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ScienceDirect
Energy Procedia 99 (2016) 89 – 107
Energy Procedia

10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, Düsseldorf, Germany

Hydropower and power-to-gas storage options: The Brazilian energy system case

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Abstract

In this study, a 100% renewable energy (RE) system for Brazil in 2030 was simulated using an hourly resolution model. The optimal sets of RE technologies, mix of capacities, operation modes and least cost energy supply were calculated and the role of storage technologies was analysed. The RE generated was not only able to fulfil the electricity demand of the power sector but also able to cover the 25% increase in total electricity demand due to water desalination and synthesis of natural gas for industrial use. The results for the power sector show that the total installed capacity is formed of 165 GW of solar photovoltaics (PV), 85 GW of hydro dams, 12 GW of hydro run-of-river, 8 GW of biogas, 12 GW of biomass and 8 GW of wind power. For solar PV and wind electricity storage, 243 GWh_{el} of battery capacity is needed. According to the simulations the existing hydro dams will function similarly to batteries, being an essential electricity storage. 1 GWh of pumped hydro storage, 23 GWh of adiabatic compressed air storage and 1 GWh of heat storage are used as well. The small storage capacities can be explained by a high availability of RE sources with low seasonal variability and an existing electricity sector mainly based on hydro dams. Therefore, only 0.05 GW of PtG technologies are needed for seasonal storage in the electricity sector. When water desalination and industrial gas sectors' electricity demand are integrated to the power sector, a reduction of 11% in both total cost and electric energy generation was achieved. The total system levelized cost of electricity decreased from 61 €/MWh to 53 €/MWh for the sector integration.

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy

Keywords: 100% renewable energy; Brazil; grid integration; solar PV; hydro dams; power-to-gas; economics.

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Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy
doi:10.1016/j.egypro.2016.10.101

1. Introduction

An energy mix that combines different renewable energy (RE) sources is the key for a regional economic and sustainable development. Brazil and most of the South American countries have not only an enormous potential for hydro, solar, wind and biomass energy generation but also a regulatory framework and low carbon initiatives that support the development of RE in the region [4]. In addition, due to the fact that Brazil is relying most in hydropower for electricity generation, the continuous modifications in the hydrological cycle and water regime in the drainage basis have been endangering the power supply in the country and an urgent need for the diversification of electricity generation sources has arisen [4,32]. According to the National Energy Balance [5], 75% of the electricity supply in Brazil comes from renewable sources, including 65% hydropower. However, in the last few years, renewable electricity auctions have increased the share of non-hydro renewable sources, such as wind and solar, in the country's energy mix. In 2014, 50% of the total installed capacity added in Brazil came from wind power [14], which has given the country the fourth position in the 2014 wind energy global ranking [31].

All the above mentioned facts have contributed to an acceleration in the development of a more diverse energy mix in Brazil, making the power sector less vulnerable to changes in the climate. In this context, this study has the objective to simulate 100% RE systems for Brazil in the year 2030 considering the optimal sets of RE technologies, mix of capacities, operation modes and least cost energy supply. Such systems will be CO_2 emission free and, consequently, contribute to limit global warming to 2°C. As energy storage technologies are essential for the renewable energy system, different types of storage technologies were considered. The tendency of future energy system towards electrification of all other energy using sectors is evident, and, therefore, the integration of the power, water desalination and industrial gas sectors and its synergetic effects on the 100% RE system was also studied.

2. Methodology

An energy system model based on linear optimization of energy system parameters under applied constraints was considered and a detailed description of the model can be found in [4] and [7]. The model is composed of a set of power generation and storage technologies that are used to supply the electricity demand of power, water desalination and synthetic natural gas (SNG) generation sectors.

2.1. Model Summary

The energy system model is based on a linear optimization of the system parameters under a set of applied constraints with the assumption of a perfect foresight of RE power generation and power demand. A multi-node approach enables the description of any desired configuration of power transmission interconnections among the sub-regions in which Brazil was divided. The main constraint for the optimization is to guarantee that for every hour of the year the total electric energy supply within the country covers the local demand from all considered sectors. This approach enables a precise system description including synergetic effects of different system components for the power system balance.

The target function of the system optimization is the minimization of the total annual energy system cost, calculated as the sum of the annual costs of installed capacities of the different technologies, costs of energy generation and generation ramping. The system also includes distributed generation and self-consumption of residential, commercial and industrial electricity consumers (prosumers) by installing respective capacities of rooftop PV systems and batteries. For these prosumers the target function is minimal cost of consumed energy calculated as the sum of self-generation, annual cost and cost of electricity consumed from the grid, minus benefits from selling of excess production.

The full description of the model, its input data including RE resources and technical assumptions can be found in [4] and [7]. All the input data can be found in the Appendices of this paper.

2.2. Applied technologies

The technologies applied in the energy system optimization can be classified into four main categories: conversion of RE resources into electricity, energy storage, energy sector bridging (for definition, see later), and electricity transmission.

The technologies for converting RE resources into electricity applied in the model are ground-mounted (optimally tilted and single-axis north-south oriented horizontal continuous tracking) and rooftop solar PV systems, concentrating solar thermal power (CSP), onshore wind turbines, hydro power (run-of-river and dams), biomass plants (solid biomass and biogas), waste-to-energy power plants and geothermal power plants.

The energy storage technologies used in the model are battery storage, pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES) and power-to-gas (PtG) technology. PtG includes synthetic natural gas (SNG) synthesis technologies: water electrolysis, methanation, CO_2 scrubbing from air, gas storage, and both combined and open cycle gas turbines (CCGT, OCGT). SNG synthesis process technologies have to be operated in synchronization because of hydrogen and CO_2 storage absence. Additionally, there is a 48-hour biogas buffer storage and a part of the biogas can be upgraded to biomethane and injected into the gas storage.

The energy sector bridging technologies provide more flexibility to the entire energy system, thus reducing the overall cost. One bridging technology available in the model is PtG technology for the case that the produced gas is consumed in the industrial sector and not as a storage option for the electricity sector. The second bridging technology is seawater reverse osmosis (SWRO) desalination, which couples the renewable water production to the electricity sector.

For electricity transmission, inter-regional transmission grids are modelled by applying high voltage direct current (HVDC) technology. Electricity distribution grid is not considered. Power losses in the HVDC grids consist of two major components: length dependent electricity losses of the power lines and losses in the converter stations at the interconnection with the AC grid.

