

APPENIDX E - Results by RCP scenario

RCP 2.6

Figure E-1 shows the projections for the optimized least-cost electricity production matrix for the BESMM from 2020 up to 2100¹ for the RCP 2.6 scenario.

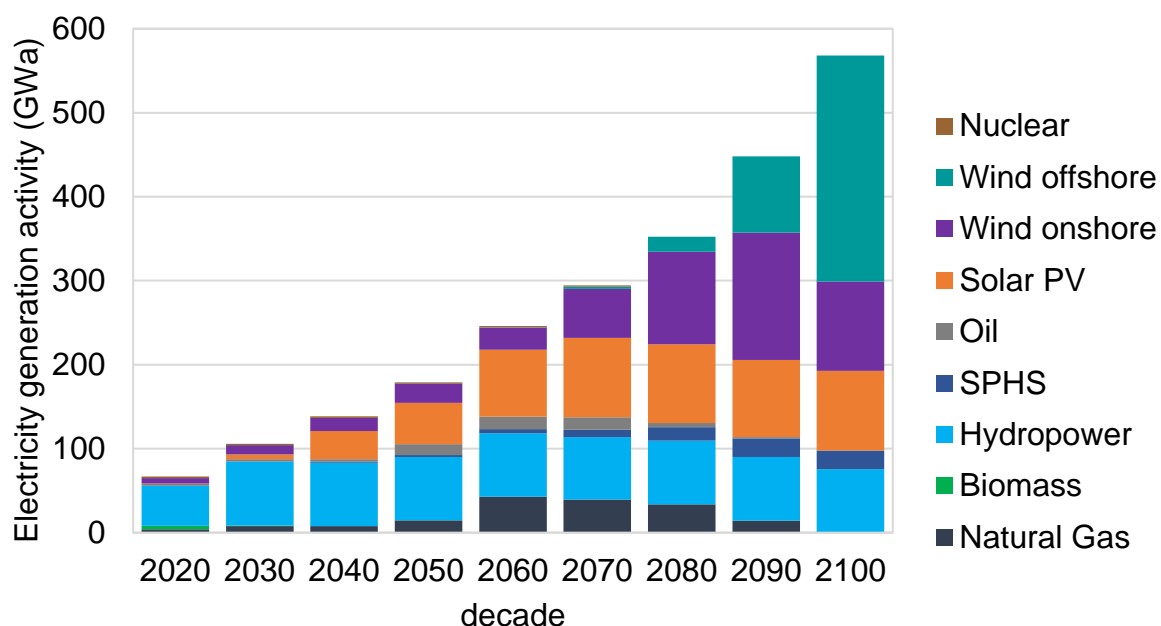


Figure E-1 – BESMM electricity generation activity up to 2100 for RCP 2.6 scenario simulated with the Brazilian Electricity System MESSAGEix Model.

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. 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-2.

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.

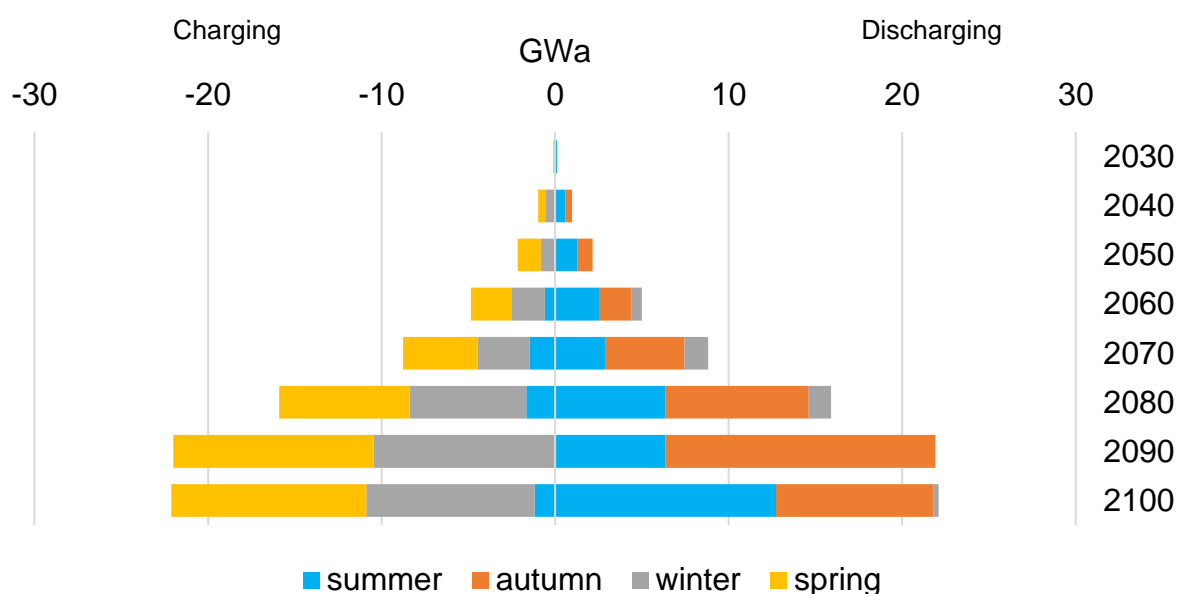


Figure E-2 – Total Seasonal pumped hydropower storage, SPHS, produced by season in the BESMM RCP 2.6 scenario.

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. In the year 2100, the EER South presented lower water inflow in all seasons in comparison to previous years, as well as the EER 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-3.

