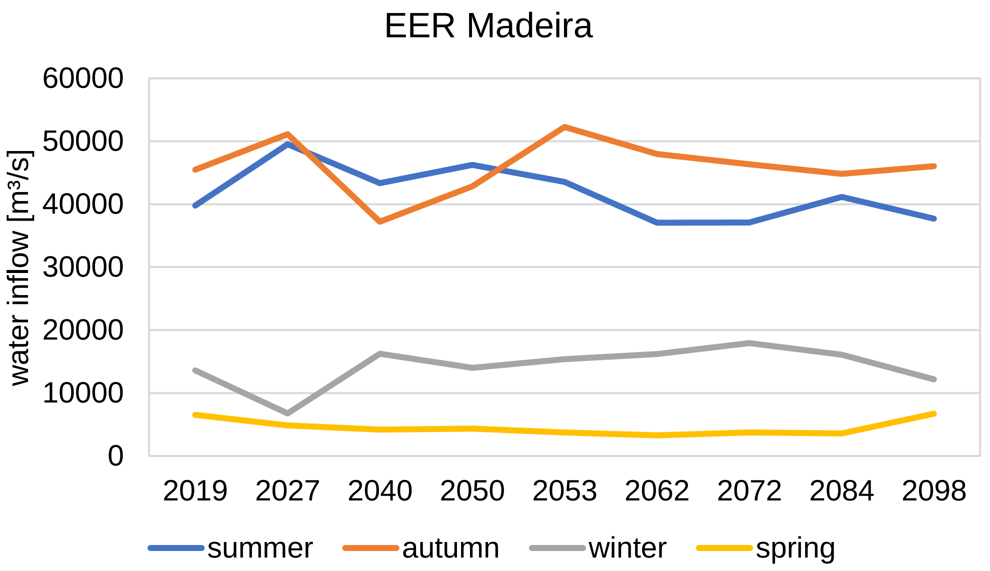


Figure D-8 - EER Madeira historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

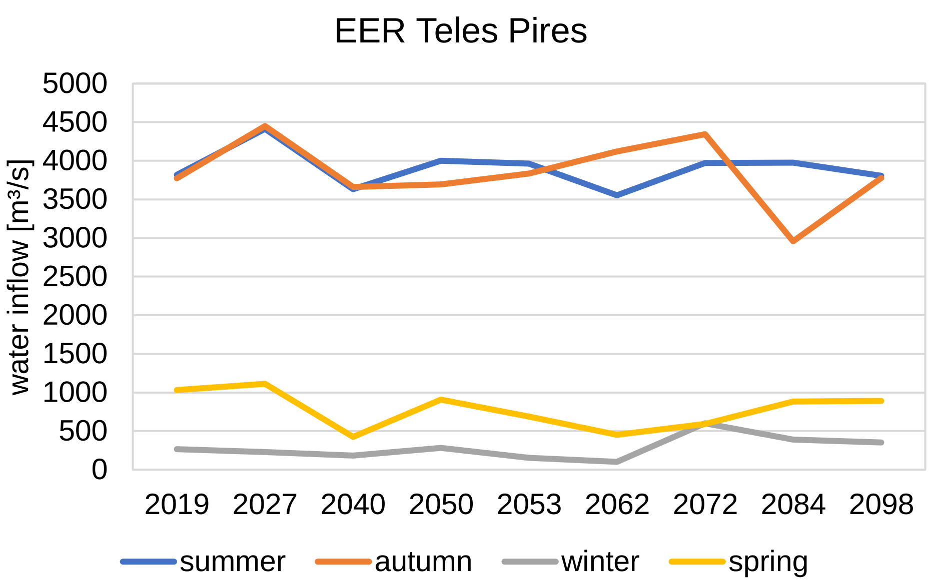


Figure D-9 - EER Teles Pires historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

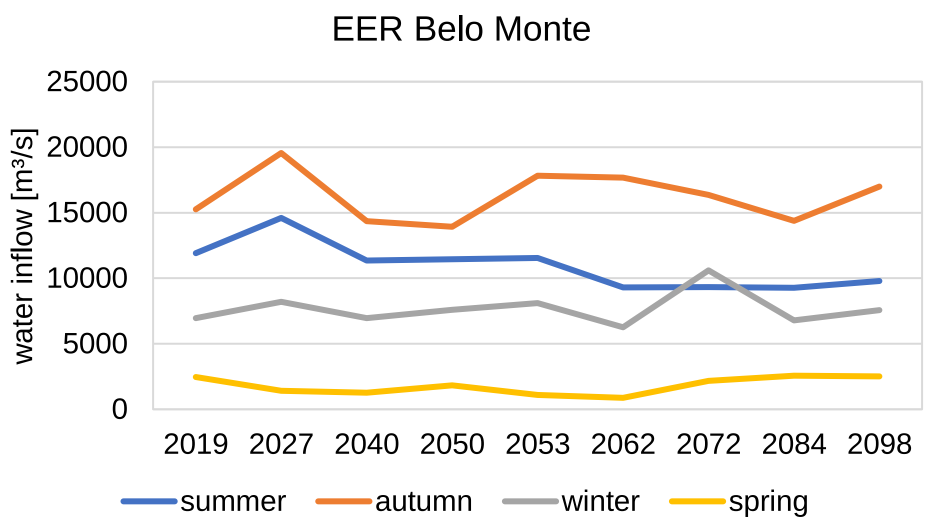


Figure D-10 - EER Belo Monte historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

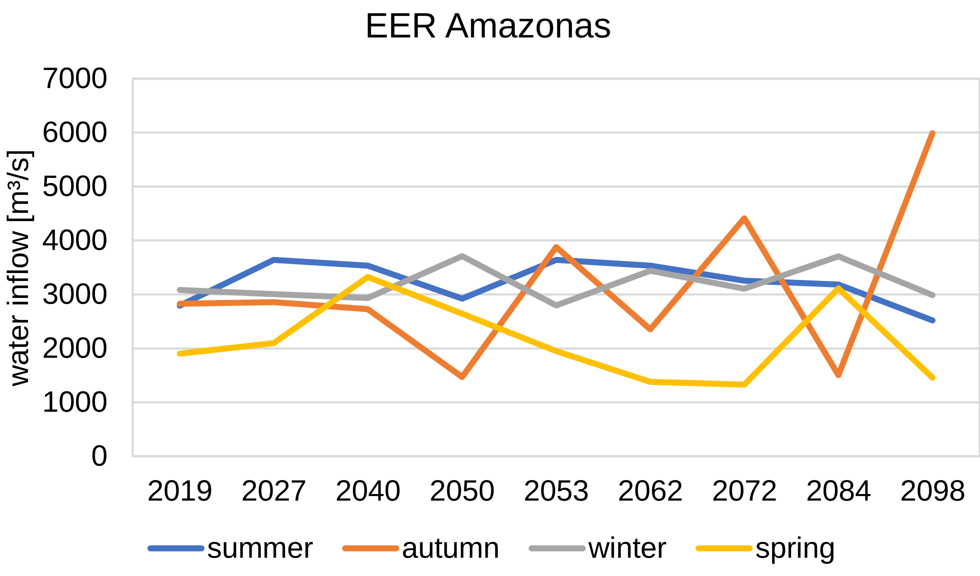


Figure D-11 - EER Amazonas historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

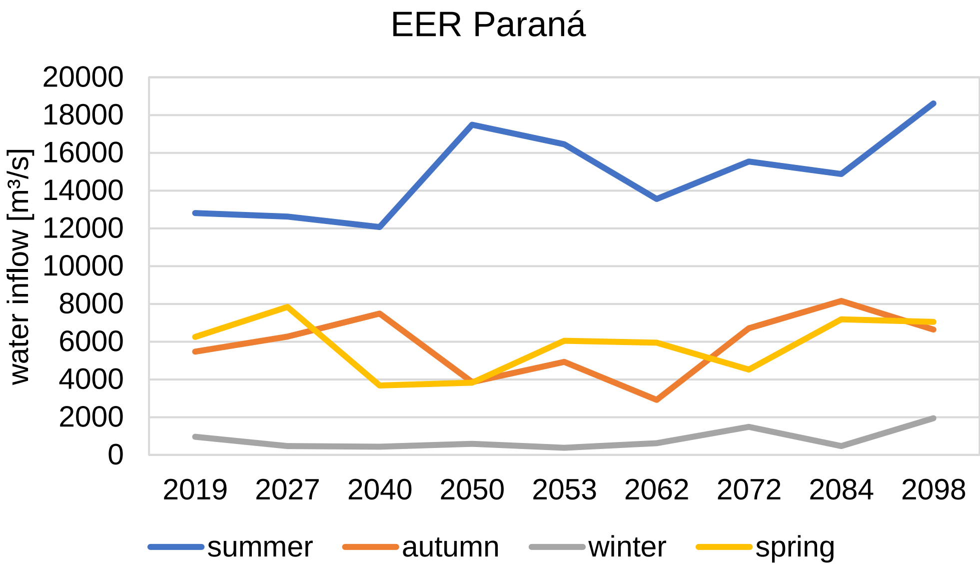


Figure D-12 - EER Paraná historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

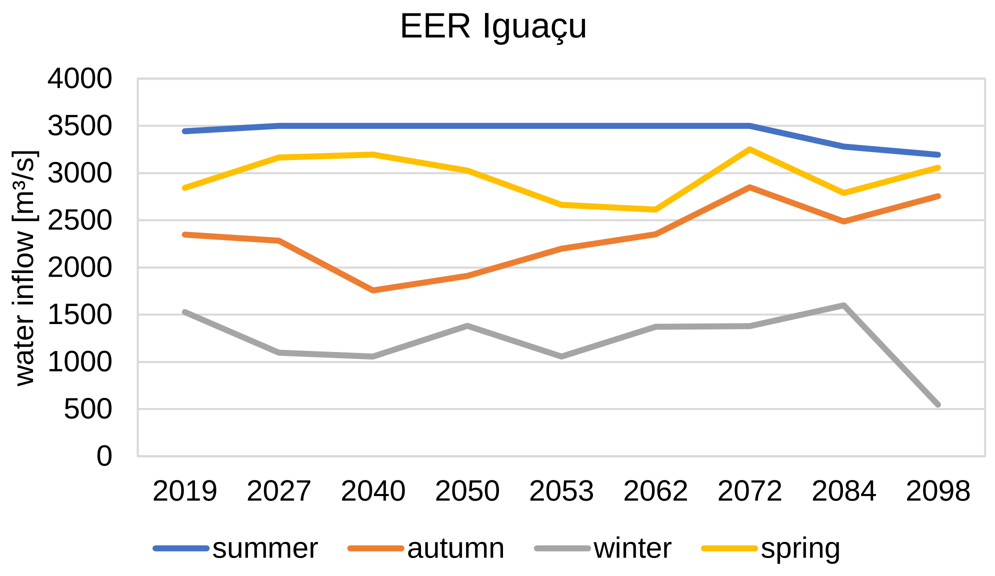


Figure D-13 - EER Iguaçu historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

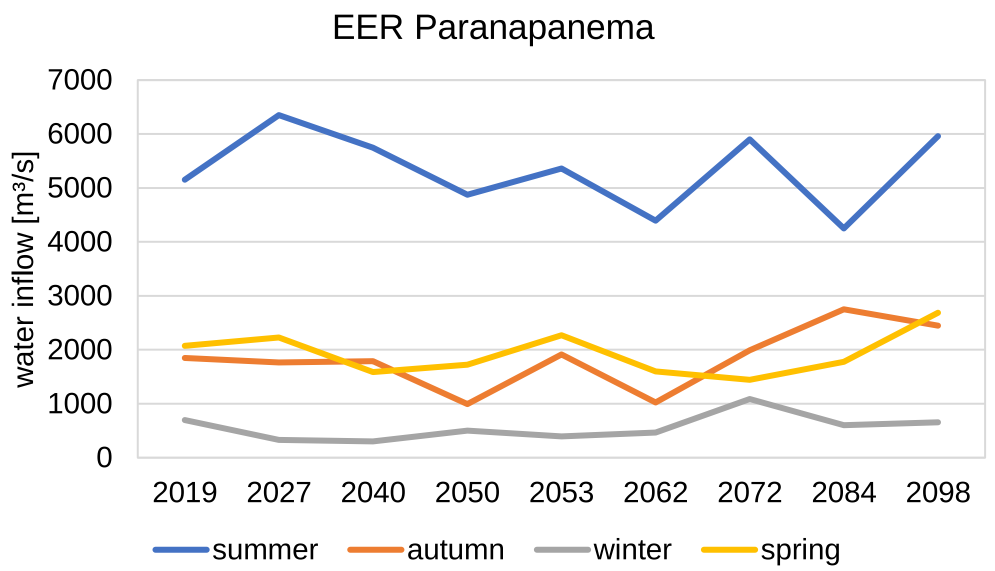
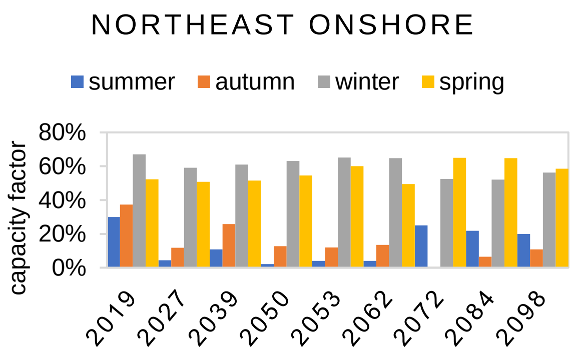
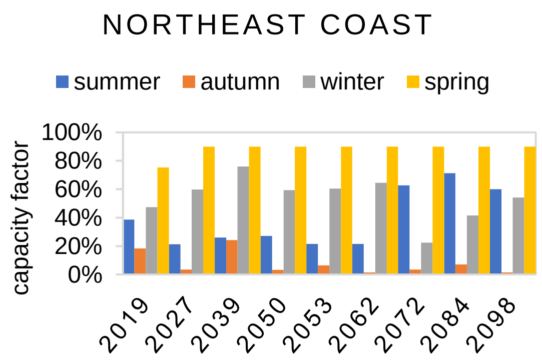


Figure D-14 - EER Paranapanema historical water inflow (2019) and updated water inflow for selected years for scenario RCP 2.6.

RCP 4.5





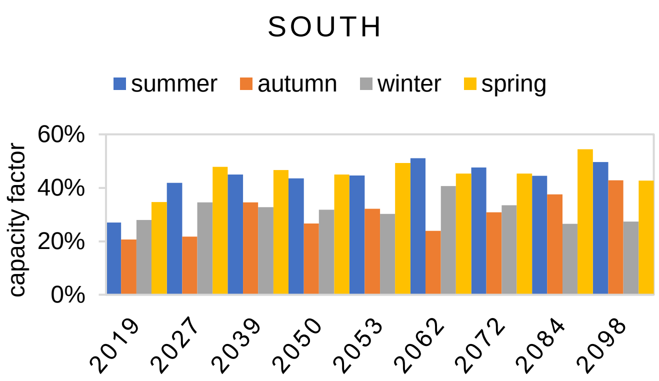
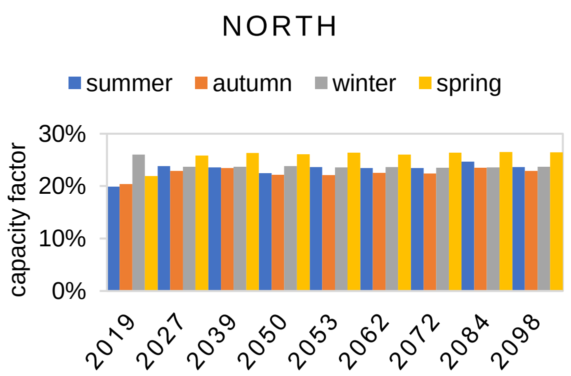
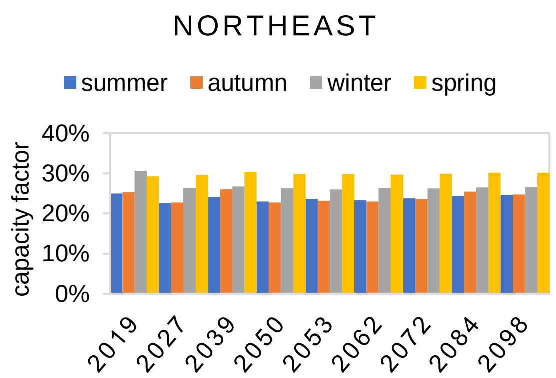
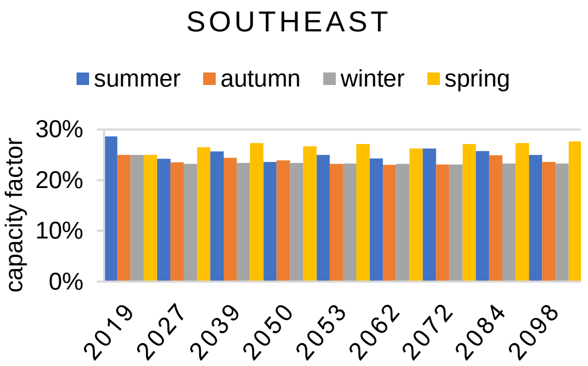


Figure D-15 – Wind power historical capacity factor (2019) and new capacity factors of solar power for selected locations and for selected years for scenario RCP 4.5.