An energy system mainly based on RE and in particular intermittent solar PV and wind energy requires different types of flexibility for an overall balanced and cost optimized energy mix. The four major categories of flexibility are generation management (e.g. hydro dams or biomass plants), demand side management (e.g. PtG, SWRO desalination), storage of energy at one location and energy shifted in time (e.g. batteries), and transmission grids connecting different locations and energy shifted in location (e.g. HVDC transmission).

The full model block diagram is presented in Fig. 1.

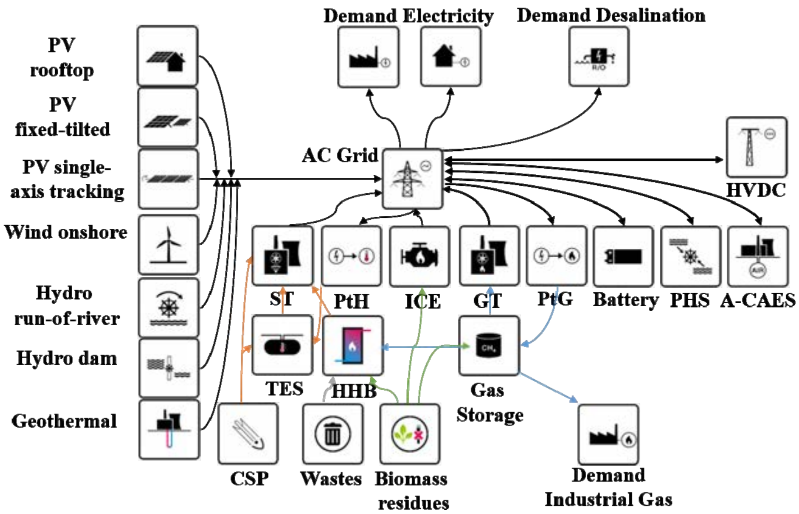


Fig. 1. Block diagram of the energy system model.

2.3. Financial and technical assumptions

The model optimization is carried out on an assumed cost basis and technological status for the year 2030 and the overnight building approach as typically applied for nuclear energy [10]. The financial assumptions for capital expenditures (capex), operational expenditures (opex) and lifetimes of all components are provided in the Appendix A. The investment cost (capex) and operation and maintenance cost (opex) numbers refer in general to a kW of electrical power, in case of water electrolysis to a kW of hydrogen thermal combustion energy, and for CO_2 scrubbing, methanation and gas storage to a kW of methane thermal combustion energy. Efficiencies of water electrolysis, CO_2 scrubbing and methanation refer to the lower heating value of hydrogen and methane, respectively. The financial assumptions for storage systems refer to a kWh of electricity, and gas storage refers to a thermal kWh of methane at the lower heating value. Financial numbers for HVDC transmission lines and converter stations are given for the net transmission capacity (NTC).Weighted average cost of capital (WACC) is set to 7% for all scenarios, but for residential PV self-consumption WACC is set to 4%, due to lower financial return requirements. The technical assumptions concerning power to energy ratios for storage technologies, efficiency numbers for generation and storage technologies, and power losses in HVDC power lines and converters are provided in the Appendices B, C and D.

Simulation scenarios assume that up to 20% of commercial, residential and industrial consumers can install their own power generation capacities based on PV generation and Li-Ion batteries to reach minimal cost of annual power consumption. Electricity prices for residential (250 €/MWh), commercial (220 €/MWh) and industrial (190 €/MWh) consumers for the year 2030 are taken from [16]. As the electricity price is on a country basis, it is assumed that the sub-regions' electricity prices have the same value. Excess generation, which cannot be self-consumed by the solar PV prosumers, is assumed to be fed into the grid for a transaction cost of 2 €cents/kWh. Prosumers cannot sell to the grid more power than their own annual consumption.

2.4. Scenarios assumptions

Brazil was divided into five different sub-regions according to area, population and national grid connections: South, São Paulo, Southeast, North, and Northeast. The regional energy systems are interconnected by HVDC grids allowing sub-regions with better renewable resources to export electricity to sub-regions with moderate ones.

In this study, two different scenarios with different energy systems were considered: i) a country wide open trade scenario energy system in which RE generation and energy storage technologies cover the interconnected country's power sector electricity demand; ii) an integrated scenario in which the demand for SWRO desalination and industrial natural gas is integrated to the country wide energy system. In this scenario, RE sources combined with PtG technology are used not only as electricity generation and storage options within the system, but also as energy sector bridging technologies to cover water desalination and industrial natural gas demand, increasing the flexibility of the system.

The sub-regions' division and national grid configuration applied in the model are presented in Fig. 2b. The current grid configuration of the country considers four different subsystems: 'Norte Interligado' (North interconnected), 'Nordeste' (Northeast), 'Sudeste/Centro-Oeste' (Southeast/Center-west) and 'Sul' (South) [26] according to Fig. 2a. The model grid interconnections are based on Brazil's current national grid although the model's sub-regions division does not permit that the modelled system represents accurately the current system. In addition, load centres were determined for each sub-region in the model according to population density and economic importance. The load centres for South, São Paulo, Southeast, North and Northeast sub-regions are, respectively: Curitiba, São Paulo, Rio de Janeiro, Brasília and Salvador and represent the interconnection point of the grid with others sub-regions. From the load centres, alternating current grids (AC), which are not part of the model, collect and distribute electricity within the sub-regions.

Fig. 2. (a) Current grid configuration in Brazil [26] ; (b) Brazil's sub-regions and HVDC transmission lines configuration in the studied model.

2.5. Upper and Lower limitations on installed capacities

Lower and upper limits are applied to renewable energy sources (PV ground-mounted, wind turbines, and hydro power) and pumped hydro storage. For CSP, waste-to-energy power plants, gas turbines, battery and gas storage, and units of the power-to-gas process, the lower limit is set to zero.

For lower limitations of PV ground-mounted systems, wind power plants, hydropower plants, biomass, biogas and PHS storage systems, data of existing installed capacities in Brazilian sub-regions have been taken from [14]. Lower limits on already installed capacities in Brazilian sub-regions are summarized in Appendix H.