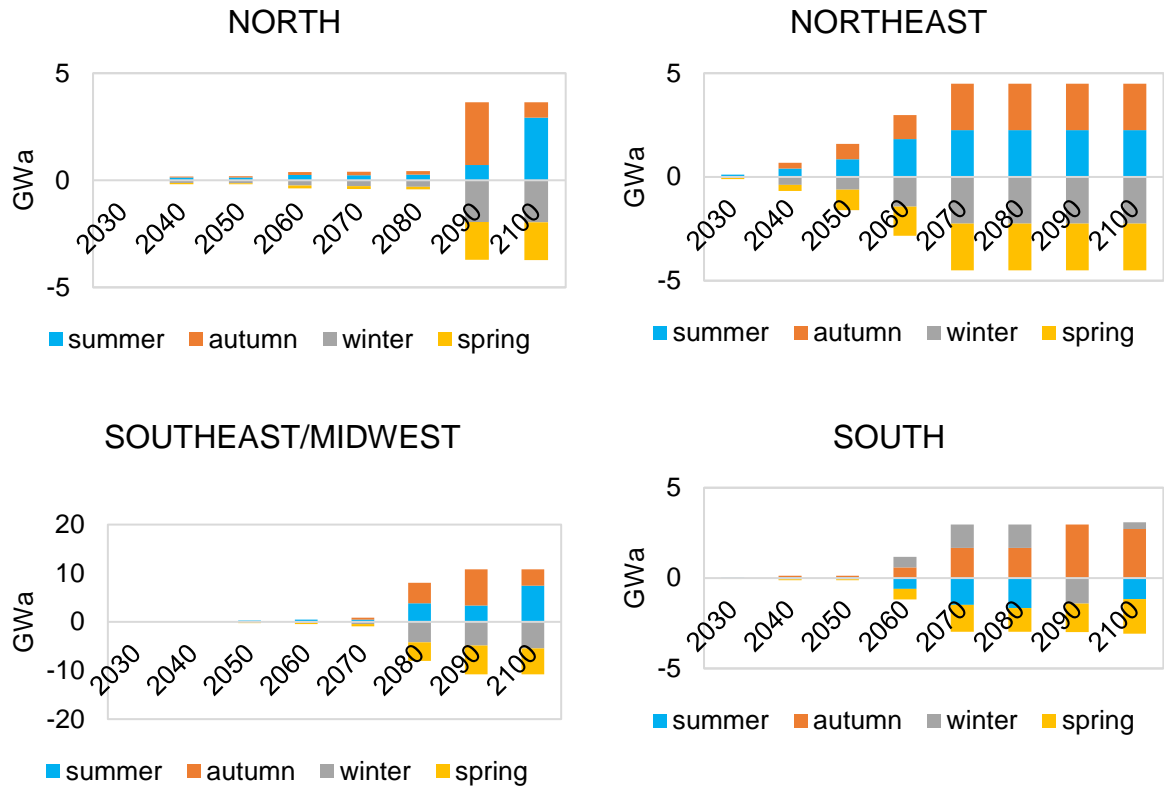


Figure E-3 - Total SPHS produced by season and by region in the BESMM scenario RCP 2.6. North (top left), Northeast region (top right), Southeast/Midwest region (bottom left), and South region (bottom right).

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-4.

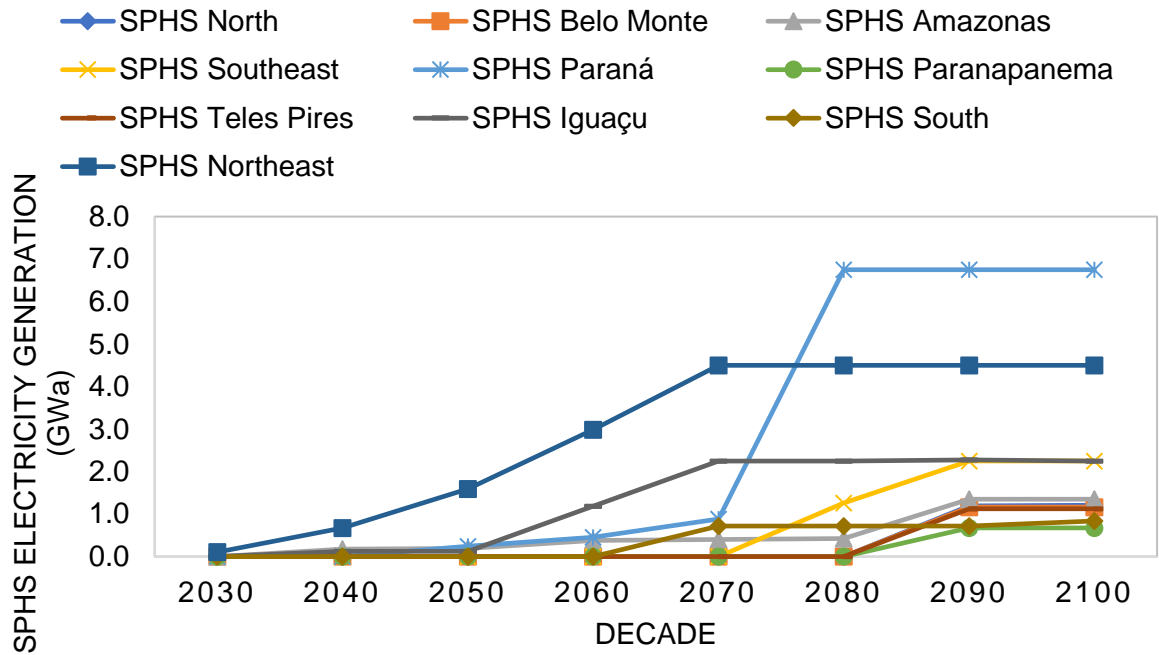


Figure E-4 - SPHS electricity generation (discharging) activities by technology for RCP 2.6 scenario.

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-5.

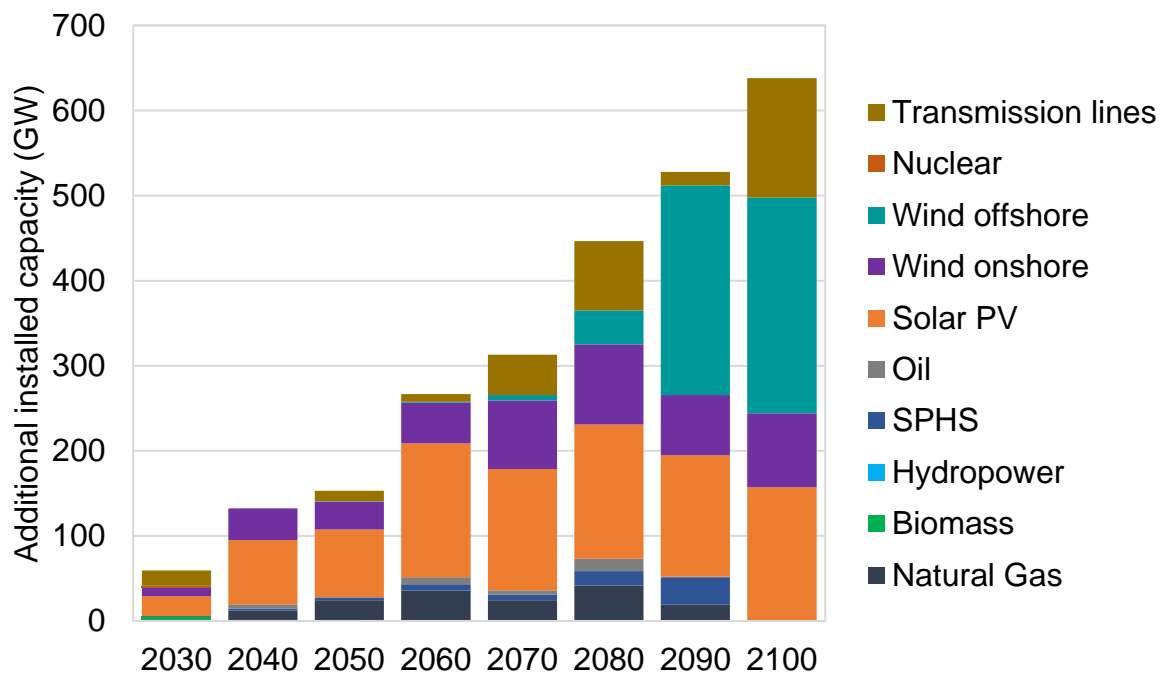


Figure E-5 – Additional installed capacity from 2030 up to 2100 for RCP 2.6 scenario.