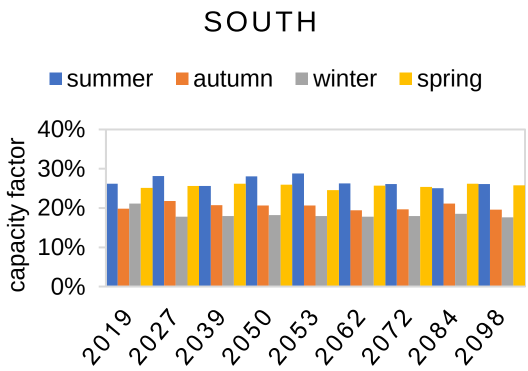


Figure D-16 – Solar power historical capacity factor (2019) and new capacity factors for selected locations and for selected years for scenario RCP 4.5.

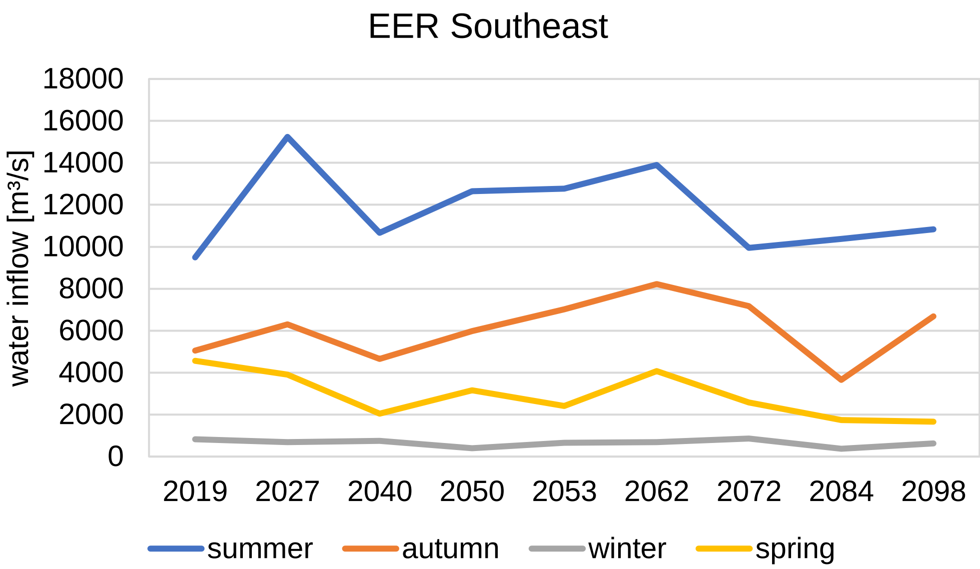


Figure D-17 - EER Southeast historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

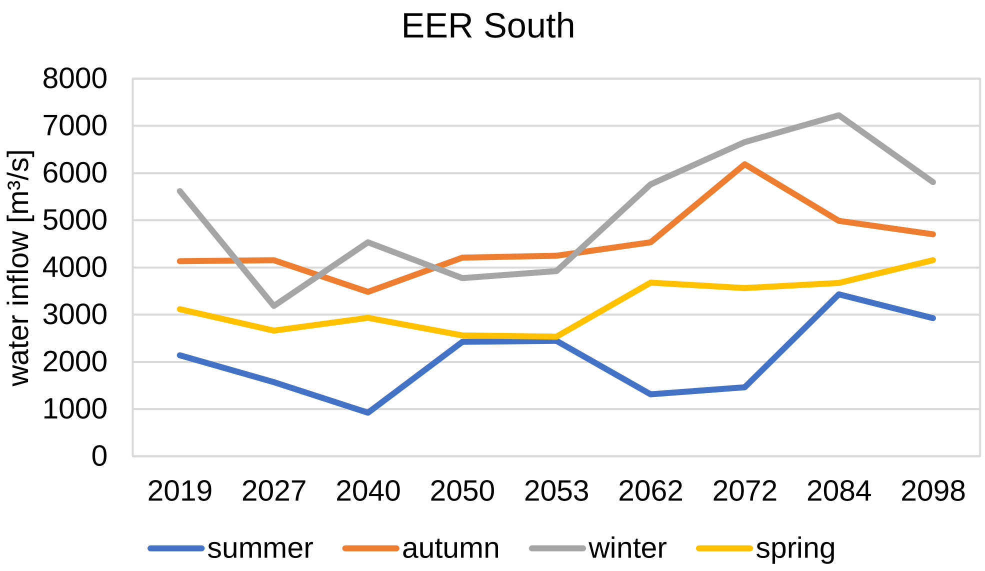


Figure D-18 - EER South historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

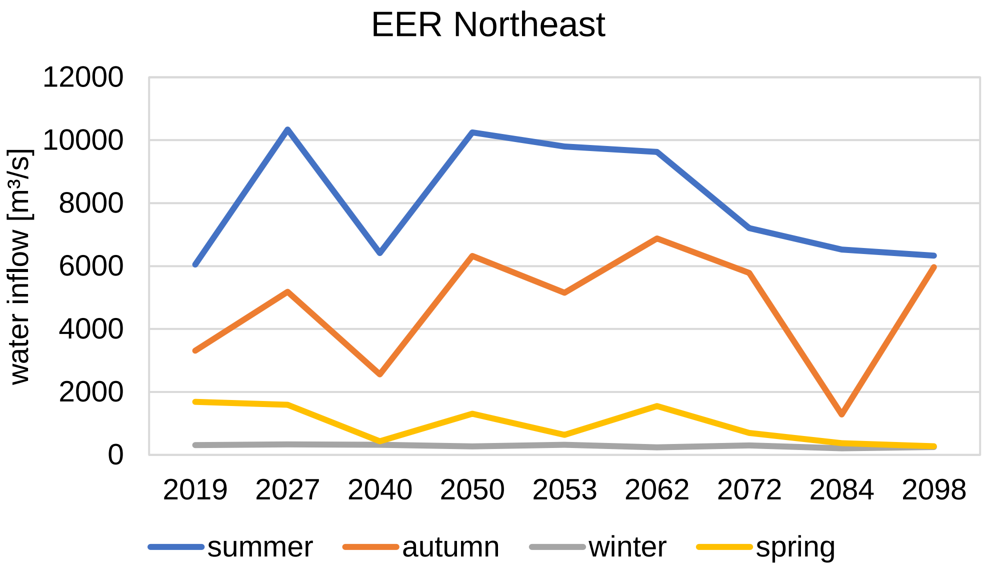


Figure D-19 - EER Northeast historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

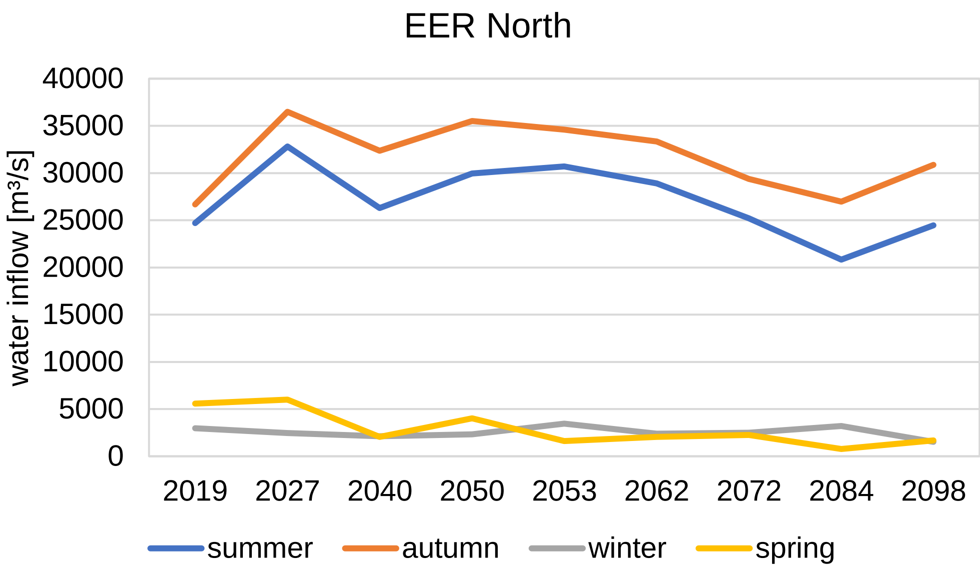


Figure D-20 - EER North historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

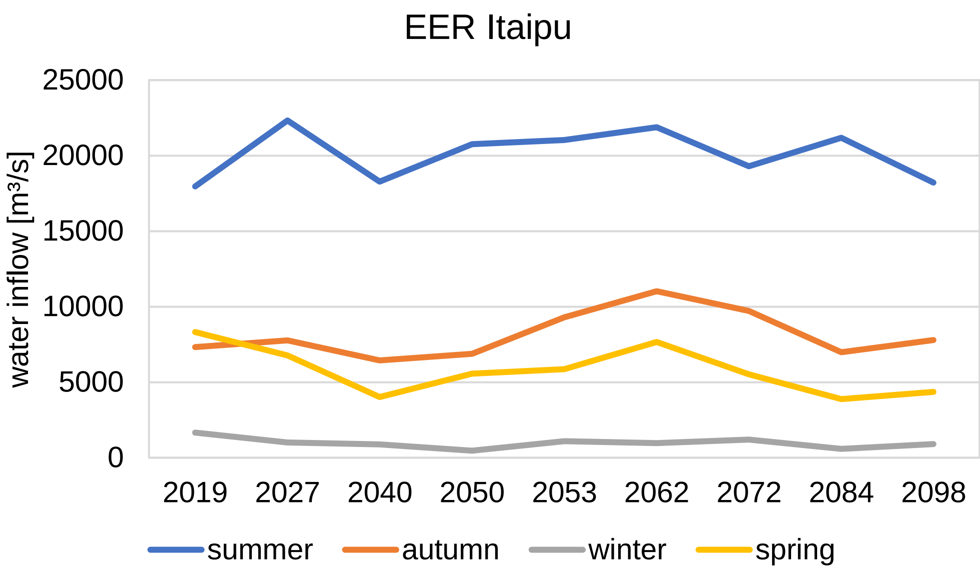


Figure D-21 - EER Itaipu historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

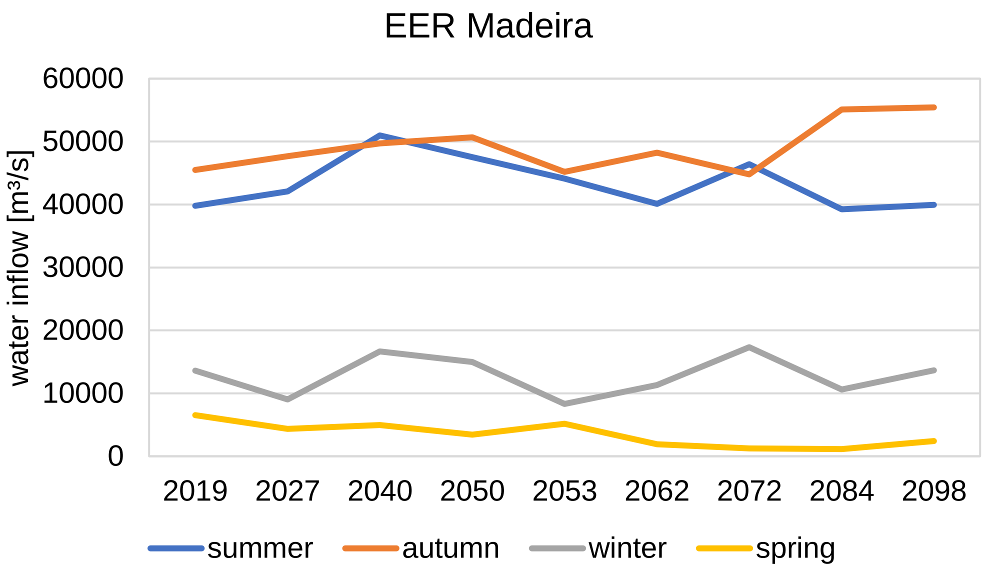


Figure D-22 - EER Madeira historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

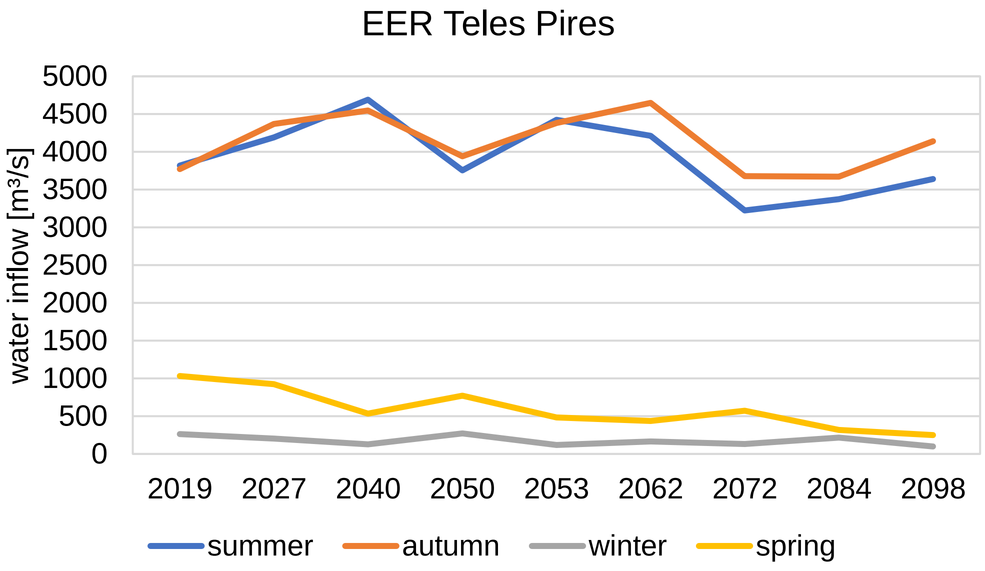


Figure D-23 - EER Teles Pires historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

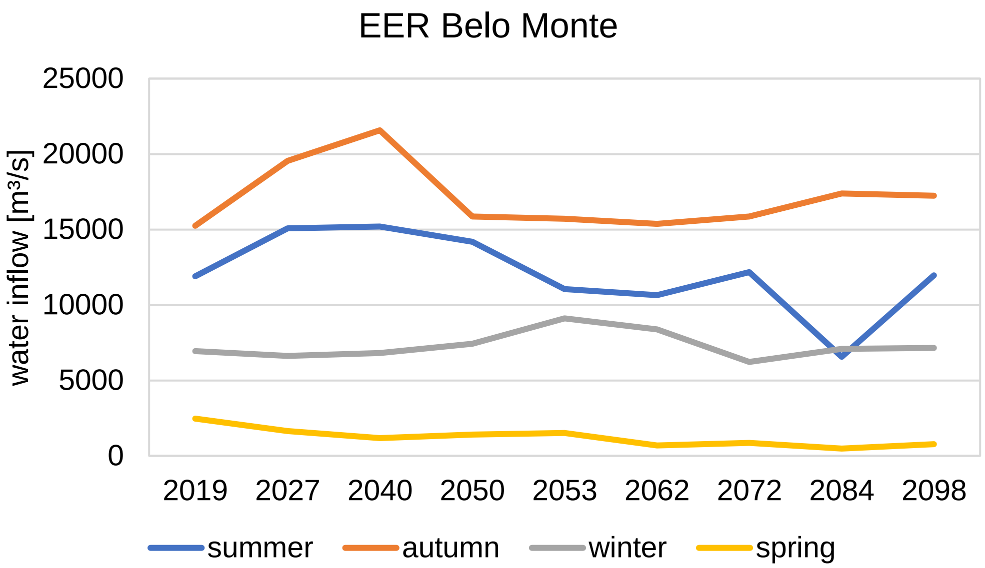


Figure D-24 - EER Belo Monte historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