Upper limits for CSP, PV ground-mounted systems, and wind power plants are based on land use limitations and the density of capacity. The maximum area covered by solar systems is set to 6% of the total sub-regions' territory and for wind power plants to 4%. The capacity densities for the CSP solar field is 225 MW_{th}/km^2, 75 MW/km^2 for PV ground-mounted systems, and 8.4 MW/km^2 for wind onshore power plants. Maximum installable capacities are computed by applying Equations (1.1) and (1.2), dimensionless distance constants (d_1, d_2) are set to $d_1 = 5$ and $d_2 = 7$ [15,19,20].

$$Cap_{wind} = area_{total} \cdot limit_{wind} \cdot \frac{P}{(d_1 \cdot d_2 \cdot d_{rot}^2)} \tag{1.1}$$

$$Cap_{solar} = area_{total} \cdot limit_{solar} \cdot (\eta_{solar} \cdot GCR \cdot I_{STC}) \tag{1.2}$$

Equations (1.1) and (1.2) describe the maximum installable capacities for PV and wind. Abbreviations: maximum installable capacity (Cap), area of sub-region ($area_{total}$), land use limitation (limit) of 6% for PV and 4% for wind, power of reference wind turbine (P) of 3 MW, rotor diameter of reference wind turbine (d_{rot}) of 101 m, dimensionless distance constants d_1 and d_2 are set to $d_1 = 5$ and $d_2 = 7$, PV system efficiency (η_{solar}) of 15%, ground cover ratio (GCR) of 0.5 [27] and irradiation under standard test conditions (ISTC) of 1 kW/m^2.

For hydro power plants and PHS storage, upper limits are set to 150% and 200% of already installed capacities by the end of 2014. All upper limits of installable capacities in Brazilian sub-regions are summarized in Appendix I.

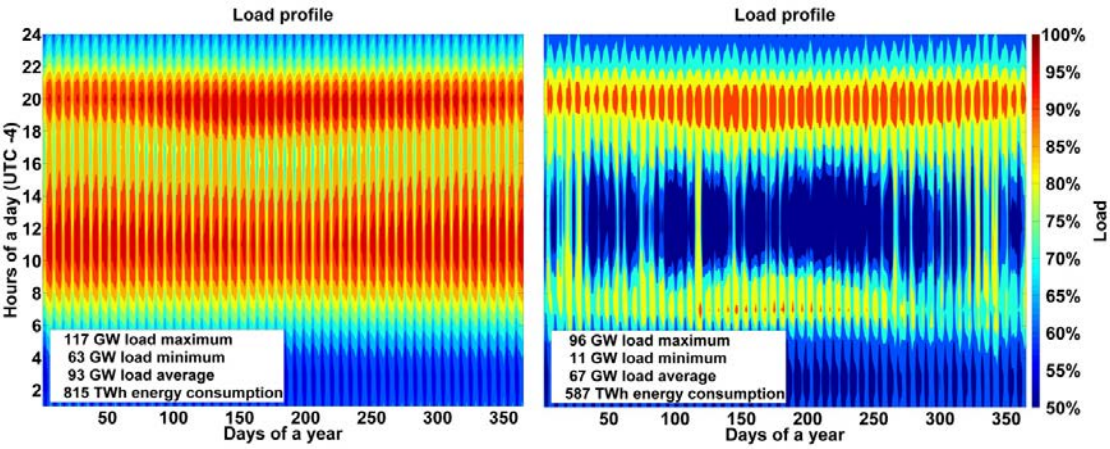


Fig. 3. (a) Aggregated load curve for country wide scenario without prosumers influence; (b) system load curve with prosumers influence for integrated scenario for the year 2030.

For all other technologies, upper limits are not specified. However, for biogas and waste-to-energy plants it is assumed, due to energy efficiency reasons, that the available and specified amount of the fuel (Appendix F) is used during the year.

2.6. Load

The demand profiles for sub-regions are computed as a fraction of the total country demand based on synthetic load data weighted by the sub-regions' population. Fig. 3 represents the area-aggregated demand of all sub-regions in Brazil for the country wide scenario without the impact of PV self-consumption prosumers (Fig.3a) and load data for the same scenario considering PV self-consumption prosumers (Fig.3b). Electricity demand increase by the year 2030 is estimated using IEA data [23]. Solar PV self-consumption prosumers have a significant impact on the residual load demand in the energy system as depicted in Fig. 3b. The overall electricity demand and the peak load are reduced by 28% and 17.9%, respectively.

Industrial gas demand (gas demand excluding electricity generation and residential sectors) and desalinated water demand for Brazilian sub-regions are presented in Appendix J. Gas demand values are based on the IEA data [24] and their distribution within the sub-regions is based on industry distribution per region [22]. Desalination demand numbers are based on water stress and water consumption projection [9].

3. Results

3.1. Brazil's optimized energy system structure and costs

For the two studied scenarios, cost minimized electrical energy system configurations are derived for the given constraints and characterized by optimized installed capacities of RE electricity generation, storage and transmission for every modelled technology, leading to respective hourly electricity generation, storage charging and discharging, electricity export, import, and curtailment. The average financial results of the two different scenarios for the total system (including PV self-consumption and the centralized system) are expressed as levelized cost of electricity (LCOE), levelized cost of electricity for primary generation (LCOE primary), levelized cost of curtailment (LCOC), levelized cost of storage (LCOS), levelized cost of transmission (LCOT), total annualized cost, total capital expenditures, total renewables capacity and total primary generation, as presented in Table 1.

From the financial results presented in Table 1, it can be observed that the total LCOE for both analysed scenarios is quite low and competitive for 100% RE energy systems for Brazil in the year 2030. Considering the two different studied scenarios, a decrease in total LCOE of 12.6% can be observed in the integration scenario due to a reduction of all analysed levelized costs, except for transmission costs. LCOE for primary generation, LCOC and LCOS decreased in 8.2%, 47.0% and 29.7%, respectively, as a result of an increase in the utilization of low-cost wind and solar electricity for SNG production, an increase in the flexibility of the system, and a better utilisation of mid-term storage. LCOT increased in 30.8% due to a higher utilization of HVDC grids. SNG producing sub-regions tend to increase the intra-regional electricity generation to fulfil the increased demand. Therefore, sub-regions with moderate renewable resources, such as South, São Paulo and Southeast, have to import electricity from regions with the best renewable resources for SNG production, increasing the need for HVDC grids. However, the impact of transmission costs on total cost is rather low. The system total annual cost and capex increased from 51 b€ to 62 b€ and from 401 b€ to 508 b€, respectively. The total RE installed capacities increased from 290 GW to 401 GW in order to generate 249 TWh (+29%) for SWRO desalination and industrial natural gas production.