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-6 shows the results of the BESMM electricity generation activity up to 2100 for RCP 2.6 w/o SPHS scenario.

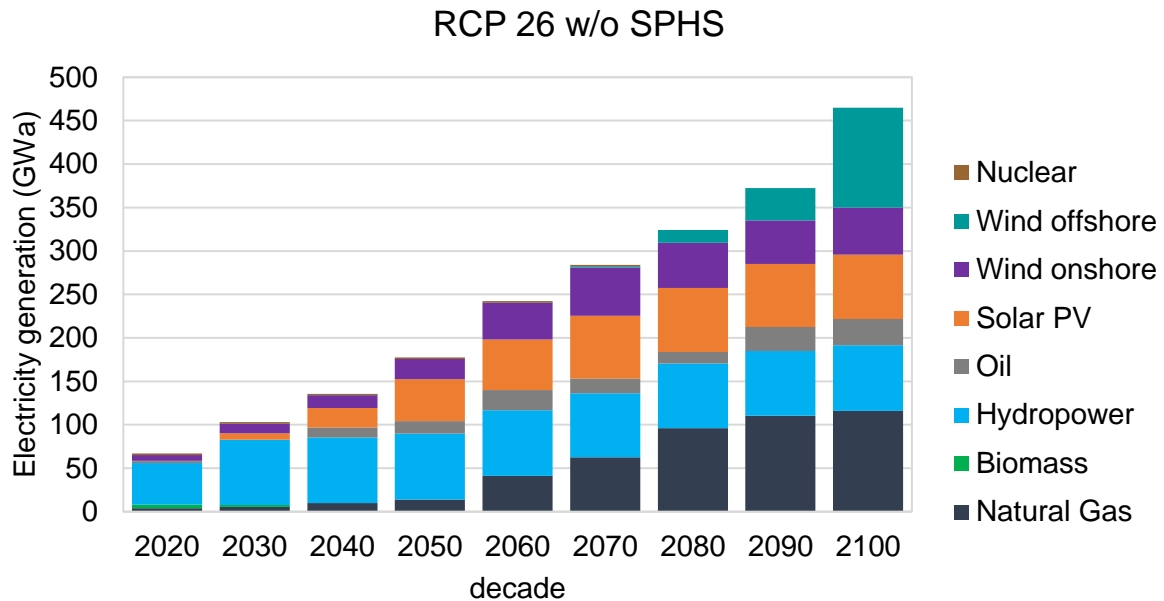


Figure E-6 - BESMM electricity generation activity up to 2100 for RCP 2.6 w/o SPHS scenario.

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-7 compares the emissions along the years for both scenarios.

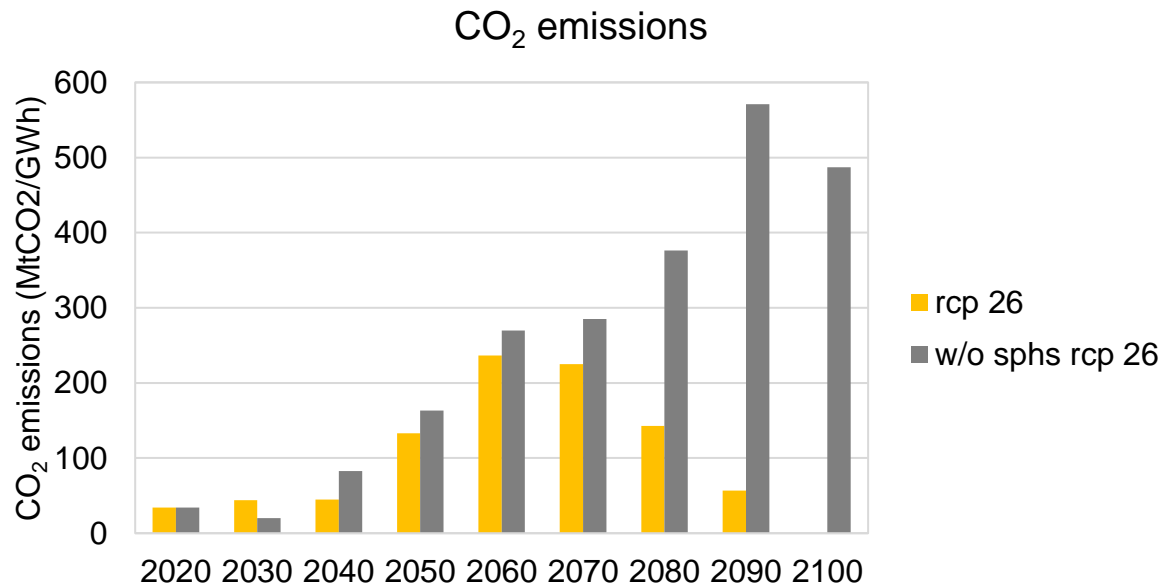


Figure E-7 – Total CO₂ emissions of RCP 2.6 scenario with and without SPHS technologies.

The scenario without SPHS is expected to emit 50% more CO₂ 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-8 shows the projected technology matrix to produce least-cost electricity for the BESMM up to 2100.

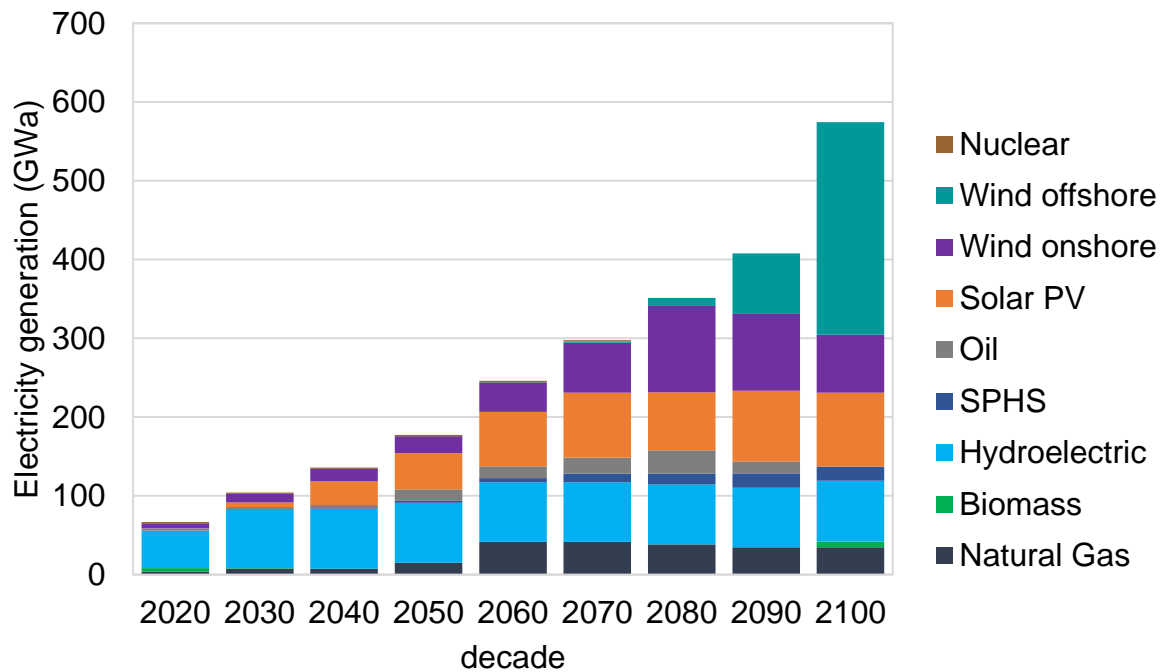


Figure E-8 - BESMM electricity generation activity up to 2100 for RCP 4.5 scenario.