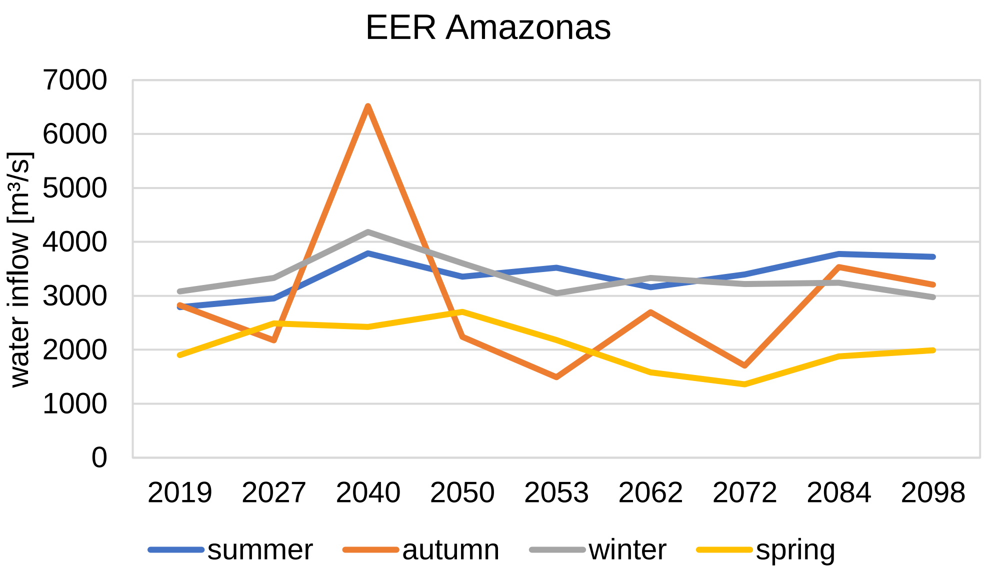


Figure D-25 - EER Amazonas historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

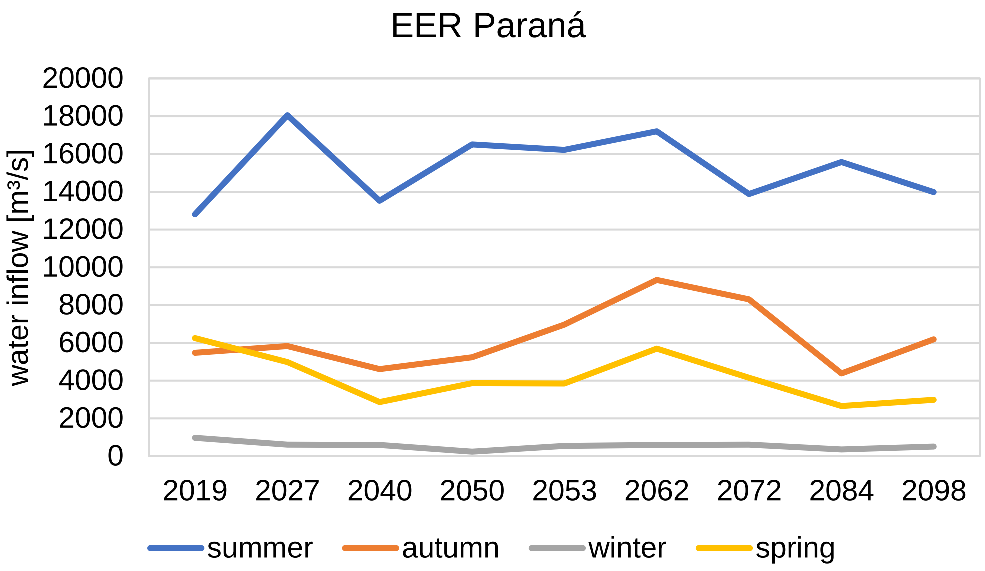


Figure D-26 - EER Paraná historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

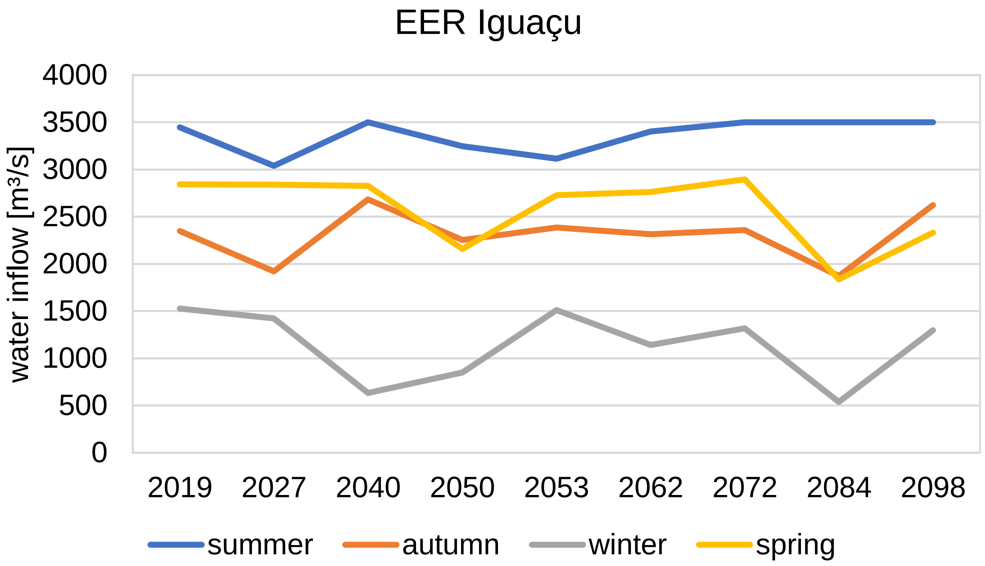


Figure D-27 - EER Iguaçu historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

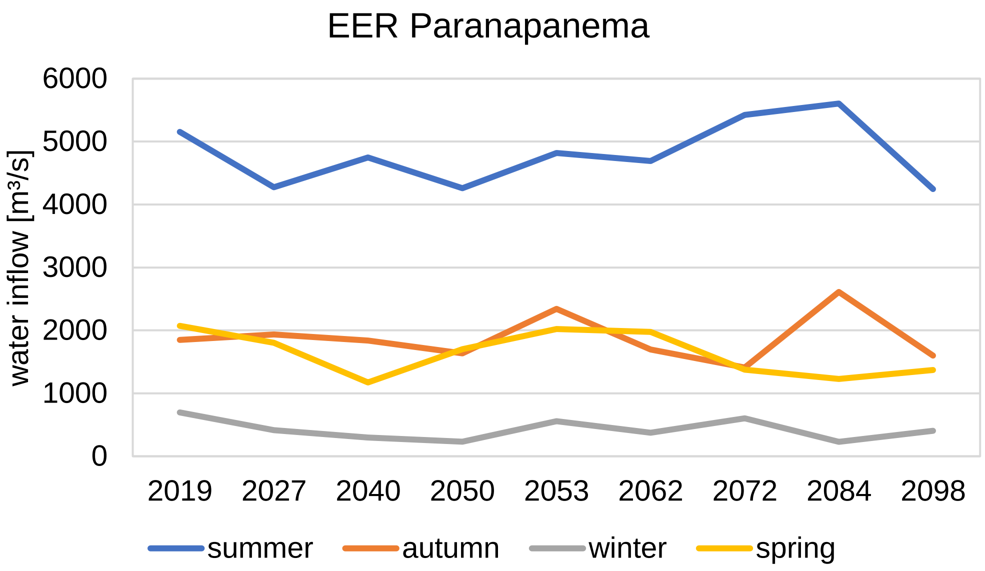


Figure D-28 - EER Paranapanema historical water inflow (2019) and updated water inflow for selected years for scenario RCP 4.5.

RCP 8.5

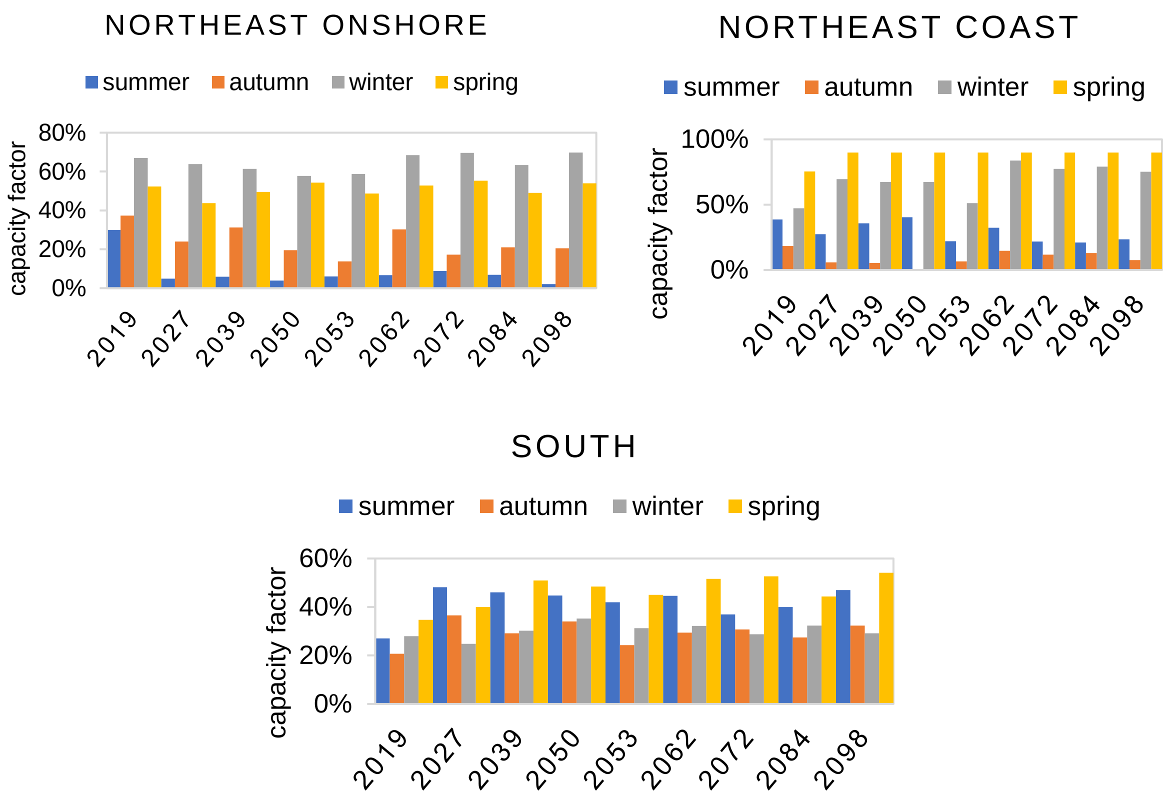


Figure D-29 – Wind power historical capacity factor (2019) and new capacity factors of solar power for selected locations and for selected years for scenario RCP 8.5.

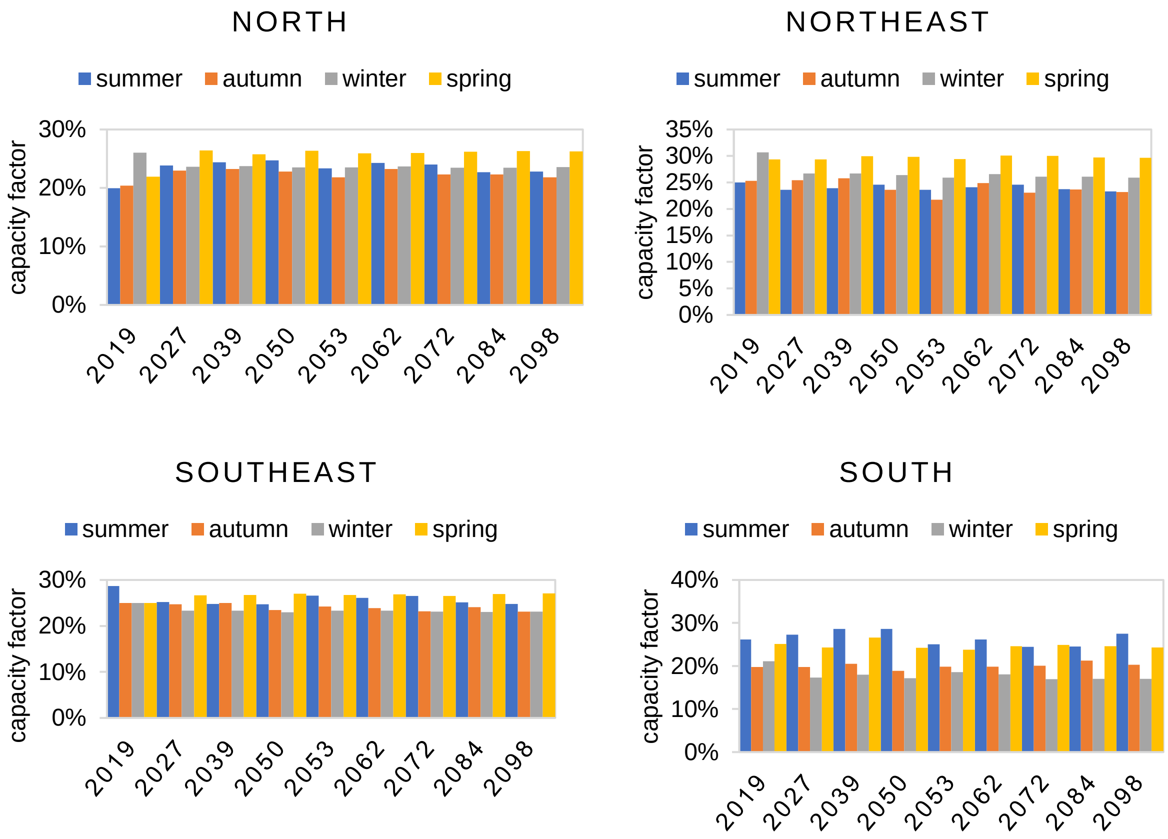


Figure D-30 - Solar power historical capacity factor (2019) and new capacity factors for selected locations and for selected years for scenario RCP 8.5.

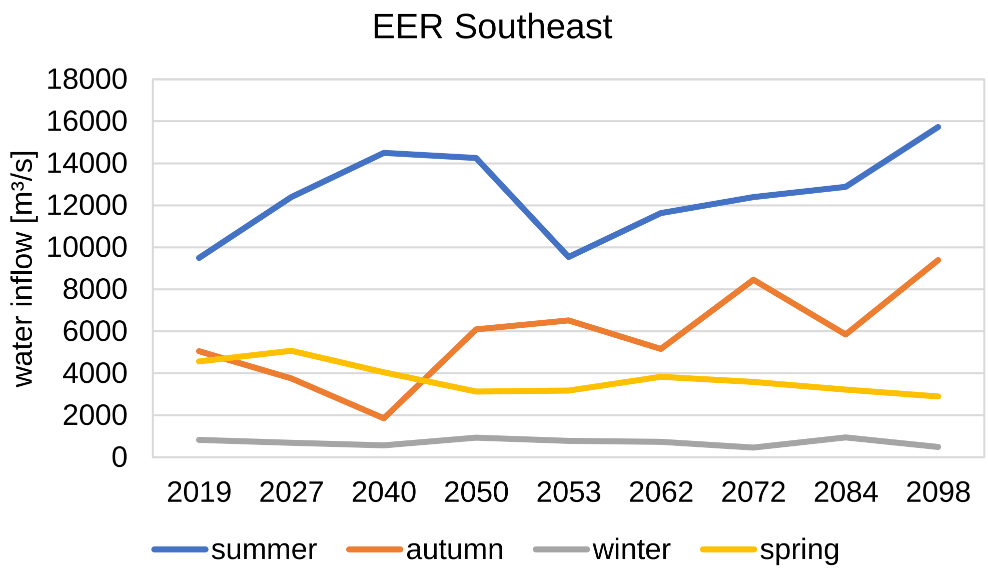


Figure D-31 - EER Southeast historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

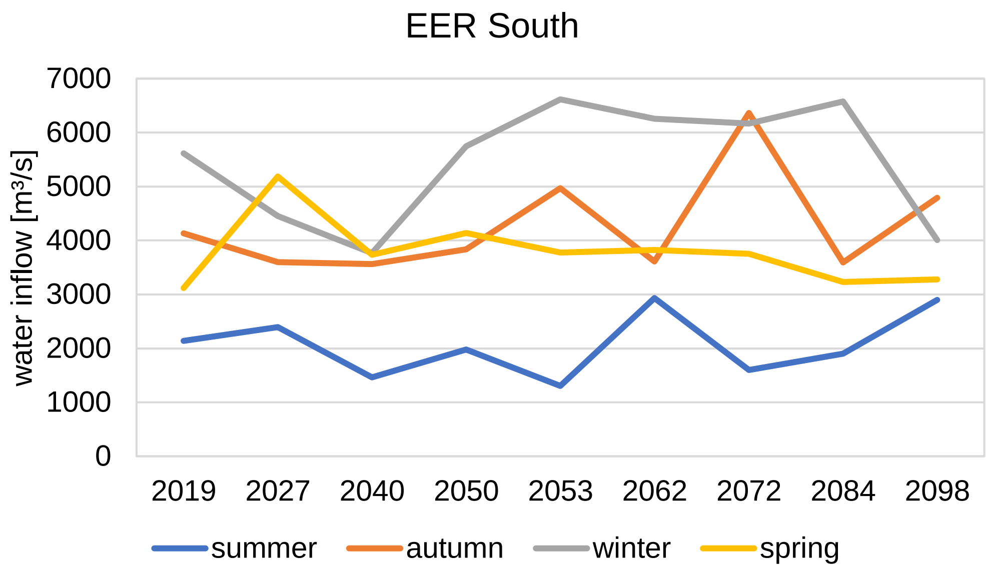


Figure D-32 - EER South historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