Concerning RE installed capacities, Table 2 shows that from all installed RE technologies, PV optimally tilted, PV single-axis tracking, wind, biogas power plants, hydro run-of-river (RoR) and hydro dams present different installed capacities in both scenarios. In order to fulfil the extra electricity demand of SWRO desalination and industrial natural gas production, 106.6 GW (+64%) of total PV and 8.6 GW (+109%) of wind energy are needed. Despite the existence of other RE resources in Brazil, the total installed capacities of other renewable sources presented an insignificant change considering the integrated scenario. According to the energy model results, solar and wind seemed to be more profitable technologies given the regions' available resources. The high share of solar PV can be explained by the fact that this is the least cost RE source for Brazil, as a consequence of assuming a fast cost reduction of solar PV and battery storage in the next fifteen years [21,34]. For biogas, in the integrated scenario, instead of using it for electricity generation, a fraction of 51% of the total biogas used in biogas power plants in the country wide scenario is re-allocated from the electricity sector to the industrial gas demand for efficiency reasons. For the sub-region Brazil Northeast, most of the 26.8 TWh industrial gas demand is supplied by biogas plants since only 0.05 TW_{el} is needed for PtG (Appendix J).

In terms of storage, the low installed capacities can be explained by the fact that Brazil has a high availability of RE sources with low seasonal variability and an existing electricity sector mainly based on hydro dams. Hydropower can store potential energy in reservoirs, providing firm capacity for intermittent renewables [32]. In the integrated scenario, an increase in the total installed capacity for short and mid-term electricity storage is observed due to the addition of total PV and wind installed capacities. Thermal energy storage and A-CAES increased by 164.3% and 40.3%, respectively. On the other hand, 25.1 GW_{el} of PtG electrolysers, which were not needed for electricity storage in the country wide scenario, are installed for industrial natural gas production.

Table 1. Financial results for the country wide and integrated scenarios in Brazil.

	Total LCOE	LCOE primary	LCOC	LCOS	LCOT	Total ann. cost	Total capex	RE capacities	Generated electricity
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[b€]	[b€]	[GW]	[TWh]
Country wide	61.1	46.3	1.7	11.8	1.3	51	401	290	859
Integration scenario	53.4	42.5	0.9	8.3	1.7	62	508	401	1108

Table 2. Overview on installed RE technologies and storage capacities for the studied scenarios.

		Country wide	Integration scenario	Relative change (%)
PV self-consumption	[GW]	152.0	152.0	0
PV optimally tilted	[GW]	0.2	0.1	-50
PV single-axis tracking	[GW]	13.1	119.8	+814.5
PV total	[GW]	165.3	271.9	+64.5
CSP	[GW]	0	0	0
Wind energy	[GW]	7.9	16.5	+108.9
Biogas power plants	[GW]	7.7	3.9	-49.3
Biomass power plants	[GW]	11.7	11.7	0
MSW incinerator	[GW]	0.2	0.2	0
Geothermal energy	[GW]	0	0	0
Hydro Run-of-River	[GW]	12.0	11.1	-7.5
Hydro dams	[GW]	85.3	86.0	+0.8
Battery PV self-consumption	[GWh]	243.3	243.3	0
Battery total	[GWh]	243.5	243.6	0
PHS	[GWh]	1.1	1.2	0
A-CAES	[GWh]	23.1	32.4	+40.2
TES	[GWh]	1.4	3.7	+164.3
PtG electrolysers	[GW_{el}]	0.05	25.2	+50300
CCGT	[GW]	7	0.1	-98.6
OCGT	[GW]	0.03	0.03	0
Steam Turbine	[GW]	0.1	0.1	0

Table 3. Total LCOE components in all sub-regions.

Country wide	LCOE primary [€/MWh]	LCOC [€/MWh]	LCOS [€/MWh]	LCOT [€/MWh]	LCOE total [€/MWh]	export (-)/ import (+) [%]
Country average	46.3	1.7	11.8	1.3	61.1	-
South	56.0	0.02	10.6	1.2	67.8	4.1
São Paulo	44.4	0.05	10.8	0.7	56.1	6.5
Southeast	44.4	0.2	15.7	2.0	62.3	16.2
North	46.9	7.3	8.6	2.7	65.5	-27.9
Northeast	41.1	0.9	14.0	0	56.0	0
Integrated scenario	**LCOE primary [€/MWh]**	**LCOC [€/MWh]**	**LCOS [€/MWh]**	**LCOT [€/MWh]**	**LCOE total [€/MWh]**	**export (-)/ import (+) [%]**
Country average	42.5	0.9	8.3	1.7	53.4	-
South	46.9	1.1	7.5	1.2	56.7	10.2
São Paulo	39.0	0.4	7.7	1.0	48.2	5.2
Southeast	41.6	0.4	10.3	2.3	54.7	16.0
North	46.8	1.7	6.7	3.7	58.8	-33.8
Northeast	40.3	1.3	10.0	0.7	52.3	-6.2