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 GWh 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-9 shows the total SPHS produced by season for BESMM scenario RCP 4.5.

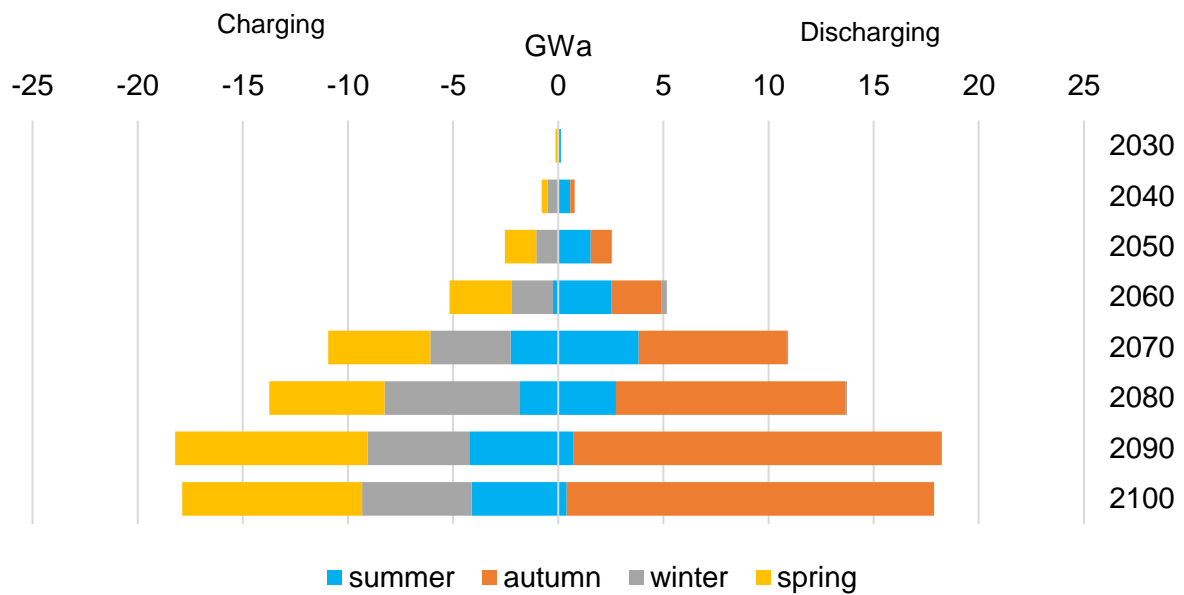


Figure E-9 - Total SPHS produced by season in the BESMM RCP 4.5 scenario.

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-10.

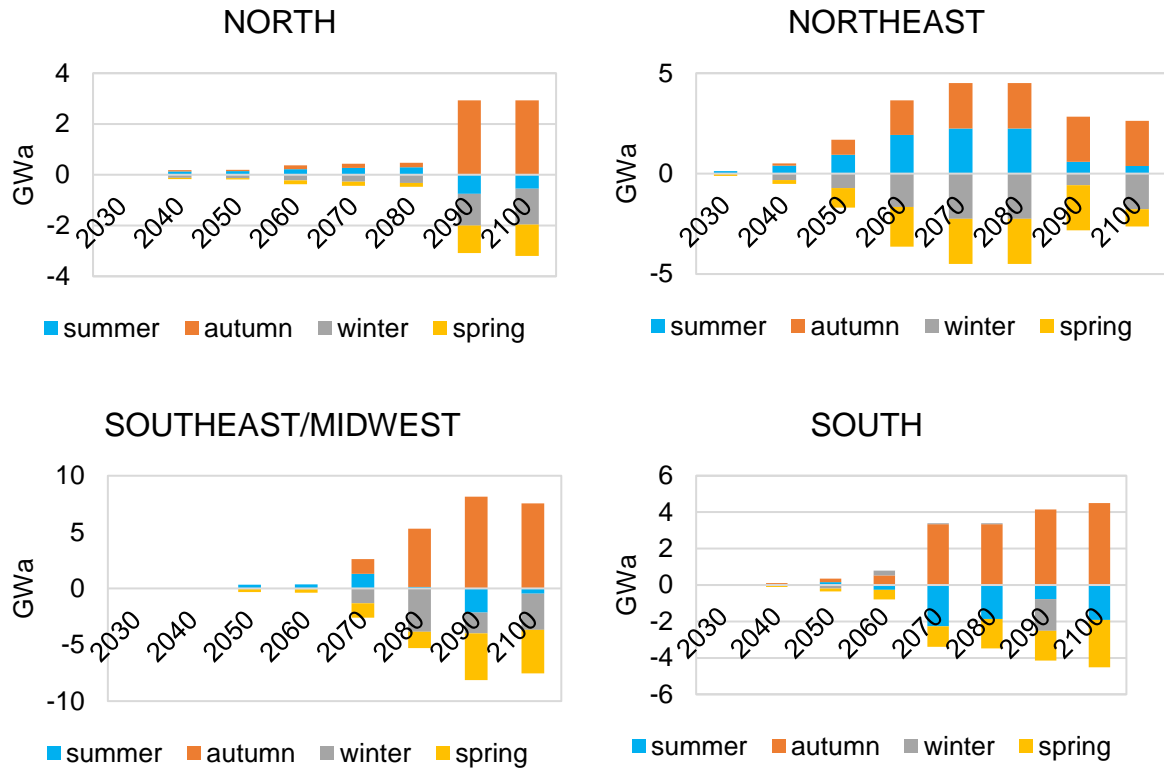


Figure E-10 - Total SPHS produced by season and by region in the BESMM RCP 4.5 scenario.

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-10. 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-11 shows in detail the SPHS activities for each EER along the RCP 4.5 scenario.