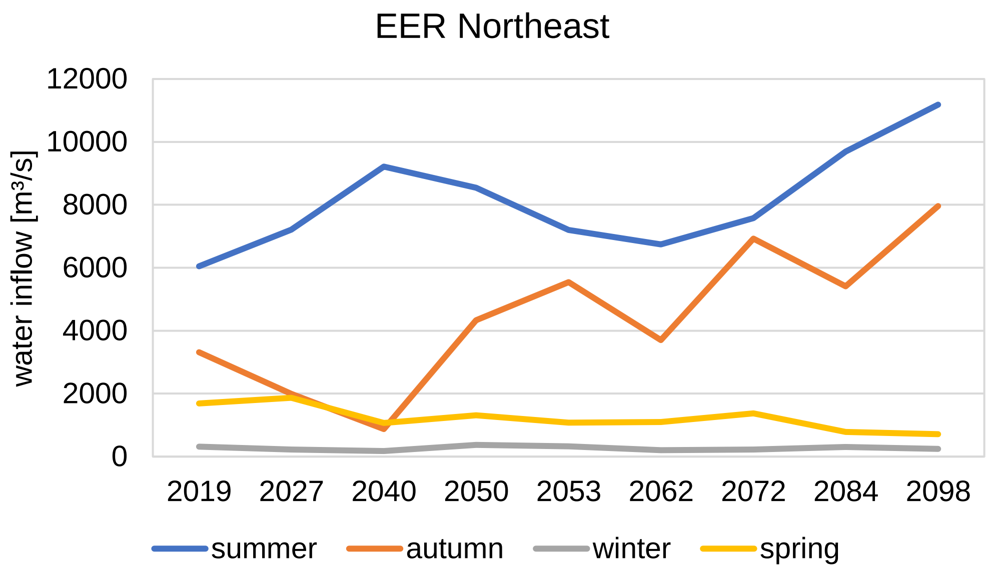


Figure D-33 - EER Northeast historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

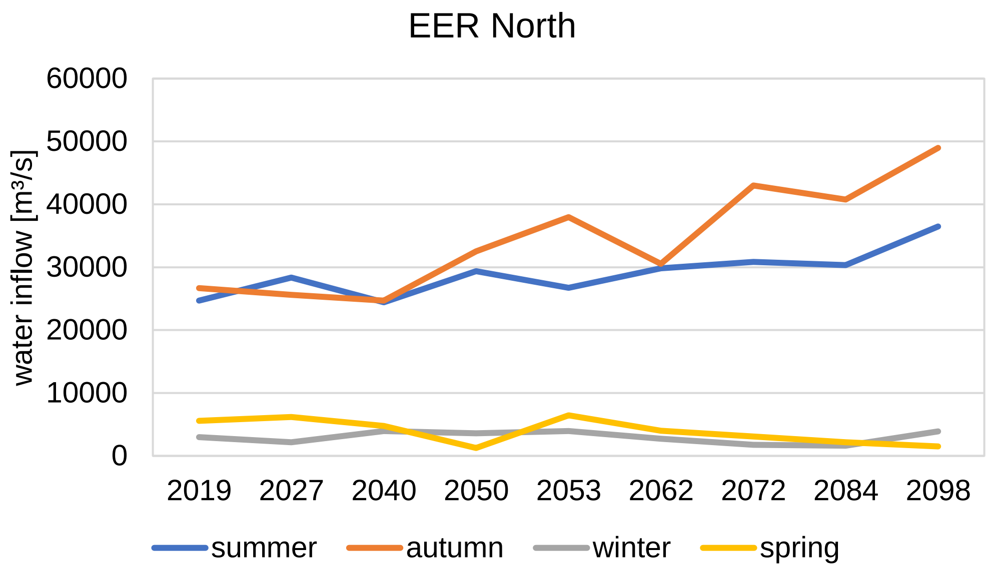


Figure D-34 - EER North historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

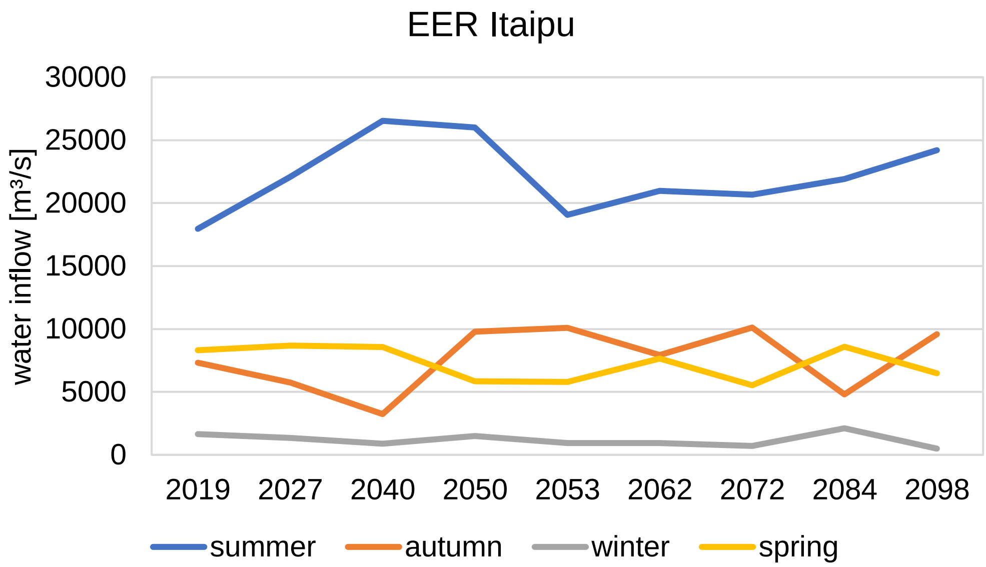


Figure D-35 - EER Itaipu historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

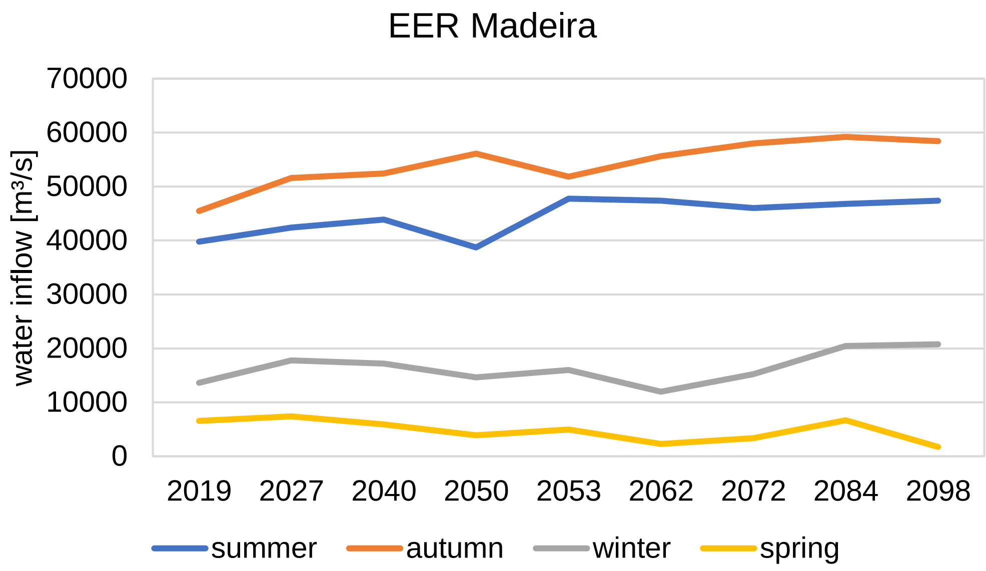


Figure D-36 - EER Madeira historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

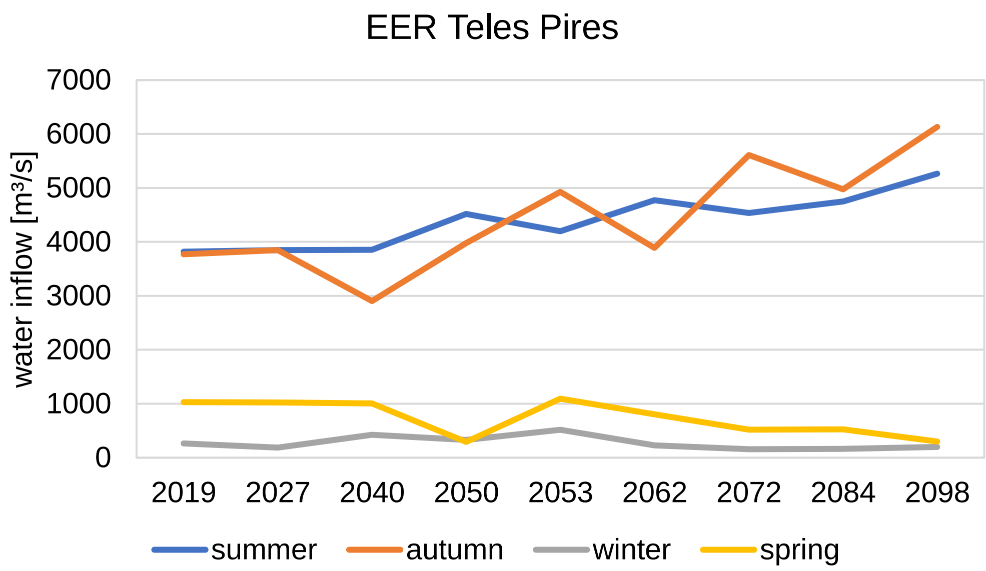


Figure D-37 - EER Teles Pires historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

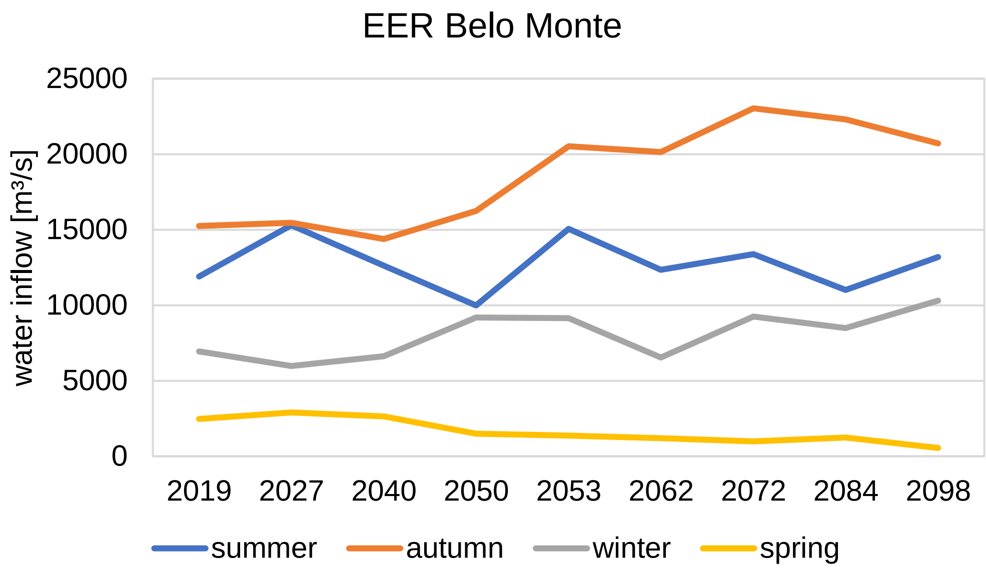


Figure D-38 - EER Belo Monte historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

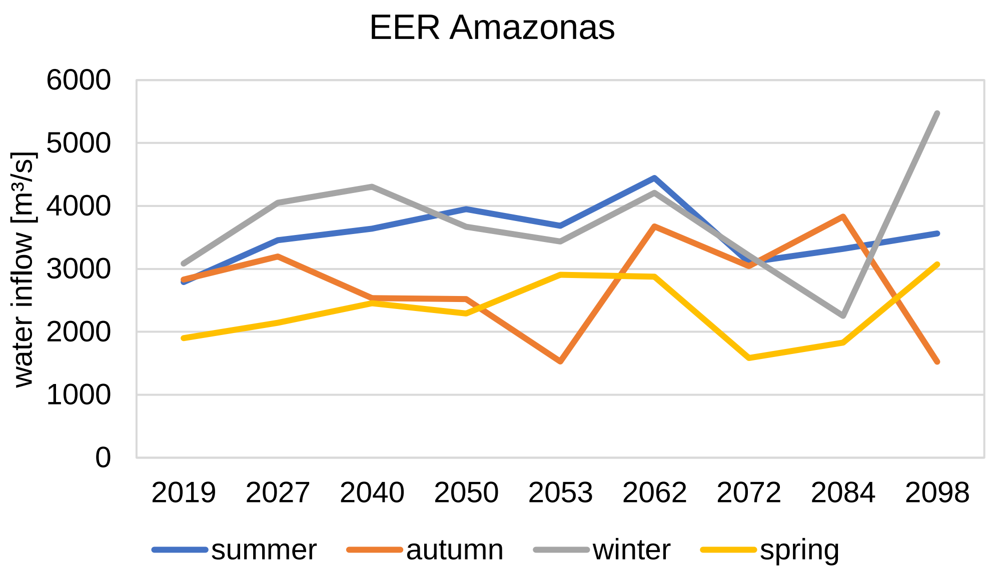


Figure D-39 - EER Amazonas historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

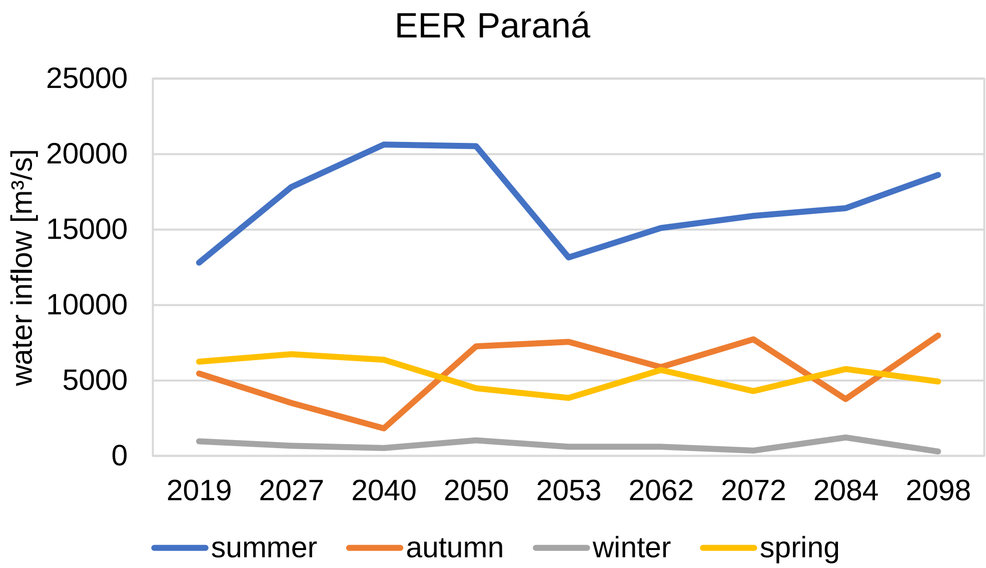


Figure D-40 - EER Paraná historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

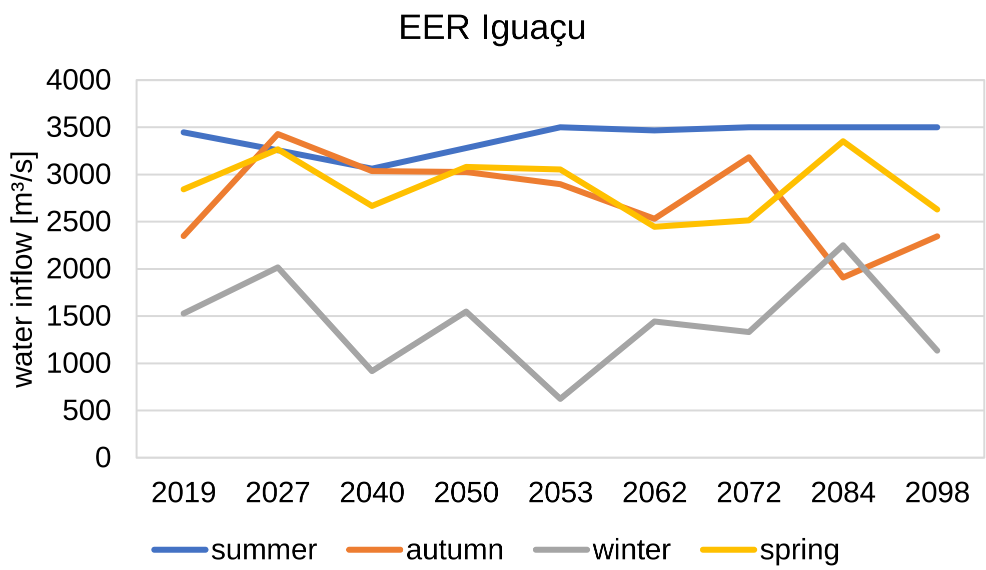


Figure D-41 - EER Iguaçu historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

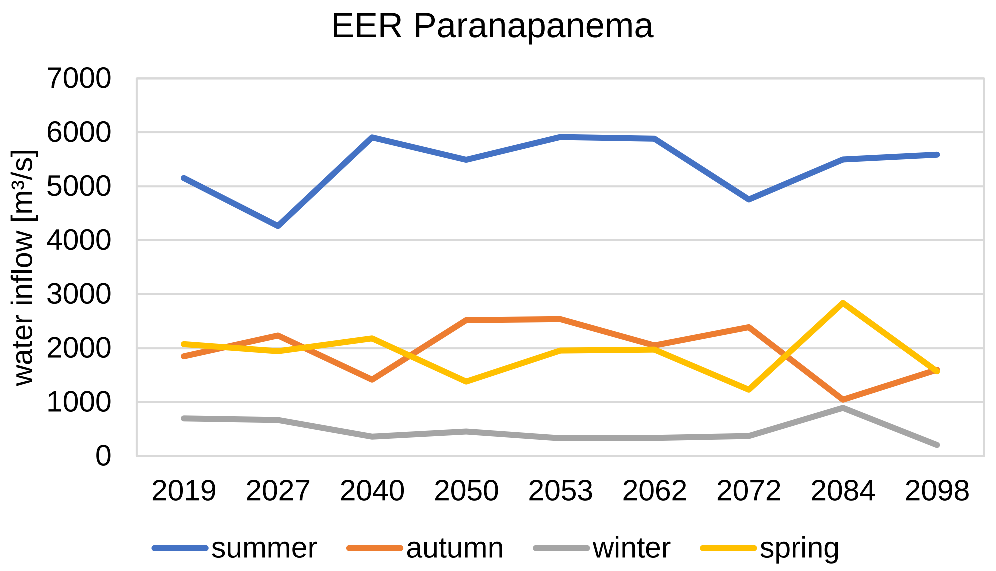


Figure D-42 - EER Paranapanema historical water inflow (2019) and updated water inflow for selected years for scenario RCP 8.5.