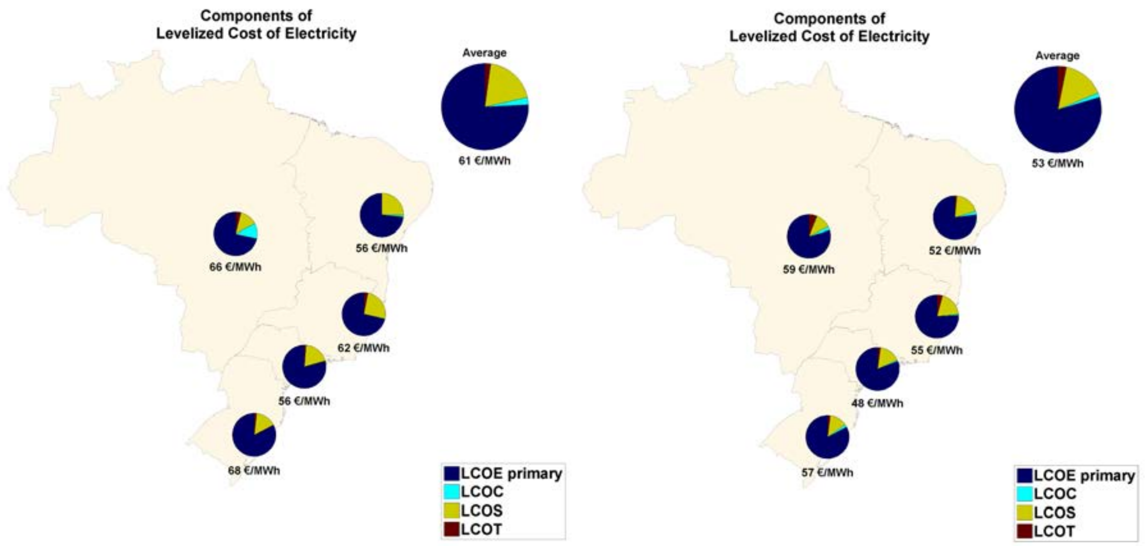


Fig. 4. LCOE components for (a) country wide and (b) integrated scenarios in a sub-region analysis.

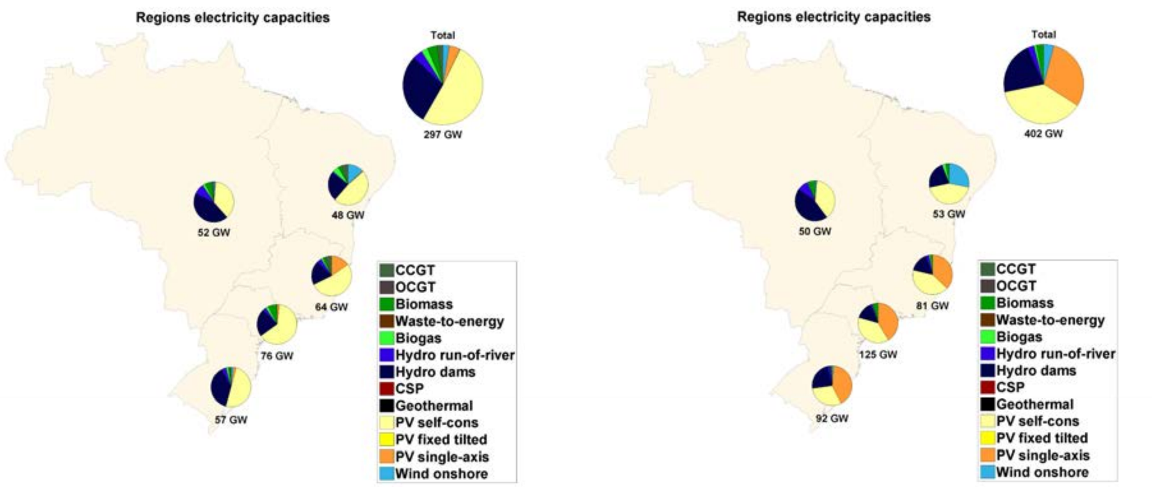


Fig. 5. RE Installed capacities for (a) country wide and (b) integrated scenarios in a sub-region analysis.

3.2. Optimized energy system structure and costs in a sub-region analysis

In order to better understand the 100% RE system in each different Brazilian sub-region, the numeric values for LCOE components and RE installed capacities in all sub-regions are presented in Fig.4, Fig. 5 and Table 3.

The sub-regions' LCOE change significantly according to the analysed scenario: the addition of least cost PV or wind installed capacities for water desalination and industrial gas demand (Fig. 5) decreases the LCOE of primary generation, especially for the regions with higher demand of industrial gas . For the country wide scenario, South and Northeast regions are the sub-regions with the highest and lowest LCOE, respectively. A high percentage of hydro dams in the South sub-region's energy mix increase the LCOE of primary generation. Hydro dams have a high LCOE and low full load hours (FLH) for this specific sub-region, increasing its total LCOE. For the Northeast region, a high share of the least cost RE technologies (solar and wind) diminishes the LCOE of primary generation. Moreover, the high diversity of the region's energy mix that includes not only solar and wind but also biogas, biomass, hydro RoR and hydro dams, balances the region's electricity generation and contributes to low curtailment and transportation costs.

Considering the integrated scenario, when additional PV and/or wind installed capacities are included in most of the sub-regions' energy mix, different LCOE values are found, with North and São Paulo having the highest and lowest LCOE, respectively. The North region has some peculiarities: fairly higher values for LCOE of primary generation, LCOC and LCOT, which can be explained by the region's high share of already existing hydropower plants, low electricity and industrial gas demand and great distance from the rest of the country. However, when SWRO desalination and industrial gas demand are integrated to the power sector, the additional flexibility of the system significantly decreases curtailment costs by 76.7% for the North region although an increase in its transportation costs of 37.0% is observed. São Paulo has the highest population, electricity and natural gas demand, and, therefore, the highest installed capacities of the least cost RE sources: PV self-consumption by prosumers and PV ground-mounted. In addition, both LCOC and LCOT are relatively low for this sub-region since it is consuming most of the electricity that is produced and it is quite close to other regions of the country such as North and Southeast from which electricity can be imported/exported.

The country's sub-regions can be divided into net exporters and net importers according to the availability of its best renewable resources. The share of export is defined as the ratio of net exported electricity to the generated primary electricity of a sub-region and the share of import is defined as the ratio of imported electricity to the electricity demand. The area average is composed of sub-regions' values weighted by the electricity demand. The classification of sub-regions as net importers/exporters does not change according to the studied scenarios, with South, São Paulo and Southeast being importing sub-regions, and North and Northeast being exporting sub-regions. In spite of that, the share of electricity being imported/exported has varied in each sub-region: the imported electricity increases 6.1% for the South sub-region, since this sub-region has a high demand for natural gas and lower FLH for PV ground-mounted, which increases electricity imported from the North region; decreases 1.3% for São Paulo because in the integrated scenario total installed capacities of RE increase by 64.5% increasing the system's flexibility and diminishing the need for importing electricity; and increases the electricity export 5.9% and 6.2% for the North and Northeast sub-regions, respectively, in order to attend the importing regions' higher demand.