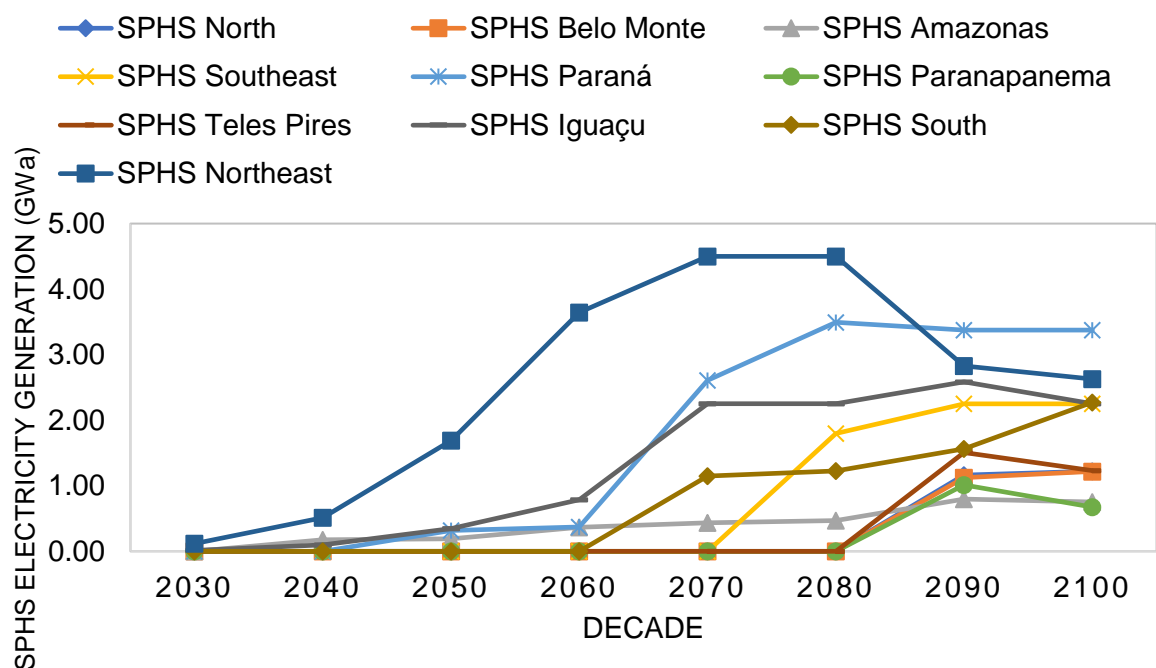


Figure E-11 – SPHS electricity generation (discharging) activities by technology for RCP 4.5 scenario.

As Figure E-11 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-12.

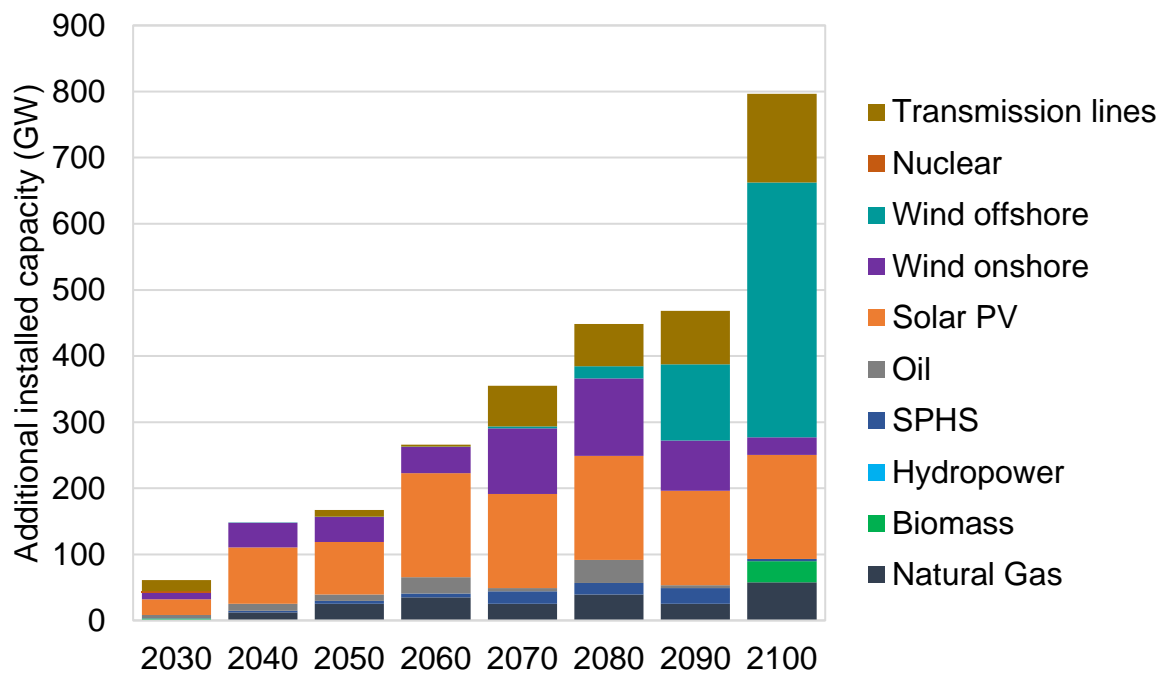


Figure E-12 - Additional installed capacity from 2030 up to 2100 for 4.5 scenario.

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-13 illustrates the results of BESMM electricity generation activity from 2020 up to 2100 under scenario RCP 4.5 without SPHS.

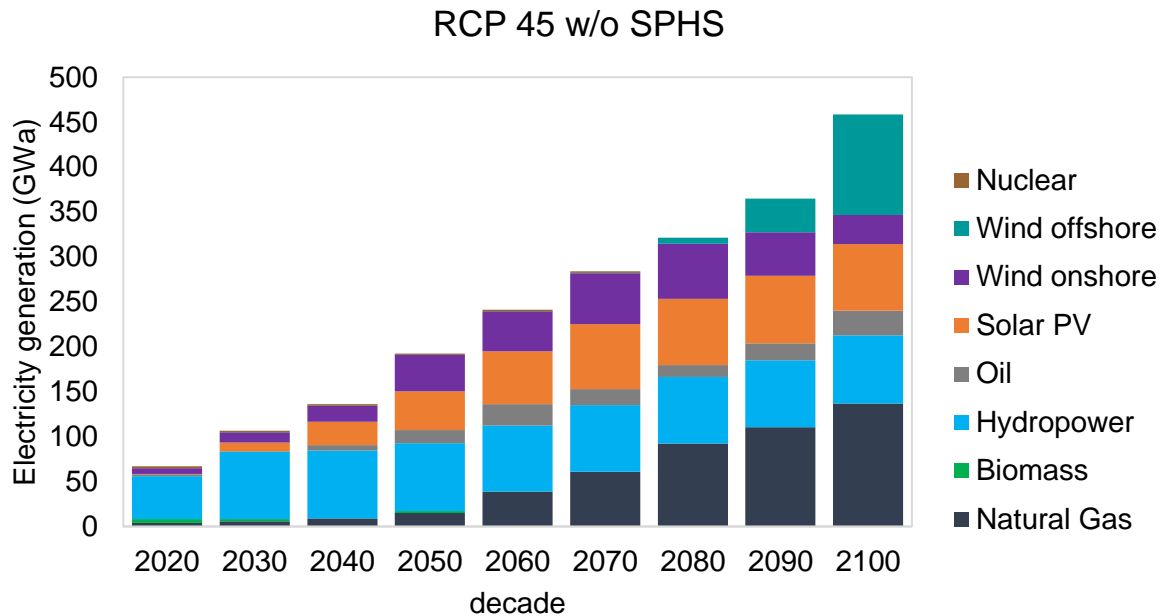


Figure E-13 - BESMM electricity generation activity up to 2100 for scenario RCP 4.5 w/o SPHS.