APPENIDX E - Results by RCP scenario

RCP 2.6

Figure E-43 shows the projections for the optimized least-cost electricity production matrix for the BESMM from 2020 up to 2100[1] for the RCP 2.6 scenario.

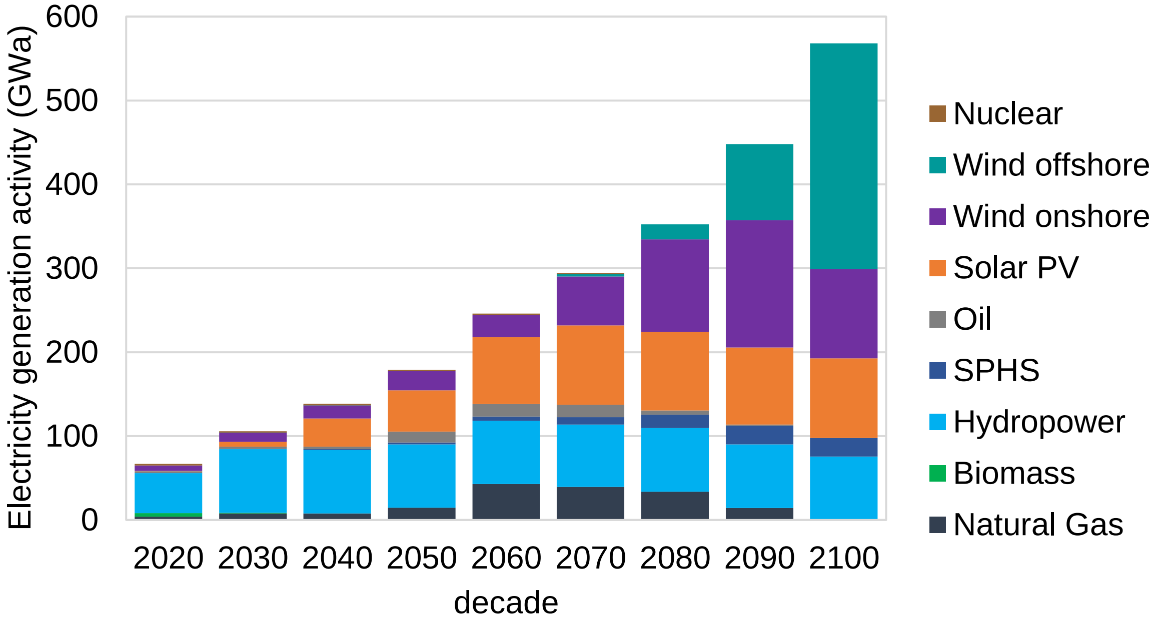


Figure *E*-43 – BESMM electricity generation activity up to 2100 for RCP 2.6 scenario simulated with the Brazilian Electricity System MESSAGEix Model.

By the end of the century, the electricity production in Brazil is foreseen to be 100% renewable, 47.3% provided by wind power offshore, 18.7% wind power onshore, 17.2% by hydropower (13.3% hydropower and 3.9% SPHS), and 16.7 % solar power. The last three decades presented the highest SPHS activity, especially in the last year, 22.1 GWa in total, which has the highest IAV (as shown in **Error! Reference source not found.**). Moreover, wind power offshore has experienced a high growth rate in the last three decades, becoming the main renewable energy technology by 2100. As the wind offshore increases, the wind power onshore decreases by the end of the century. The total SPHS produced by season in the BESMM RCP 2.6 scenario is shown in Figure E-44.

[1] Each decade represents the results of the selected years. The selected years are the years in each decade with the highest IAV. The results are presented in decades as the BES simulation results are defined by decades.

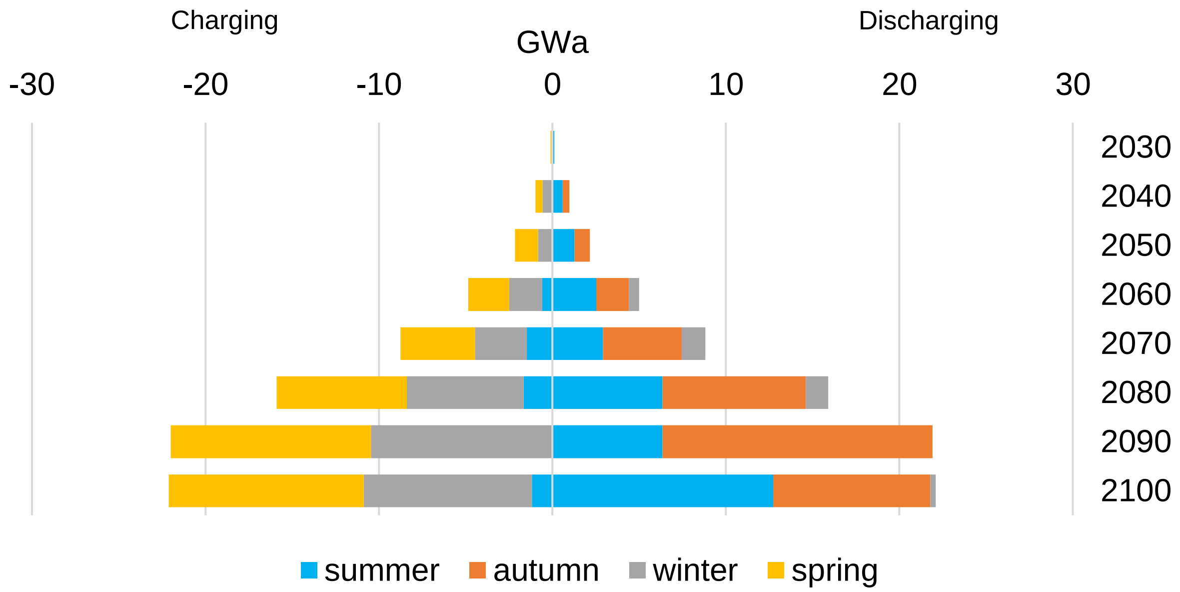


Figure *E*-44 – Total Seasonal pumped hydropower storage, SPHS, produced by season in the BESMM RCP 2.6 scenario.

SPHS produced 40.6% of its electricity during the autumn season, followed by 32.8% during the summer. In contrast, most of the charging activities occurred during spring and in the winter, 50.5% and 43.0% respectively, when the turbine is pumping back the water to the dam. The year with the highest SPHS activity was 2100 and the year with the lowest activity was 2030. 2050 was a year with an increase in the summer water inflow in the most important EERs of the country: EER Paraná, EER Southeast, and EER Northeast (can be seen in **Error! Reference source not found.**). In the year 2100, the EER South presented lower water inflow in all seasons in comparison to previous years, as well as the ERR Northeast in autumn and Iguaçu in winter. At the same time wind power onshore in the Northeast had the lowest wind power resources in all seasons. This combination leads the SPHS to peak its activity. The results of total SPHS production by season and by region, based on the BESMM RCP 2.6 scenario are shown in Figure E-45.

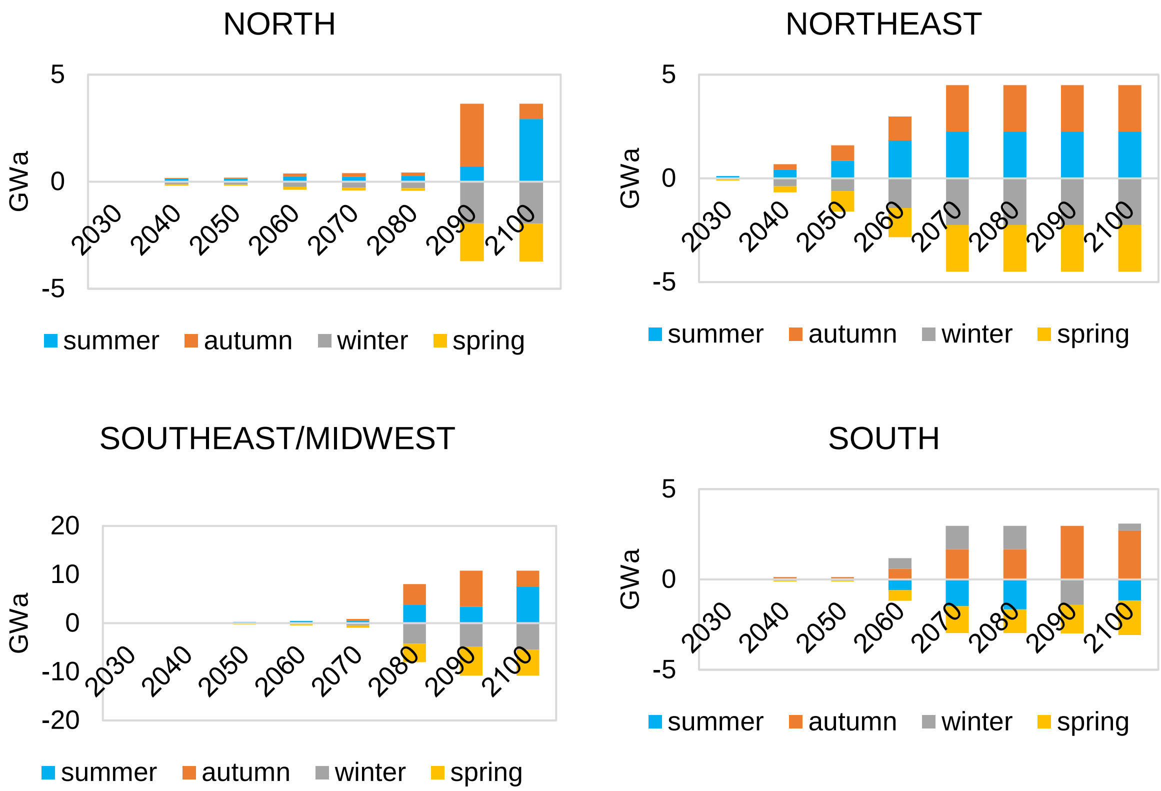


Figure *E*-45 - Total SPHS produced by season and by region in the BESMM scenario RCP 2.6. North (top left), Northeast region (top right), Southeast/Midwest region (bottom left), and South region (bottom right).

The Southeast/Midwest had the highest level of SPHS activity compared to any other region, which was expected as the potential is greater in this region. Although in this region the SPHS activity was higher only during the last three decades. As opposed to the Northeast region in which had a lower activity, although it was almost constant throughout the decades. The SPHS activities of each EER along the RCP 2.6 scenario is detailed in Figure E-46.

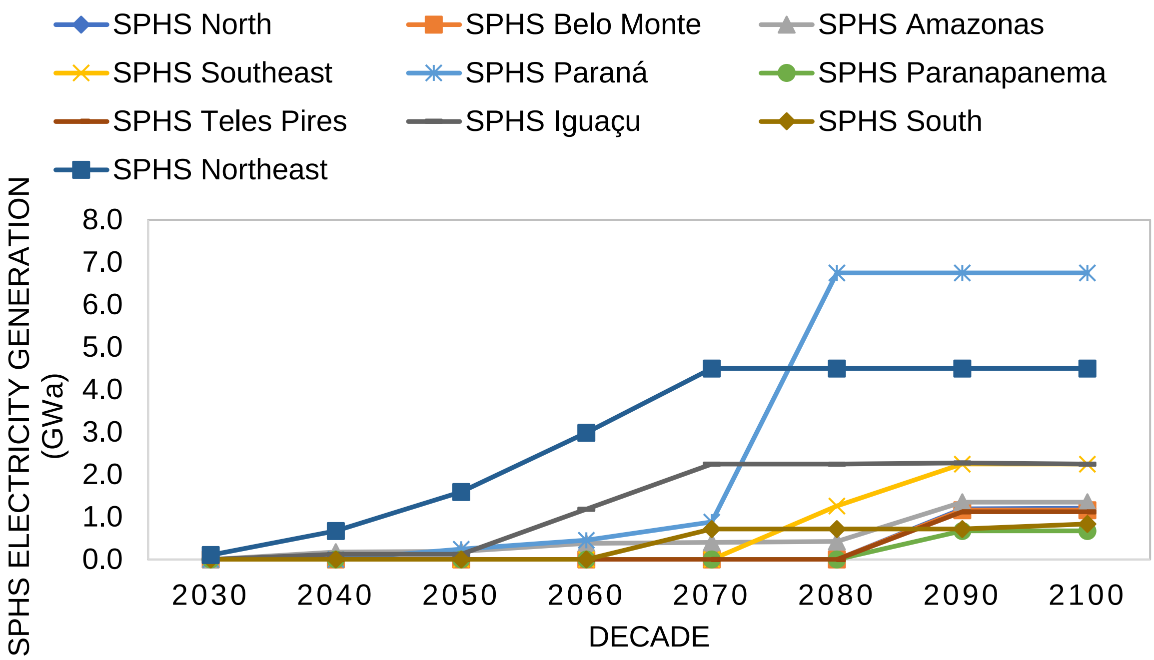


Figure E-46 - SPHS electricity generation (discharging) activities by technology for RCP 2.6 scenario.

The SPHS with the highest activity were the ones located in the EER Paraná, and EER Northeast. Among them, the SPHS Paraná had the highest activity, especially in the year 2100. The lowest activity during the studied years was seen in the SPHS Paranapanema and SPHS South. These results can be related to the low seasonal differences in the inflow of these two EERs. The additional installed capacity necessary to generate the required energy including SPHS from 2030 up to 2100, for RCP 2.6 scenario, is shown in Figure E-47.

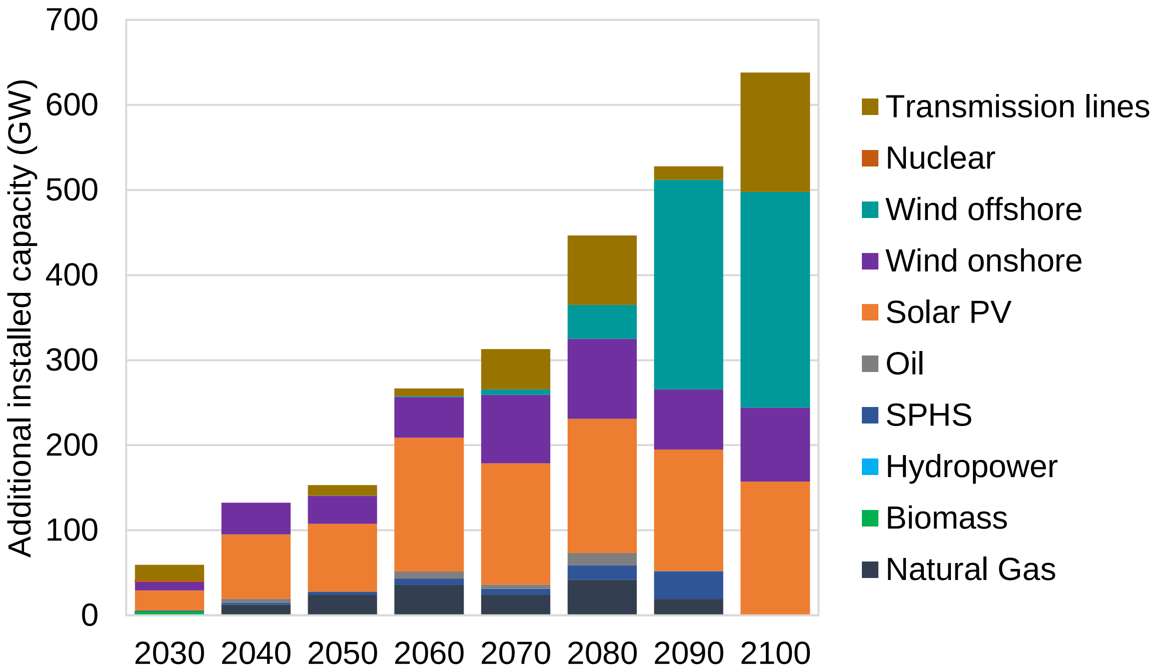


Figure E-47 – Additional installed capacity from 2030 up to 2100 for RCP 2.6 scenario.