When RE installed capacities are analysed for the different scenarios, it is clearly evident that the introduction of an additional electricity demand for SWRO desalination and industrial gas production modifies the entire system structure of all the studied sub-regions. This happens because of shifting optimal cost structure parameters and areas being confronted with their upper resource limits. The regions with higher industrial gas demand, such as South, São Paulo and Southeast, present an increase in PV total installed capacities by 124%, 102% and 46%, respectively. On the contrary, in the Northeast sub-region, wind installed capacities increased by 143% due to the fact that this sub-region has excellent wind conditions and, therefore, low cost wind energy. For the North sub-region, slight reductions in PV single-axis, wind, hydro RoR and biogas have decreased the sub-region's total installed capacity by 2 GW.

3.3. Energy flow in the 100% RE power system

The findings for the integrated scenario can be summarized in an energy flow diagram comprised of the primary RE generation, the energy storage technologies, HVDC transmission grids, total demand of each sector and losses. Potentially usable heat and ultimate system losses consist of the difference of primary power generation and final electricity demand. Both are comprised of curtailed electricity; heat produced by biomass, biogas and waste-to-energy power plants; heat of transforming power-to-hydrogen in the electrolysers, hydrogen-to-methane in methanation and methane-to-power in the gas turbines; and the efficiency losses in A-CAES, PHS, battery storage, as well as by the HVDC transmission grid. This energy flow for the integrated system is presented in Fig. 6.

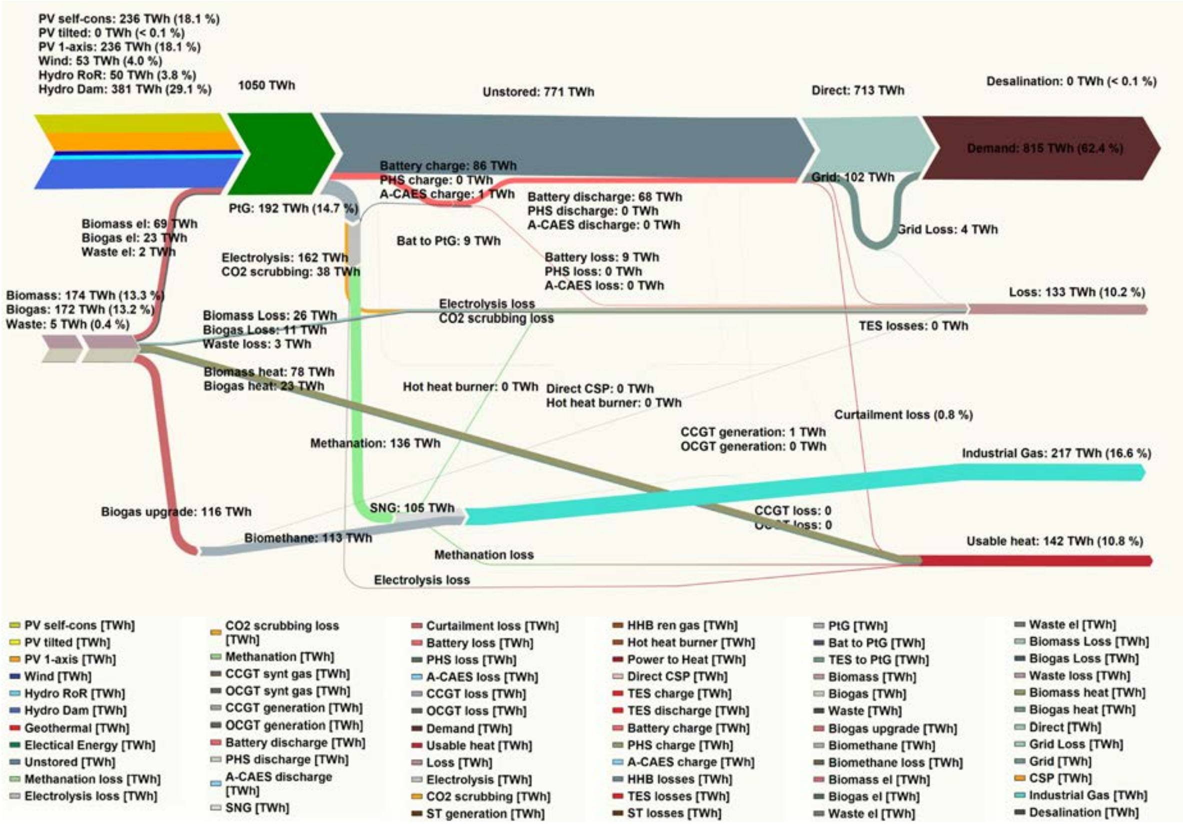


Fig. 6. Energy flow of the system for the integrated scenario.

4. Discussion

According to the results found for 100% RE systems for Brazil in the year 2030, it can be concluded that the region has a huge potential for RE generation and for a global climate change mitigation contribution. The LCOE of 61.1 €/MWh and 53.4 €/MWh for the country wide and integration scenarios, respectively, suggest that among the alternatives for achieving a low carbon based energy system, RE options are the most competitive and least-cost solution. The LCOEs for other alternatives are about 65-160% higher than the results found on this study: 112 €/MWh for new nuclear (assumed for 2023 in the UK and Czech Republic), 112 €/MWh for gas CCS (assumed for 2019 in the UK) and 126 €/MWh for coal CCS (assumed for 2019 in the UK) [1].

In terms of installed capacities, PV technologies have the highest share in GW, representing 56.9% and 67.7% of the total RE installed capacities in country wide and integrated scenarios. These results are in accordance with the fact that PV technologies have well distributed FLH all over the sub-regions and are the least cost RE technology in most of the cases. Besides, the installation of distributed small-scale and centralized PV plants is already profitable in numerous regions in the word and PV electricity generation cost tends to decrease even more in the coming years [8,34], especially in regions with high PV FLH. In Brazil, tax exemptions for solar electricity and solar components have already been introduced by many states, such as Pernambuco, Minas Gerais, Tocantins, São Paulo and Rio de Janeiro, and will be crucial for the development of the solar market in the country [29,30].