By 2100, it 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-14 compares the emissions along the years for both RCP 4.5 scenarios with and without SPHS technologies.

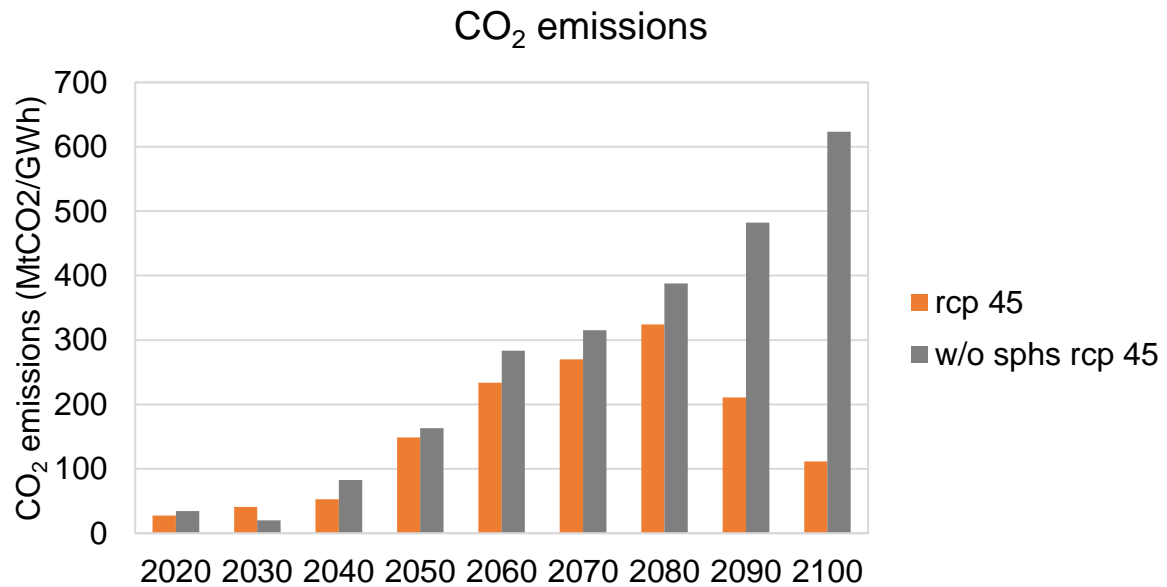


Figure E-14 - Total CO₂ emissions of RCP 4.5 scenario with and without SPHS technologies.

The scenario without SPHS is expected to emit 68% more CO₂ 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-15 illustrates the projected technology matrix for producing least-cost electricity for the BESMM up to 2100 for scenario RCP 8.5.

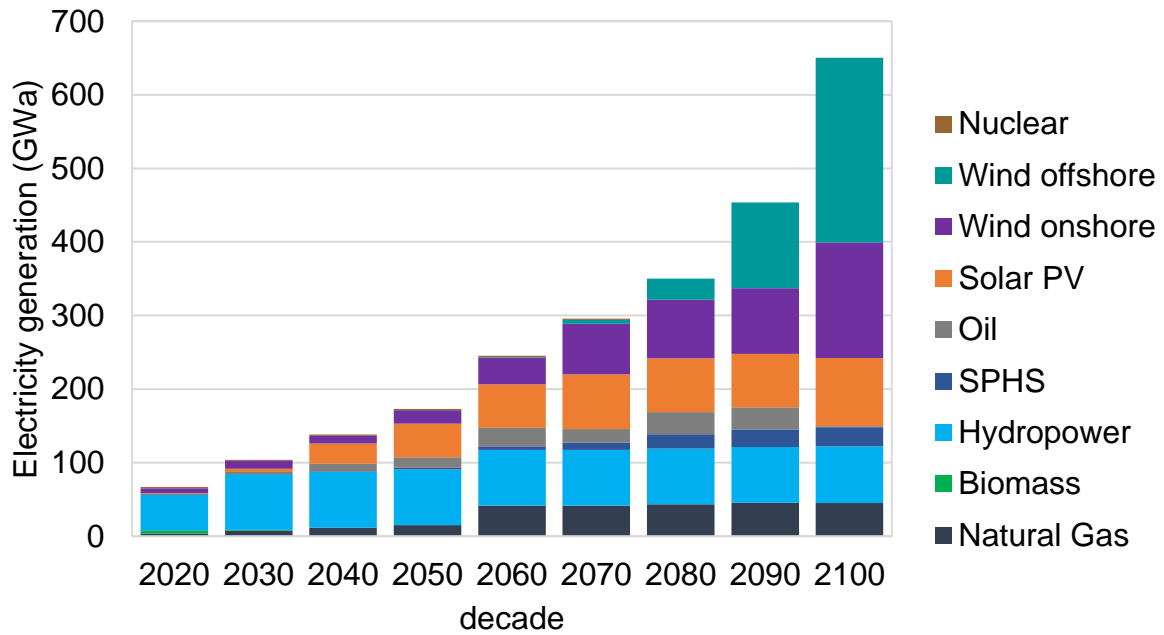


Figure E-15 - BESMM electricity generation activity up to 2100 for RCP 8.5 scenario.

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 GWh. 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-16.