Solar power is the technology which requires the highest installed capacity along the years. To achieve the required capacity over the years, in average 12 GW of solar power is needed to be installed annually. It seems feasible to install 12 GW of solar power per year as in Brazil was added 9.3 GW of solar power in just one year, 2022. [Portal Solar, 2023]. Regarding wind power onshore, an average of 5.3 GW per year is required according to the BESMM. While for wind power offshore, an average of 18.2 GW should be installed in order to achieve the necessary capacity. In total, 69.7 GW of SPHS are required to provide the BESMM with the required flexibility during the studied period. With 15 GW of SPHS installed, EER Paraná was the EER with the highest installed capacity. There will be a need for fossil fuel power plants until wind power offshore becomes more affordable and SPHS activities reach their peak.

The next step was to generate a scenario without SPHS technologies and with the same inputs as BESMM RCP 2.6, and then compare the results. Figure E-48 shows the results of the BESMM electricity generation activity up to 2100 for RCP 2.6 w/o SPHS scenario.

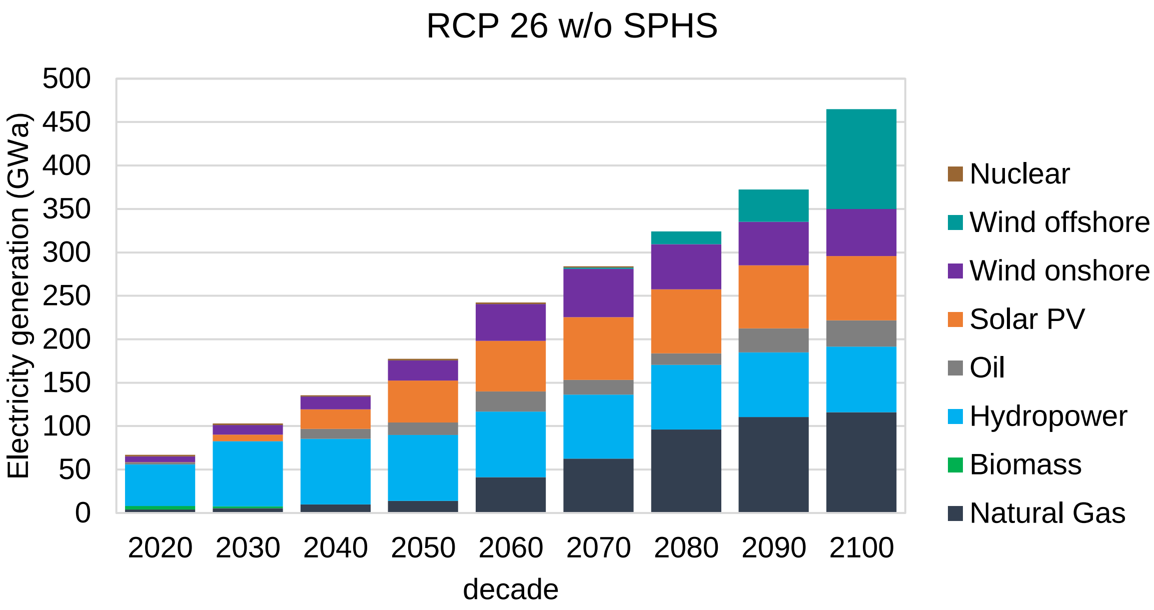


Figure E-48 - BESMM electricity generation activity up to 2100 for RCP 2.6 w/o SPHS scenario.

In this scenario thermal power plants have a higher activity than the scenario with SPHS. Approximately 72% of the electricity produced in 2100 is expected to be renewable. This includes 25.8% wind power offshore, 20.4% hydropower, 16.0% solar power, and 9.6% wind power onshore. As for the remaining part, 20.6% was produced by natural gas and 7.6% by oil power plants. Thus, in a scenario without SPHS the renewable energy penetration is 28% lower than in a scenario with SPHS. The renewable source most affected was the wind power offshore. Which is a technology with high capacity of electricity production due to availability of higher wind speeds, although it has strongly seasonality patterns. According to the results, SPHS would balance offshore wind power production and lead to 100% renewable energy power matrix. Ultimately, Figure E-49 compares the emissions along the years for both scenarios.

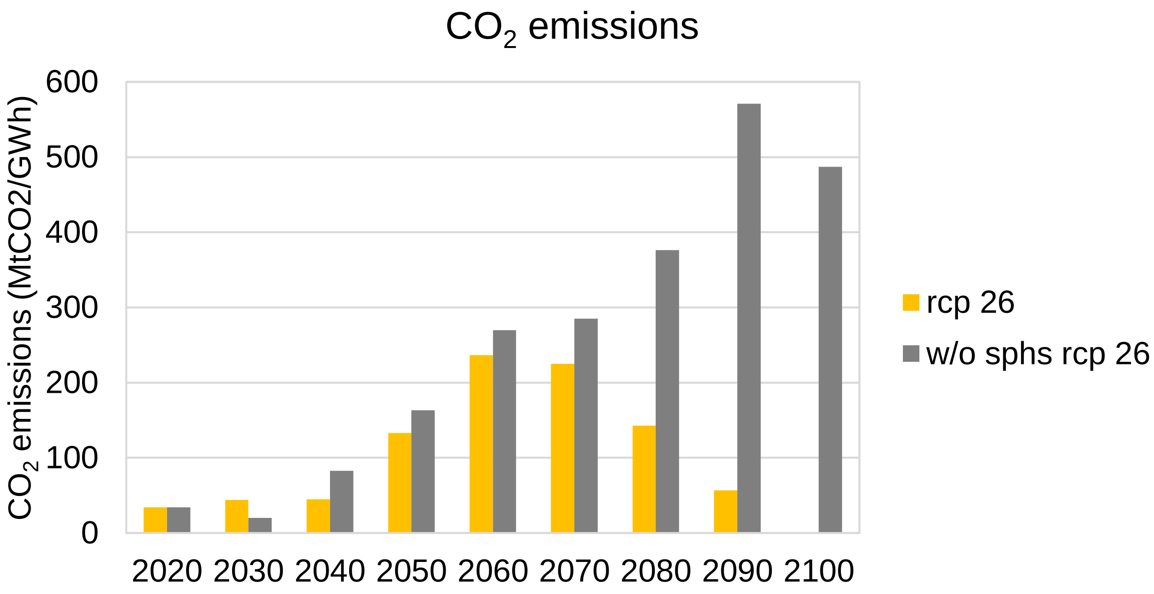


Figure E-49 – Total CO_2 emissions of RCP 2.6 scenario with and without SPHS technologies.

The scenario without SPHS is expected to emit 50% more CO_2 gas than a scenario with SPHS along the studied period. Thus, SPHS contributes significantly to climate mitigation and the attainment of 100% renewable power by 2100. Not only through the production of more hydropower but particularly through the integration of renewable energy sources with high seasonality patterns, such as offshore wind power.

RCP 4.5

For the RCP 4.5 scenario, Figure E-50 shows the projected technology matrix to produce least-cost electricity for the BESMM up to 2100.

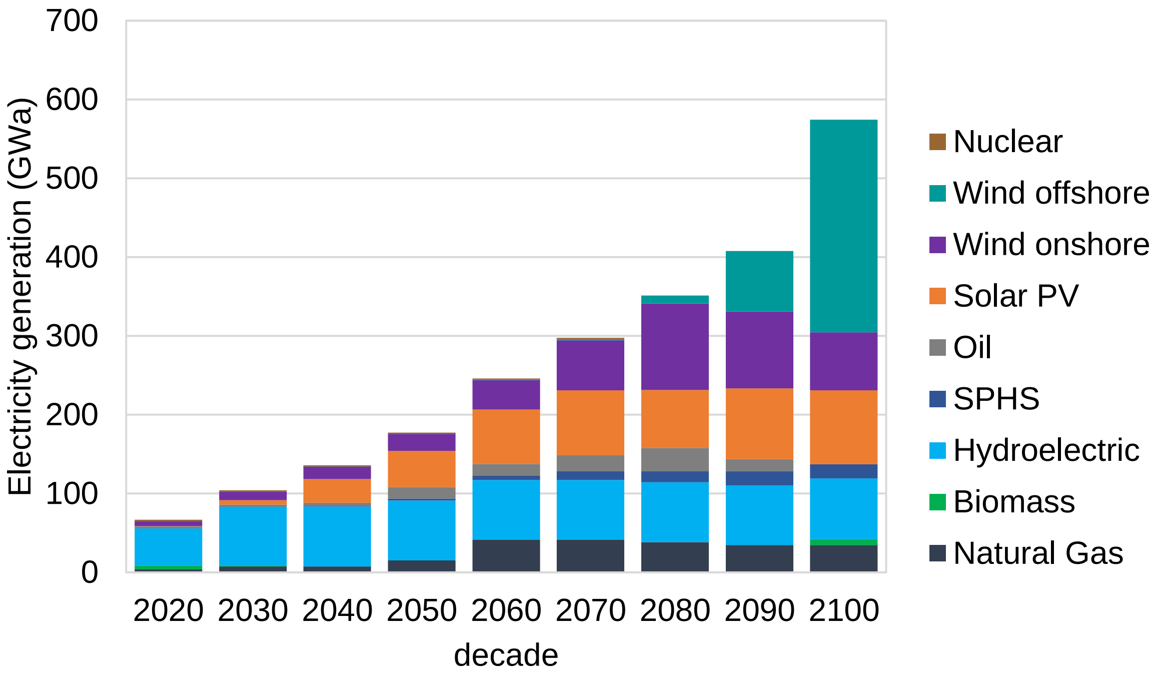


Figure E-50 - BESMM electricity generation activity up to 2100 for RCP 4.5 scenario.

According to that scenario, Brazil's electricity production is projected to be 94% renewable by the year 2100, with 47.0% coming from offshore wind power, 16.6% from hydropower (13.3% hydropower and 3.1% SPHS), 16.4% from solar power, and 12.8% from onshore wind power. The last three decades presented the highest SPHS activity, especially in the year 2090, 18.2 GWa in total. Furthermore, offshore wind power has experienced a high growth rate over the past three decades and can produce half of the Brazilian electric power by 2100. In contrast to offshore wind power, onshore wind power has decreased over the last decade. Figure E-51 shows the total SPHS produced by season for BESMM scenario RCP 4.5.

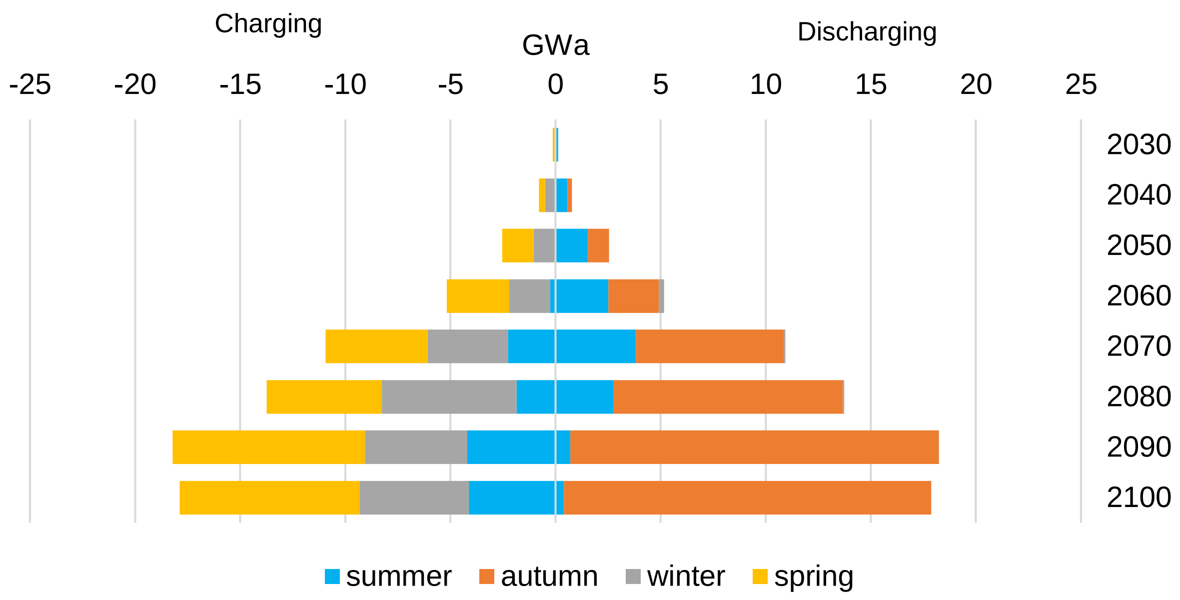


Figure E-51 - Total SPHS produced by season in the BESMM RCP 4.5 scenario.

The majority of SPHS electricity production (discharging) was during autumn, 81.5%. On the other hand, most charging activities occurred during spring and winter, 47.4% and 34.3%, respectively, when the turbine pumps water back to the dam. The total SPHS production by season and by region for scenario RCP 4.5 is detailed in Figure E-52.

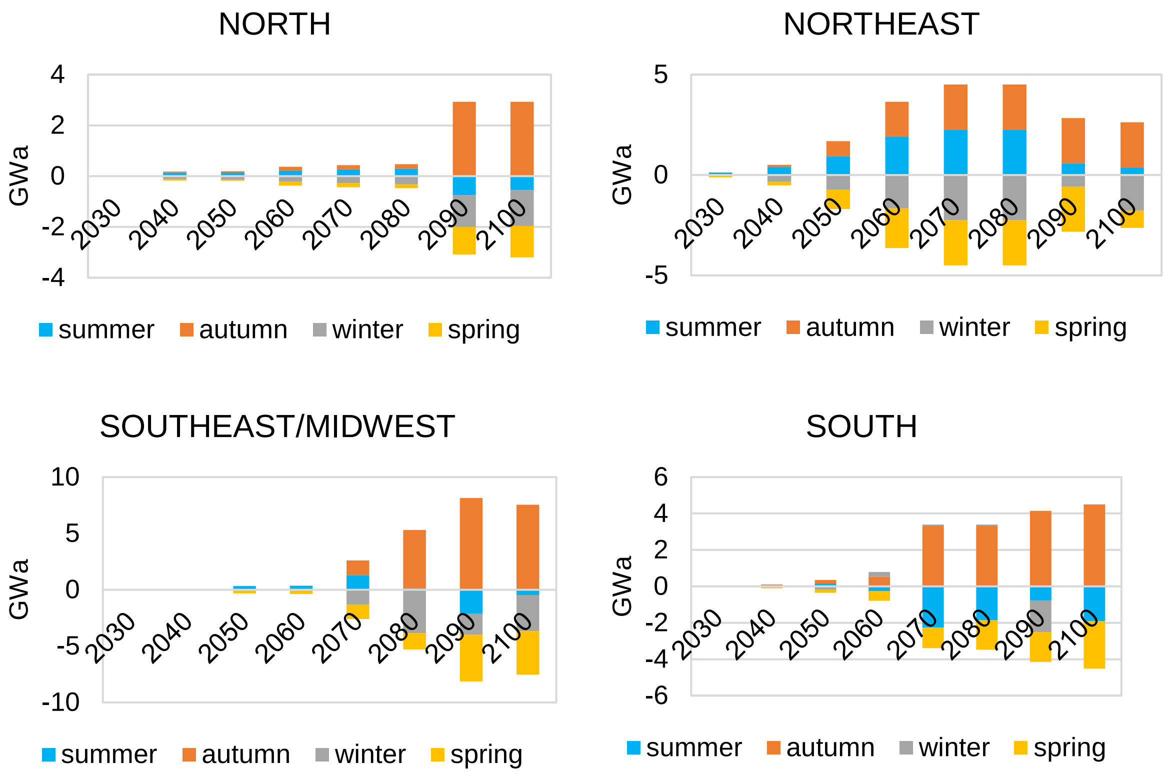


Figure E-52 - Total SPHS produced by season and by region in the BESMM RCP 4.5 scenario.