On the other hand, in terms of TWh of electricity production, hydropower continues to dominate in the electricity sector due to the already existing hydropower plants. The new configuration of the energy system, however, is capable of solving the vulnerability of the existing power sector to a changing hydrological profile: a high share of other complementary renewable sources will diminish the dependency on hydropower plants leading to the least-cost solution for the problem under the given constraints. Hydropower generation (in TWh) would be reduced from 77% [5] to a range of 50-39% (for the given scenarios) in the country's energy mix.

The findings for Brazil that only 0.05 GW of PtG technology is needed in the power sector for 100% RE represents a singularity among all large regions in the world investigated so far with this methodology. The average ratio of electrolysers to the total installed power generation capacity in a geographical fully integrated region reaches 2.9% for Eurasia [6], 3.5% for Northeast Asia [7], 0.6% for Southeast Asia [18], 1.7% for India/SAARC [17], 1.3% for Sub-Saharan Africa [3] and 0.02% for Brazil. The ratio of hydro dams to the total installed power generation capacity reaches 16.9% for Eurasia, 3.1% for Northeast Asia, 5.6% for Southeast Asia, 3.0% for India/SAARC and 5.3% for Sub-Saharan Africa, but 29.4% for Brazil. Seasonal variations with a respective impact on the generation profile of PV and wind power plants, and also on the load demand, seems to be the decisive factor for a higher required PtG capacity. This is the case not only for Northeast Asia and Eurasia but also for India/SAARC, due to the monsoon period, and for Sub-Saharan Africa, due to the rainy season. Southeast Asia shows the same stable equatorial conditions as Brazil and requires also low PtG capacities. The role of hydro dams, which can also balance seasonal variations in generation and demand characteristics, comparable to PtG technology, seems to be less dominating than the seasonal effect, since the rather high share of hydro dams in Eurasia cannot compensate fully the seasonal demand and RE generation. However, in Brazil hydro dams are able to fully balance the remaining generation and demand fluctuations due to their very high share in the generation mix.

The integrated scenario is considered for the reason that both newly integrated sectors require only electricity to cover projected natural gas demand (except the gas demand for power generation and residential purposes that are not considered in this study) and renewable water demand by SNG generation and SWRO desalination, respectively. In parallel with supplying demand, such integration gives the system additional flexibility, especially for seasonal fluctuation compensation. The availability of RE in Brazil is sufficient to cover additional electricity demand for producing 217 TWh_{LHV} of SNG and 8.7 million m^3 of renewable water. Adding 249 TWh_{el} for gas synthesis and SWRO desalination requires additional RE capacities of 106.6 GW of PV and 8.6 GW of wind energy. An integration benefit can be observed: if both water and industrial gas sectors were considered separately from the power sector an increase in about 7 b€ of the annual system cost would occur. In addition, the integration decreases the electricity generation by 140 TWh and the curtailed electricity by 11 TWh. These benefits account for a reduction of 11% in total cost and electricity generation and 34% in curtailed electricity, compared to the non-integrated system. Further, the cost of renewable water seems to be quite affordable at 1.4 €/m^3 and the cost of electricity decreases by 13% to 53 €/MWh for the integrated scenario compared to the country wide scenario without sector integration. However, the cost of synthetic gas, at 71.1 €/MWh_{LHV}, appears to be significantly higher than the current price.

5. Conclusions

For the year 2030, RE technologies can generate enough energy to fulfil all electricity demand in Brazil on a price level of 48 - 68 €/MWhel, depending on geographical position and sectoral integration. The electricity demand of other sectors, such as industrial natural gas and SWRO desalination, can be produced by RE sources as well, providing the region 100% renewable synthetic natural gas and renewable water supply. However, government regulation and/or subsidies are still needed to ensure the financial viability of this synthetic fuel: the synthetic gas price of 71 €/MWh_{LHV} is substantially higher than 5-25 €/MWh_{LHV}, which is the price level of natural gas over the last 10 years in Brazil [5].

In Brazil a 100% RE system in the power sector can be run with extremely low seasonal storage based on PtG technology, which seems to be a singularity in the world, since for all other regions in the world for which comparable studies had been carried out respective PtG capacities are always required ranging typically in the order of 1.5 - 3.5% of the total installed power generation capacity (except Southeast Asia with 0.6%). The key reason for the special conditions in Brazil is not only the equatorial weather conditions but also the very high share of hydro dams which can flexibly balance generation and demand over the entire year for which typically PtG technology is need in other regions in the world.

When the electricity demand of other sectors is included in the energy system, an integration benefit can be achieved since in parallel with supplying demand, such an integration gives the system additional flexibility, especially for seasonal fluctuation compensation. For the studied integrated scenario the response of the energy system to additional electricity demand displaced SNG storage to SNG generation as seasonal storage for the electricity sector. Instead of applying gas turbines for regulating power supply the system curtails SNG generation for industrial gas use as a major source of flexibility. In such a system the role of SNG turns upside down: from regulating generation to regulating load.

In order to better understand the findings for a new and 100% RE system for Brazil, a fully integrated renewable energy system has to be simulated and deeply studied. However, this research work indicates that a 100% renewable resources-based energy system is a real low cost option for a not-too-distant future and that Brazil can have a crucial role in addressing climate change.

Acknowledgements

The authors gratefully acknowledge the public financing of Tekes (Finnish Funding Agency for Innovation) for the 'Neo-Carbon Energy' project under the number 40101/14 and CNPq (Brazil Council for Scientific and Technological Development). The authors would like to thank Svetlana Afanasyeva, Arman Aghahosseini and Michael Child for helpful support.