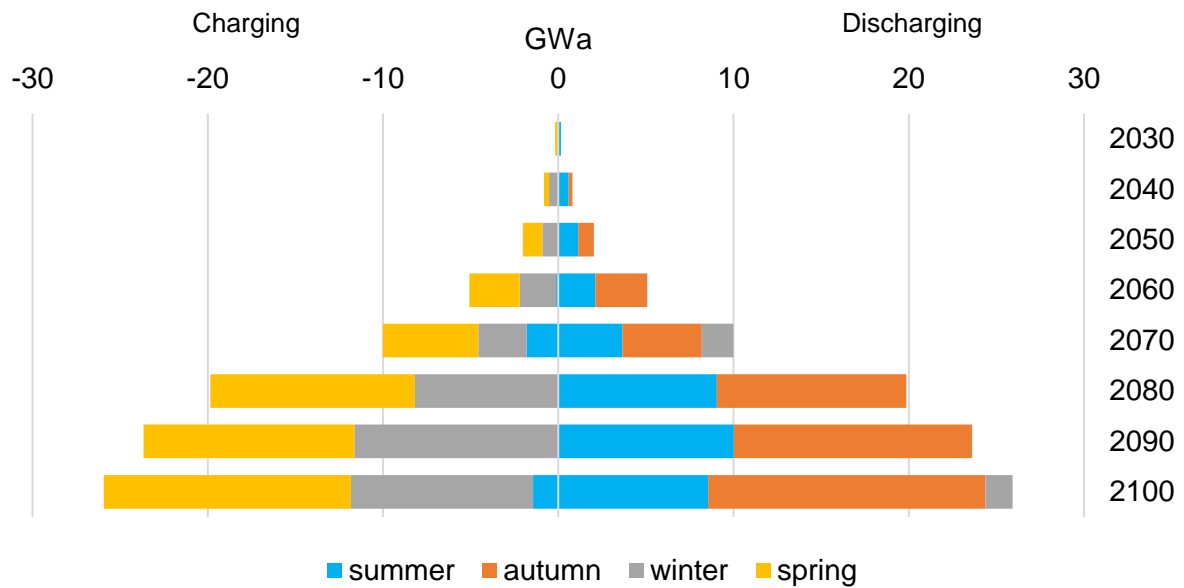
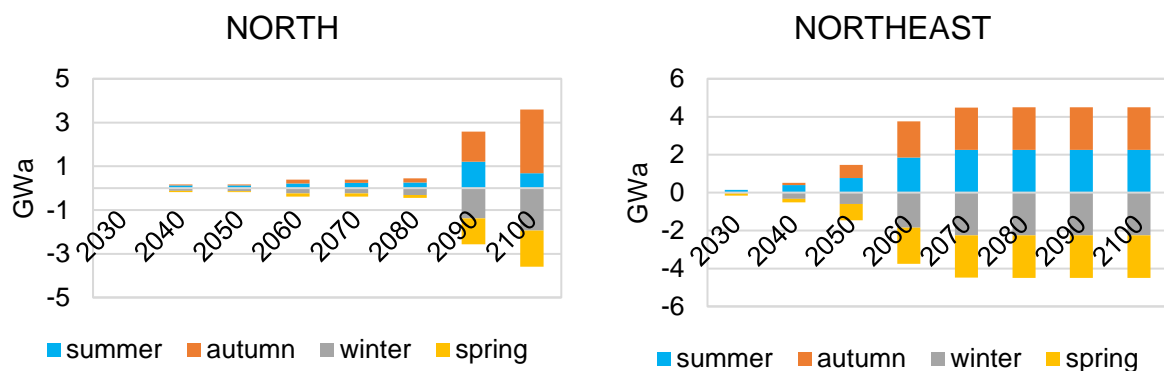


Figure E-16 - Total SPHS produced by season in the BESMM scenario RCP 8.5.

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-17.



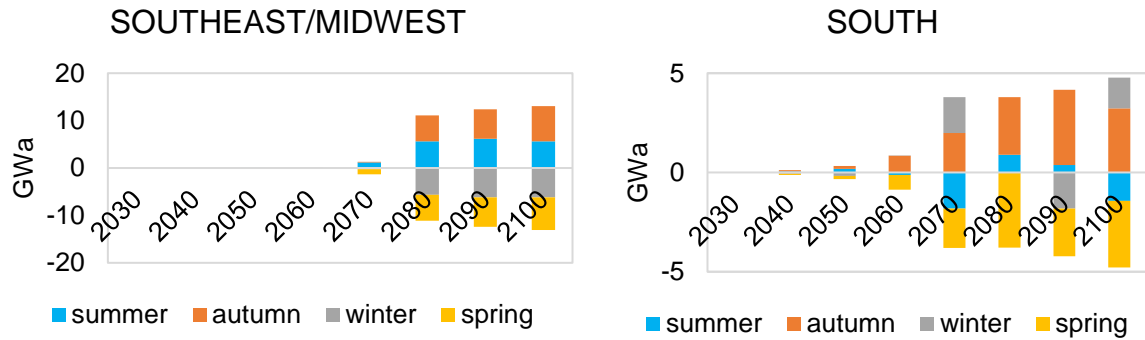


Figure E-17 - Total SPHS produced by season and by region in the BESMM scenario RCP 8.5

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-18.

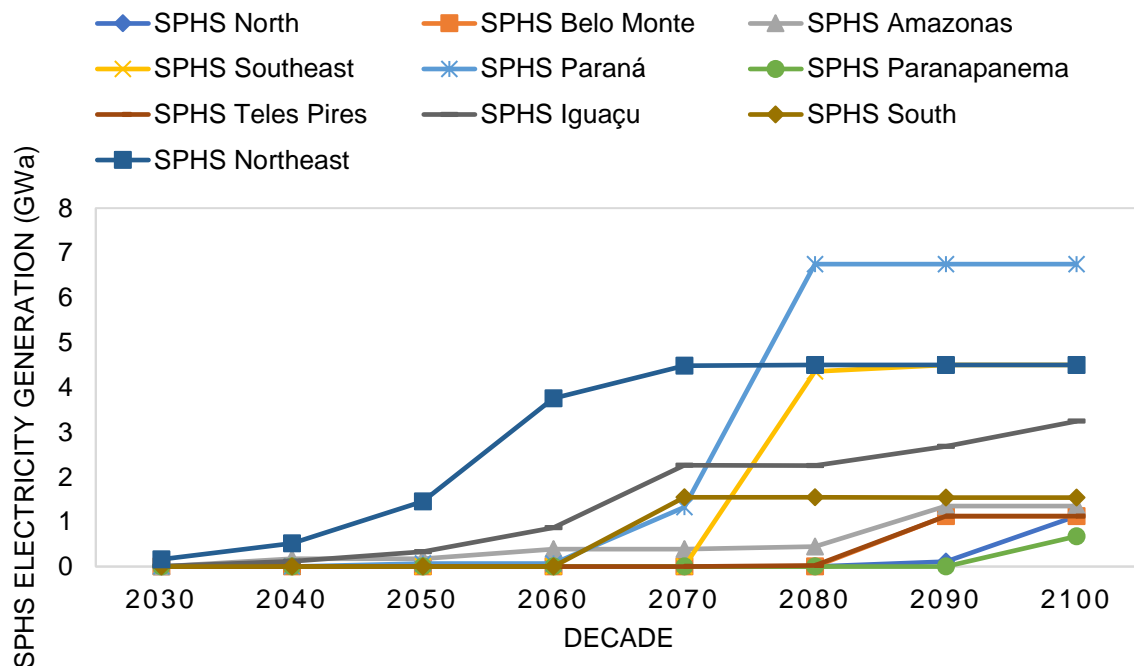


Figure E-18 - SPHS electricity generation (discharging) activities by technology for scenario RCP 8.5.

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-19.