As in RCP 2.6 the Southeast/Midwest had the highest level of SPHS activity compared to any other region, which was expected as the potential is greater in this region, as shown Figure E-52. The higher activity was observed only in the last three decades. Similar to the RCP 2.6, the Northeast region presented a higher activity starting from 2050. The North region is the one with the lowest SPHS activity, and the years with high activity were the years with higher seasonality. In the South the year with the highest activity was 2100, as RCP 2.6.

Figure E-53 shows in detail the SPHS activities for each EER along the RCP 4.5 scenario.

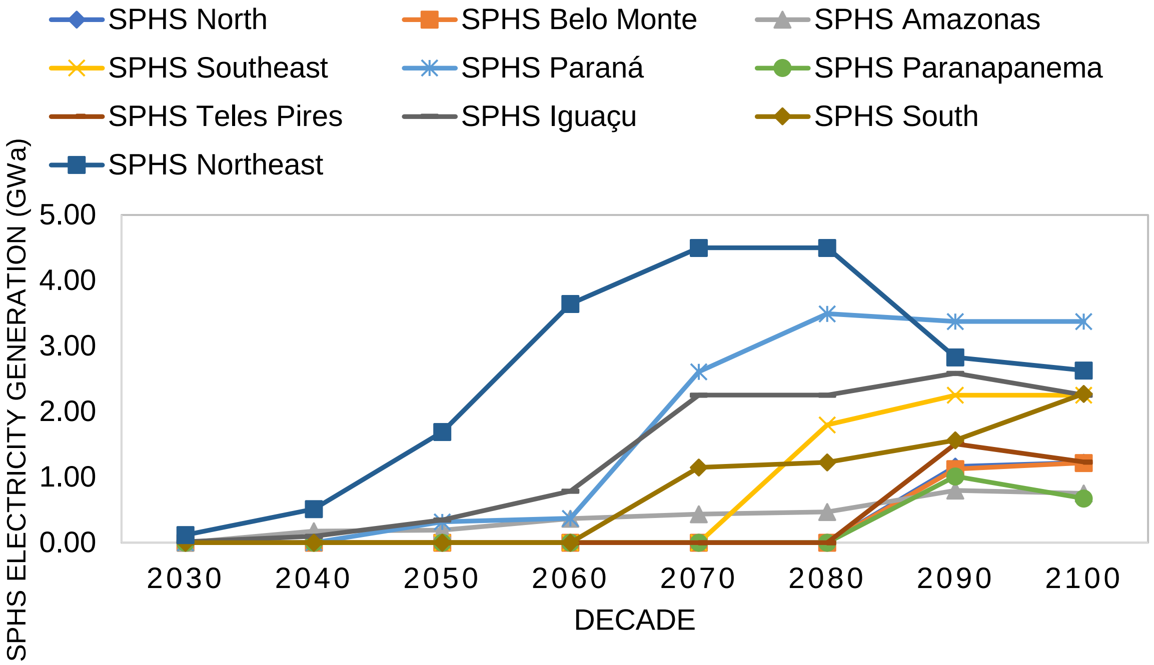


Figure E-53 – SPHS electricity generation (discharging) activities by technology for RCP 4.5 scenario.

As Figure E-53 shows the SPHS with the highest activity were the ones located in the EER Northeast, 21.6% of total activity along the studied period, EER Paraná, 16.7%, and EER Iguaçu, 12.4%. Among them the SPHS Northeast displayed the highest activity in the years 2070 and 2080. The least activity was seen in the SPHS Amazonas, 0.03% of total activity. The additional installed capacity necessary to generate the required energy including SPHS from 2030 up to 2100, for RCP 4.5 scenario, is shown in Figure E-54.

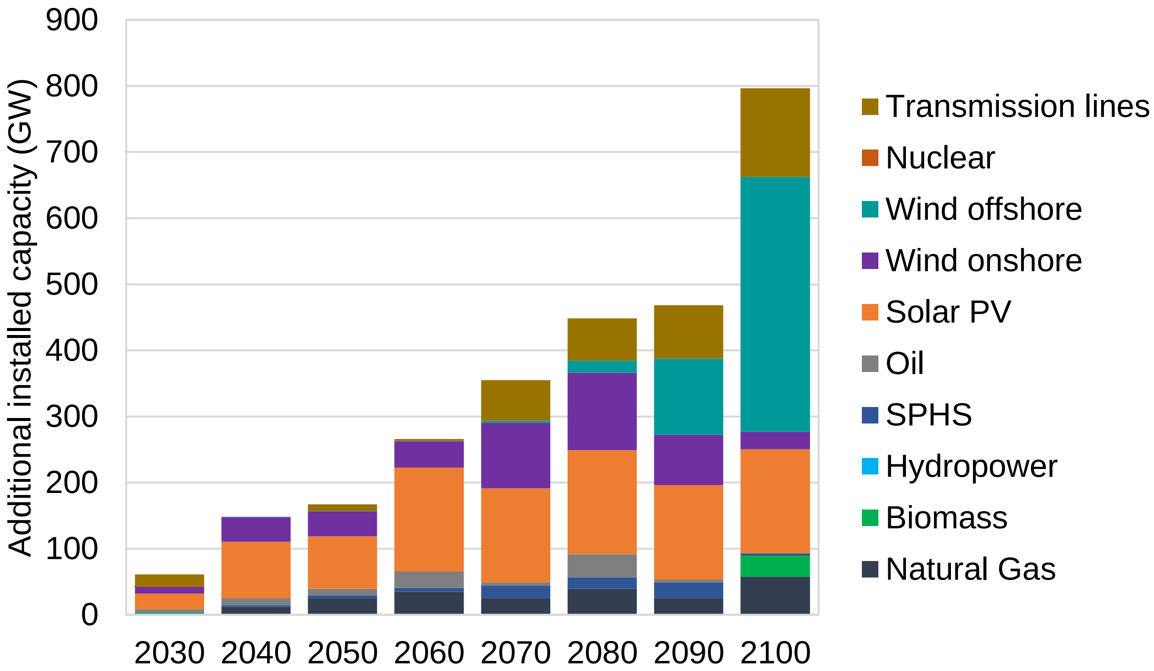


Figure E-54 - Additional installed capacity from 2030 up to 2100 for 4.5 scenario.

As in scenario 2.6, solar power is the technology which required the highest installed capacity over the years. To achieve the required capacity over the years, in average 12 GW of solar power will need to be installed annually. Annually an average of 5.3 GW of onshore wind power, as well as 18.2 GW offshore wind power, should be installed. In total, 76.0 GW of SPHS are required to provide the BESMM with the required flexibility during the studied period. With 15 GW of SPHS installed, EER Paraná was the EER with the highest installed capacity. There will be a need for fossil fuel power plants until wind power offshore becomes more affordable and SPHS activities reach their peak.

The BESMM activity without SPHS technologies was simulated to examine the impact of SPHS technologies in the RCP 4.5 scenario. Figure E-55 illustrates the results of BESMM electricity generation activity from 2020 up to 2100 under scenario RCP 4.5 without SPHS.

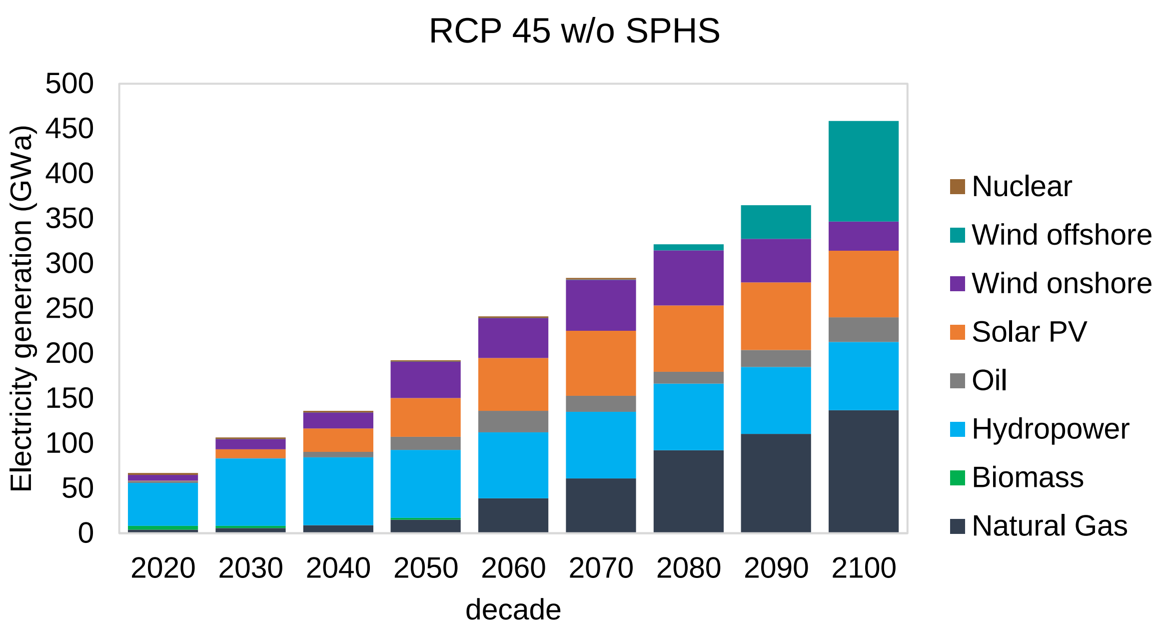


Figure E-55 - BESMM electricity generation activity up to 2100 for scenario RCP 4.5 w/o SPHS.

By 2100, is estimated that 64% of the electricity produced will be renewable. This includes 22.3% wind power offshore, 20.7% hydropower, 16.2% solar power, and 4.9% wind power onshore. As for the remaining part, 29.9% was produced by natural gas and 6.0% by oil power plants. Thus, in scenario 4.5 without SPHS the renewable energy penetration is 36% lower than in a scenario with SPHS. As in scenario RCP 2.6 the SPHS technologies can balance the seasonal fluctuations of the offshore wind power production and lead to 100% renewable energy power matrix. Ultimately, Figure E-56 compares the emissions along the years for both RCP 4.5 scenarios with and without SPHS technologies.

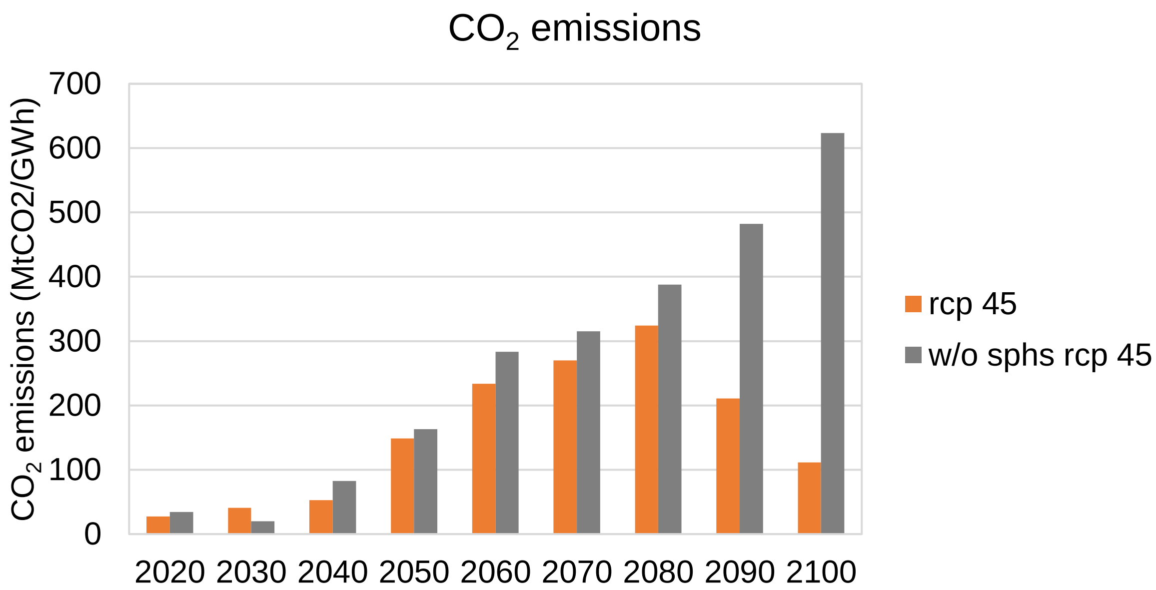


Figure E-56 - Total CO_2 emissions of RCP 4.5 scenario with and without SPHS technologies.

The scenario without SPHS is expected to emit 68% more CO_2 gas than a scenario with SPHS during the studied period. This means that the SPHS in scenario RCP 4.5 will also contribute significantly to climate mitigation and to the achievement of 94% renewable power by 2100.

RCP 8.5

Figure E-57 illustrates the projected technology matrix for producing least-cost electricity for the BESMM up to 2100 for scenario RCP 8.5.

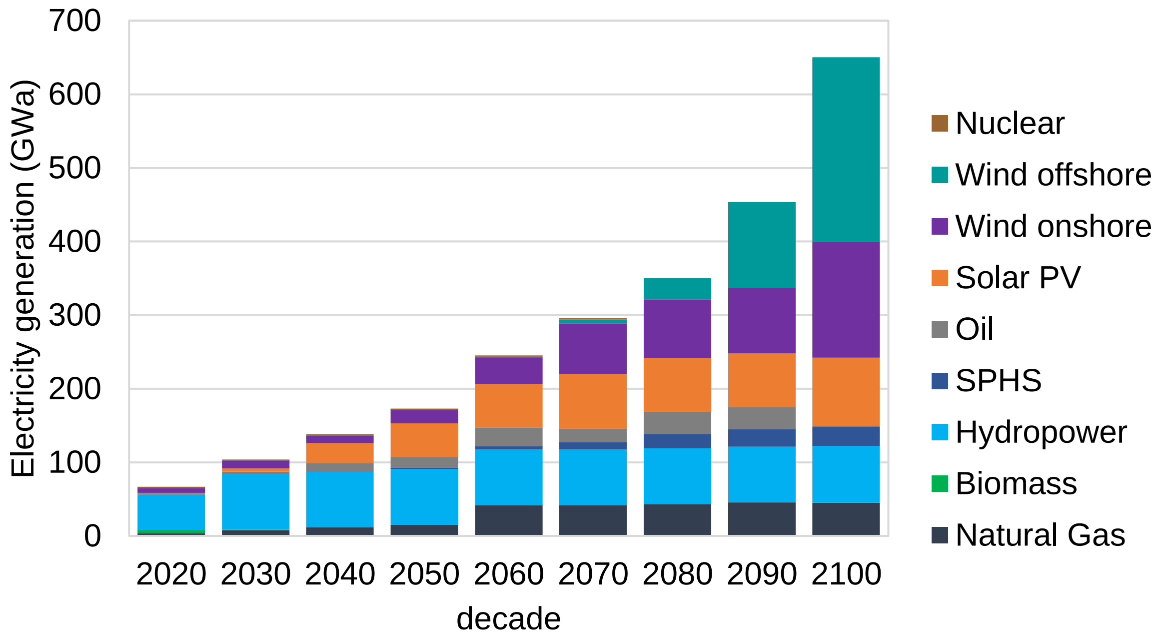


Figure E-57 - BESMM electricity generation activity up to 2100 for RCP 8.5 scenario.

It is estimated that by the year 2100, Brazil's electricity production will be 93% renewable, with 38.6% coming from offshore wind power, 15.9% from hydropower (11.9% hydropower and 4.0% SPHS), 24.2% from onshore wind power, and 14.2% from solar power. In this scenario, as in the previous scenarios, SPHS activity has been highest in the last three decades, especially last year, with a total activity of 24.9 GWa. It is also worth noting that RCP 8.5 scenario is the only scenario in which onshore wind power also had a rapid growth rate in the last three decades. This is due to the fact that, in this scenario, wind energy resource capacity increased especially in the Northeast, as can be seen in APPENDIX D. The total SPHS produced by season for BESMM RCP 8.5 scenario is shown in Figure E-58.

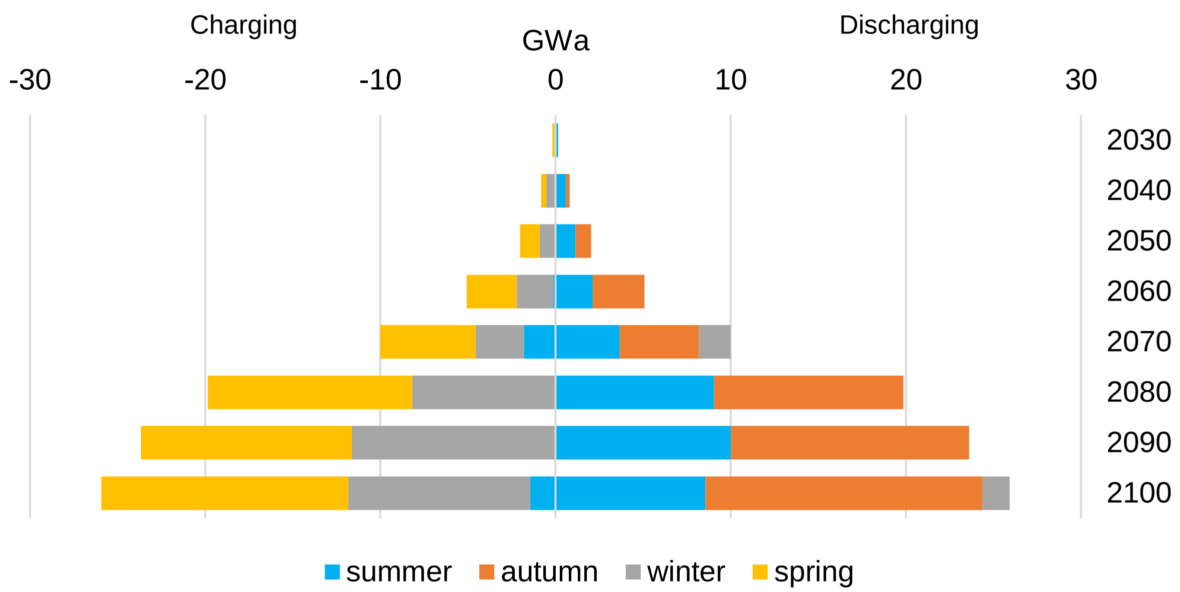
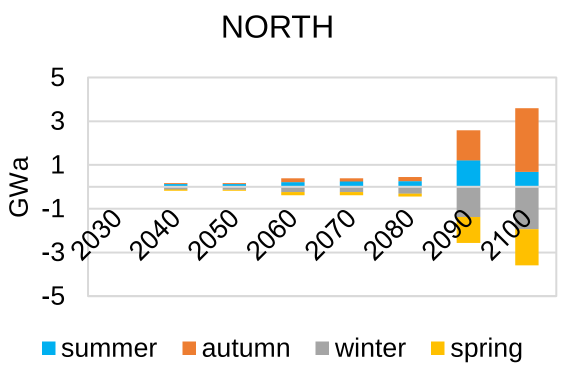
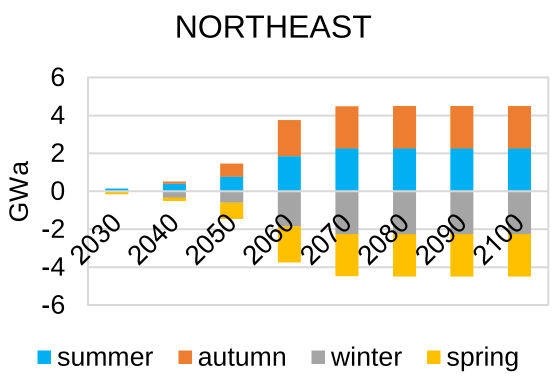


Figure E-58 - Total SPHS produced by season in the BESMM scenario RCP 8.5.

Half of SPHS electricity production (discharging) occurred in autumn, 55.8%. On the other hand, most charging activities, when SPHS turbines pump water back to the dams, occurred during spring and winter, 54.5% and 41.7%, respectively. The total SPHS production by season and by region for RCP 8.5 scenario is shown in Figure E-59.





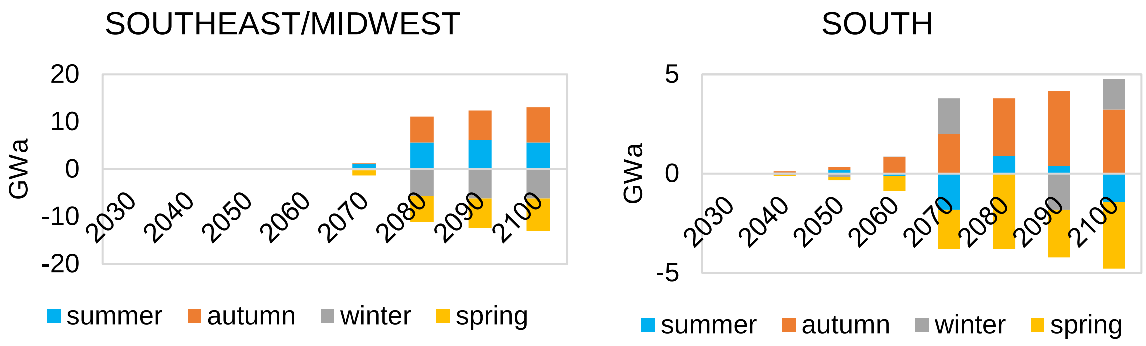


Figure E-59 - Total SPHS produced by season and by region in the BESMM scenario RCP 8.5

In previous scenarios, the Southeast/Midwest had the highest level of SPHS activity compared to any other region, as their potential is greater. Similar to RCP 2.6 and RCP 4.5, the Northeast region presented constant activity since 2060. As other scenarios, the North region is the one with the lowest SPHS activity. SPHS activities along the RCP 8.5 scenario are shown in detail in Figure E-60.

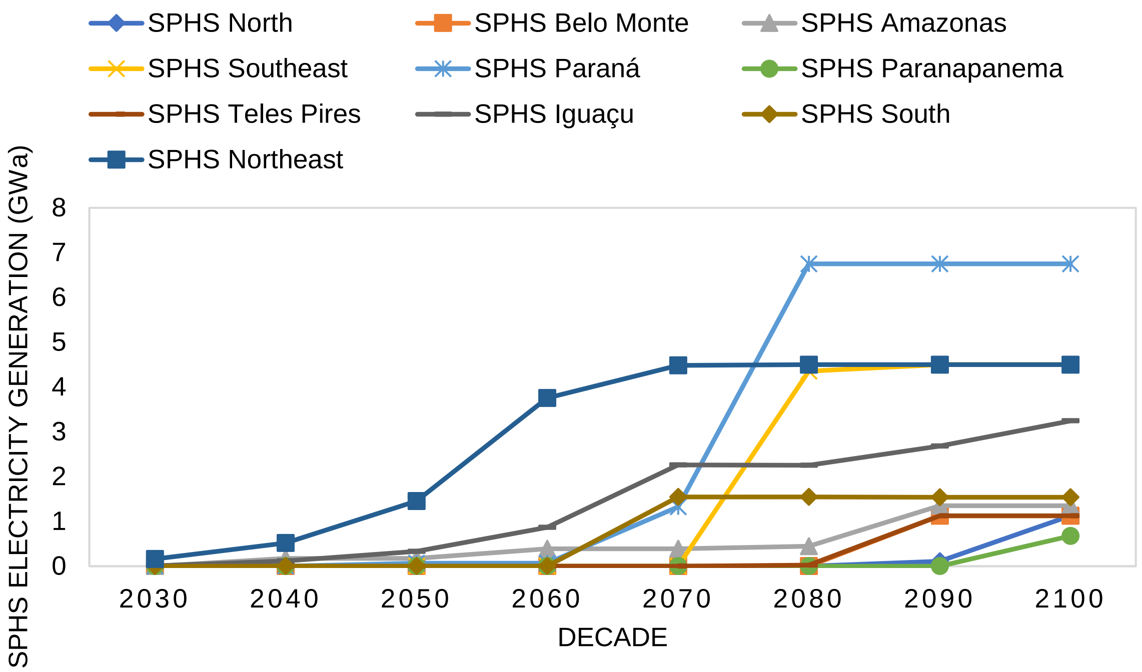


Figure E-60 - SPHS electricity generation (discharging) activities by technology for scenario RCP 8.5.

The SPHS with the highest activity were the ones located in the EER Northeast, 37.5% of total activity during the studied period, EER Paraná, 34.1%, and EER Paranapanema, 13.3%. The least activity was seen in the SPHS Paranapanema, 1.1%

of total activity, and SPHS North, 1.9%, both located in the north region. The additional installed capacity necessary to generate the required energy including SPHS from 2030 up to 2100, for RCP 8.5 scenario, is shown in
Figure E-61.

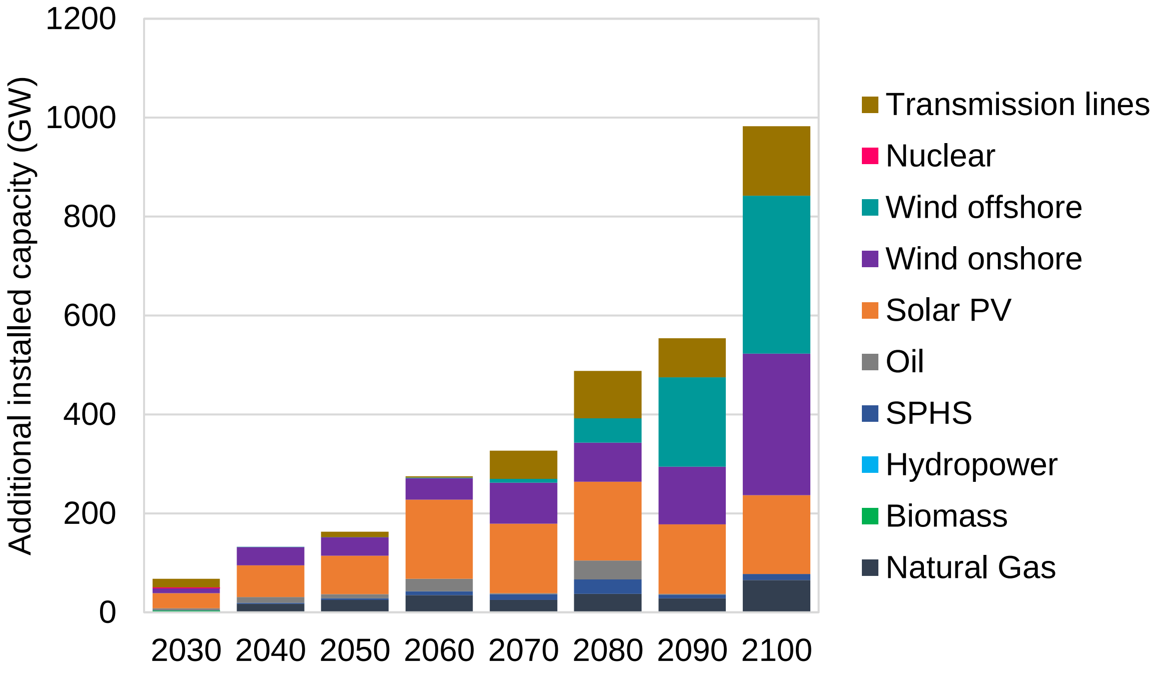


Figure E-61 - Additional installed capacity from 2030 up to 2100 for scenario 8.5.

As in previous scenarios, solar power is the technology which required the highest installed capacity over the years. To achieve the required capacity over the years, in average 12 GW of solar power will need to be installed annually. Annually an average of 5.3 GW of onshore wind power, as well as 18.2 GW offshore wind power, should be installed. In total, 73.5 GW of SPHS are required to provide the BESMM with the required flexibility during the studied period. With 15 GW of SPHS installed, EER Paraná was the EER with the highest installed capacity. There will be a need for fossil fuel power plants until wind power offshore becomes more affordable and SPHS activities reach their peak.

A simulation of the BESMM activity without SPHS technologies was conducted in order to examine the impact of SPHS technologies under the RCP 8.5 scenario. Figure E-62 illustrates the results of BESMM electricity generation activity under scenario RCP 8.5 without SPHS.

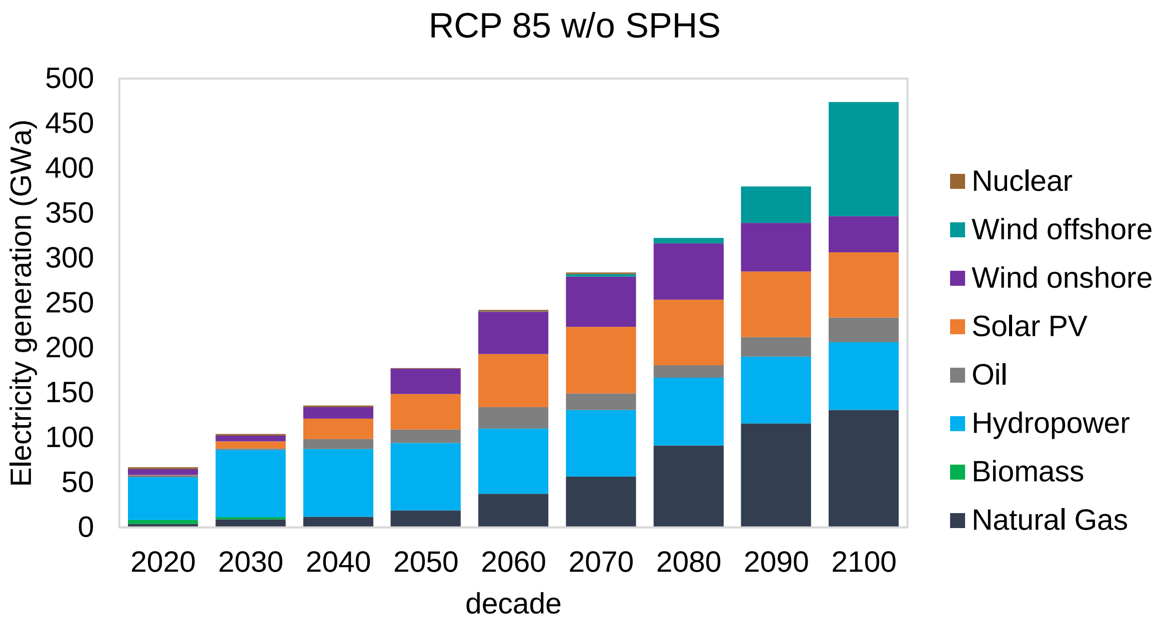


Figure *E*-62 - BESMM electricity generation activity up to 2100 for scenario RCP 8.5 w/o SPHS.

By 2100, is estimated that 67% of the electricity produced will be renewable. This includes 26.8% wind power offshore, 19.9% hydropower, 15.3% solar power, and 4.6% wind power onshore. As for the remaining part, 27.6% was produced by natural gas and 5.8% by oil power plants. Thus, in scenario 8.5 without SPHS, renewable energy penetration is 33% lower than in scenario 8.5 with SPHS. There is no doubt that the SPHS technology can balance the seasonal fluctuations in offshore wind power production, and it can lead to a 100% renewables power matrix just as it has in previous scenarios. Lastly, Figure E-63 compares the emissions along the years for both RCP 8.5 scenarios with and without SPHS technologies.

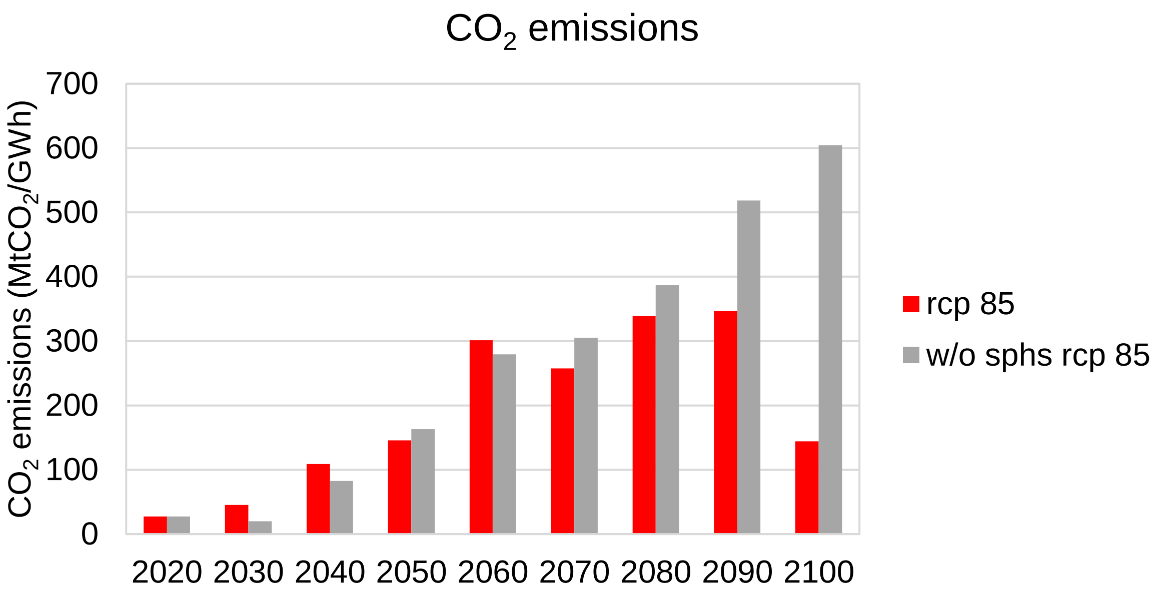


Figure E-63 - Total CO_2 emissions of RCP 8.5 scenario with and without SPHS technologies.

The scenario without SPHS is estimated to emit 40% more GHG than a scenario with SPHS during the studied period. In light of this, it is important to stress that the SPHS in scenario RCP 8.5 will also make a significant contribution to climate mitigation, as well as to the achievement of 100 percent renewable energy by the year 2100.