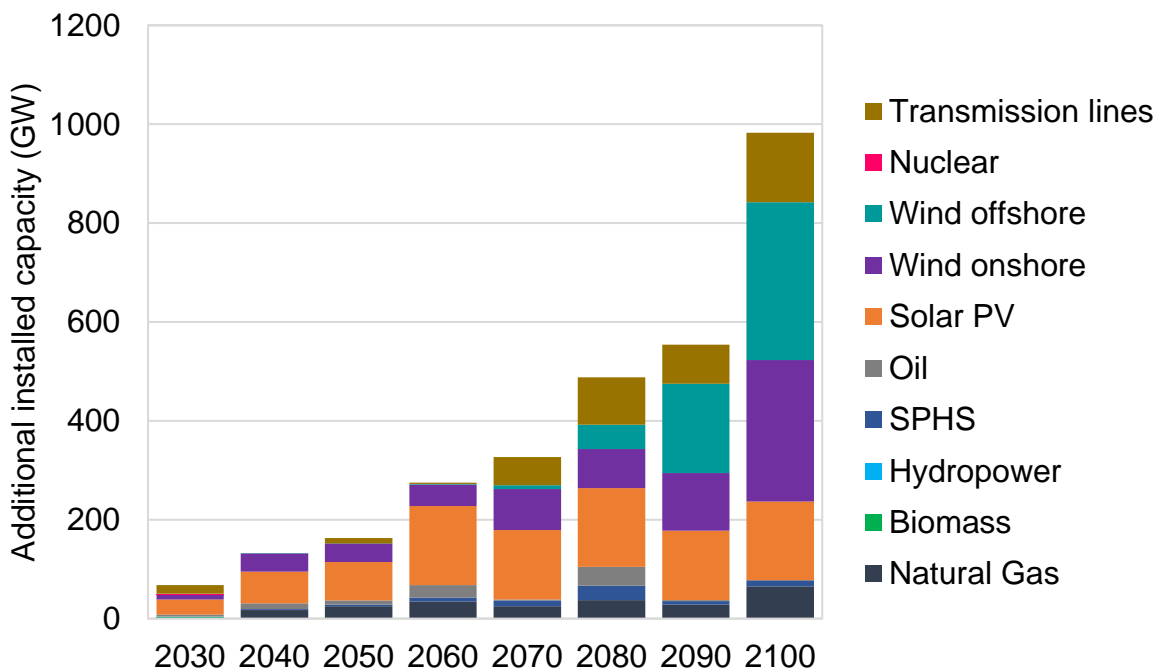


Figure E-19 - Additional installed capacity from 2030 up to 2100 for scenario 8.5.

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-20 illustrates the results of BESMM electricity generation activity under scenario RCP 8.5 without SPHS.

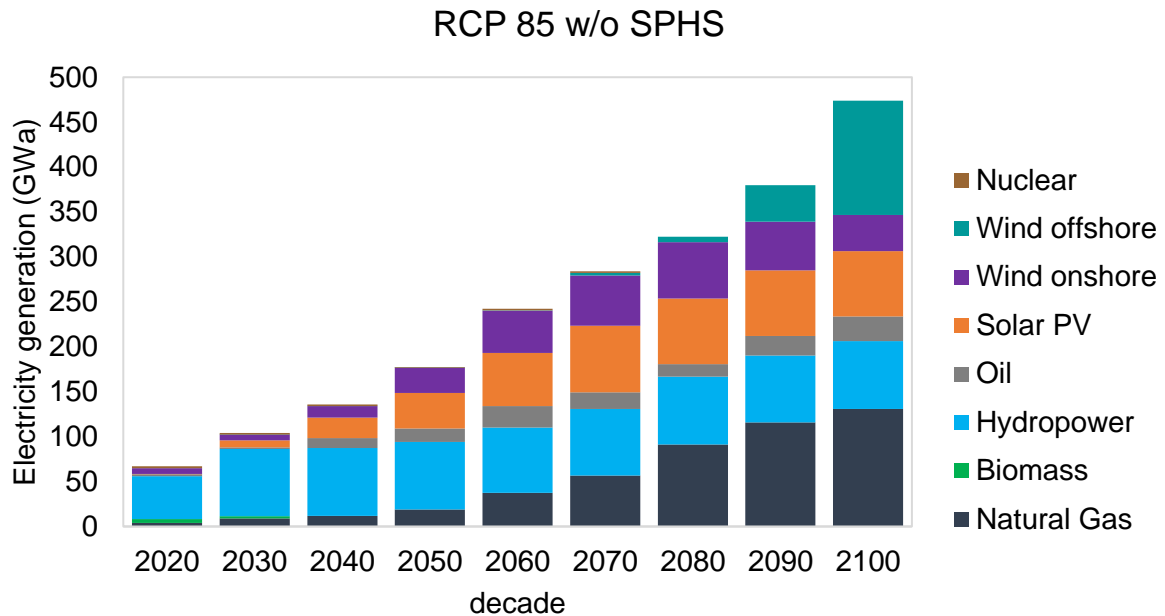


Figure E-20 - BESMM electricity generation activity up to 2100 for scenario RCP 8.5 w/o SPHS.

By 2100, it 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-21 compares the emissions along the years for both RCP 8.5 scenarios with and without SPHS technologies.

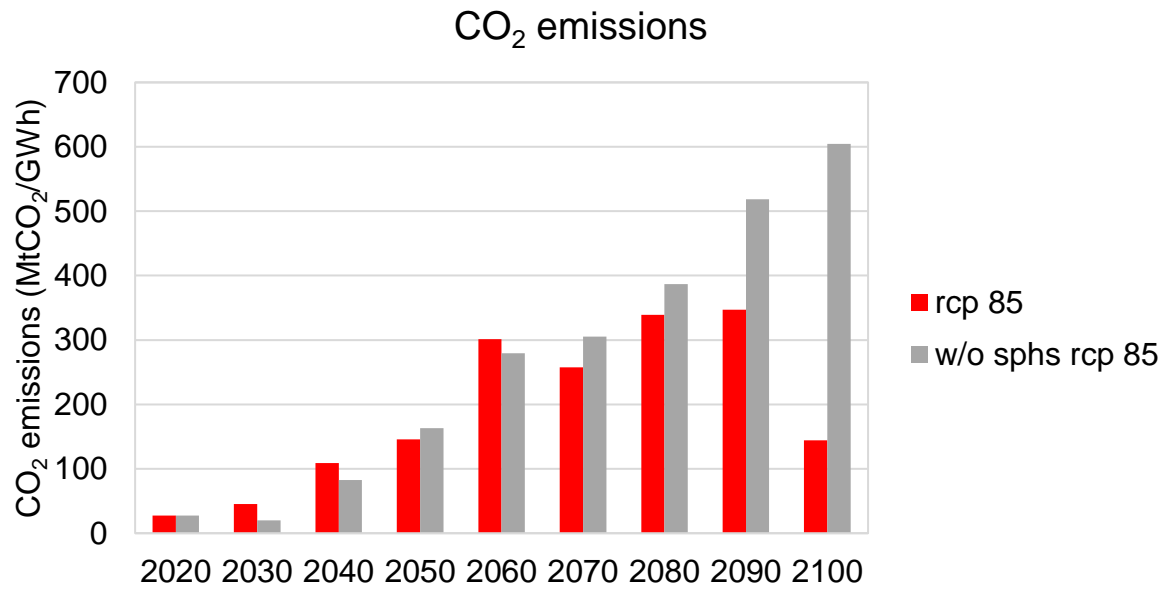


Figure E-21 - Total CO₂ emissions of RCP 8.5 scenario with and without SPHS technologies.

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.