Appendix A. Financial assumptions for energy system components [2,9,13,21,25,28,33,34]

Technology	Capex [€/kW]	Opex fix [€/(kW·a)]	Opex var [€/(kWh)]	Lifetime [a]
PV optimally tilted	550	8	0	35
PV single-axis tracking	620	9	0	35
PV rooftop	813	12	0	35
Wind onshore	1000	20	0	25
CSP (solar field)	528	11	0	25
Geothermal	4860	87	0	30
Hydro run-of-river	2560	115.2	0.005	60
Hydro dam	1650	66	0.003	60
Water electrolysis	380	13	0.0012	30
Methanation	234	5	0.0015	30
CO_2 scrubbing	356	14	0.0013	30
CCGT	775	19.4	0.001	30
OCGT	475	14.25	0.001	30
Steam turbine	600	12	0	30
Hot heat burner	100	2	0	30
Heating rod	20	0.4	0.001	30
Biomass CHP	2500	175	0.001	30
Biogas CHP	370	14.8	0.001	30
Waste incinerator	5240	235.8	0.007	20
Biogas digester	680	27.2	0	20
Biogas upgrade	250	20	0	20

	Capex [€/(m^3·a)]	Opex fix [€/(m^3·a)]	Opex var [€/m^3]	Lifetime [a]
Water desalination	2.23	0.09	0	30

	Capex [€/(kWh)]	Opex fix [€/(kWh·a)]	Opex var [€/kWh]	Lifetime [a]
Battery	150	10	0.0002	10
PHS	70	11	0.0002	50

A-CAES	31	0.4	0.0012	40
TES	24	2	0	20
Gas storage	0.05	0.001	0	50

	Capex [€/(m^3)]	**Opex fix [€/(m^3·h·a)]**	**Opex var [€/m^3]**	**Lifetime [a]**
Water storage	65	1.3	0	30

	Capex [€/(kW$_{NTC}$·km)]	**Opex fix [€/(kW$_{NTC}$.km·a)]**	**Opex var [€/kWh$_{NTC}$]**	**Lifetime [a]**
HVDC line on ground	0.612	0.0075	0	50
HVDC line submarine	0.992	0.0010	0	50

	Capex [€/(m^3·h·km)]	**Opex fix [€/(m^3·h·km·a)]**	**Opex var [€/m^3·h·km]**	**Lifetime [a]**
Horizontal pumping and pipes	19.3	0.39	0	30
Vertical pumping and pipes	15.5	0.31	0	30

Appendix B. Efficiencies and energy to power ratio of storage technologies. Assumptions are mainly taken from [28].

Technology	**Efficiency [%]**	**Energy/Power Ratio [h]**	**Self-Discharge [%/h]**
Battery	90	6	0
TES	90	8	0.002
PHS	85	8	0
A-CAES	70	100	0.001
Gas storage	100	80*24	0

Appendix C. Efficiency assumptions for energy system components for the 2030 reference years. Assumptions are mainly taken from [21, 28].

	η_{el} [%]	**η_{th} [%]**
CSP (solar field)		51
Steam turbine	42	
Hot heat burner		95
Heating rod		99
Water electrolysis		84
Methanation		77
CO_2 scrubbing		78
CCGT	58	
OCGT	43	
Geothermal	24	
Biomass CHP	40	45
Biogas CHP	42	43
Waste incinerator	34	
Biogas upgrade		98

Appendix D. Efficiency assumptions for HVDC transmission [12].

	Power losses
HVDC line	1.6%/1000 km
HVDC converter pair	1.4%

Appendix E. Average full load hours and LCOE for optimally tilted and single-axis tracking PV systems, and wind power plants in Brazil. Abbreviation: full load hour, FLH.

Region	Pop. [mio. Pop]	Electr. demand [TWh]	PV fixed tilted FLH	PV single-axis FLH	Wind FLH	PV fixed tilted LCOE [€/MWh]	PV single-axis LCOE [€/MWh]	Wind LCOE [€/MWh]
Total area	228	815	1555	2007	3083	33	28	36
South	33	141	1470	1877	2012	34	30	53
São Paulo	50	240	1544	1984	1653	33	29	64
Southeast	46	183	1588	2069	1541	32	28	69
North	36	111	1499	1904	823	34	30	129
Northeast	63	140	1668	2296	3371	30	25	31

Appendix F. Regional biomass [11] and geothermal energy potentials.

	Biomass potential [TWh_{LHV}/a]			Geothermal
Region	Solid waste	Solid biomass	Biogas sources	Potentials [TWh_{th}/a]
Total area	5.1	510.8	172.3	54.2
South	0.7	57.7	24.7	0
São Paulo	1.1	72.5	37.4	0
Southeast	1.1	78.3	34.9	54.2
North	0.8	180.0	27.5	0
Northeast	1.4	122.3	47.8	0

Appendix G. Regional biomass costs, calculated based on biomass sources mix in the region. Solid wastes cost are based on assumption of 75 €/ton gate fee paid to the MSW incinerator.

Region	Biomass costs [$€/MWh_{th}$]		
	Solid waste	Solid biomass	Biogas sources
Total area	-15.25	9.88	10.60
South	-15.25	8.08	10.60
São Paulo	-15.25	6.30	10.60
Southeast	-15.25	7.71	10.60
North	-15.25	13.57	10.60
Northeast	-15.25	8.81	10.60

Appendix H. Lower limits of installed capacities in South and Central American regions. Data were taken from [14].

Region	Installed capacity [MW]					
	Solar PV	**Wind**	**Hydro RoR and dams**	**PHS**	**Biomass**	**Biogas**
Total area	158.5	11241.9	91960	126	11746	112
South	3	1068.3	23720	0	979	2
São Paulo	1.1	0	13890	0	5258	48
Southeast	3	29.2	15040	126	1401	30
North	100.4	680.7	27230	0	2757	11
Northeast	51	9463.7	12080	0	1351	21

Appendix I. Upper limits on installable capacities in Brazil in units of GW_{th} for CSP and GW_{el} for all other technologies.

Region	area [1000 km^2]	Limits [GW]					
		Solar CSP	**Solar PV**	**Wind**	**Hydro RoR**	**Hydro dams**	**PHS**
Total area	8515	2082	38320	2861	18	120	0.2
South	577	7786	2595	194	3	32	0
São Paulo	248	3351	1117	83	3	18	0
Southeast	676	9131	3044	227	4	19	0.2
North	5460	73711	24570	1835	7	34	0
Northeast	1554	20983	6994	522	1	17	0

Appendix J. Annual industrial gas [22,23,24] and water demand [9] for year 2030.

Region	Annual gas demand	Annual electricity demand for gas synthesis	Annual water desalination demand	Annual electricity demand for water desalination
	TWh_{th}	TWh_{el}	10^6 m^3	TWh_{el}
Total area	216.9	200.6	1.4	0.03
Brazil South	55.2	73.3	0	0
Brazil São Paulo	72.9	90.4	0	0
Brazil Southeast	41.7	33.9	0	0
Brazil North	20.3	2.9	0	0
Brazil Northeast	26.8	0.05	1.4	0.03

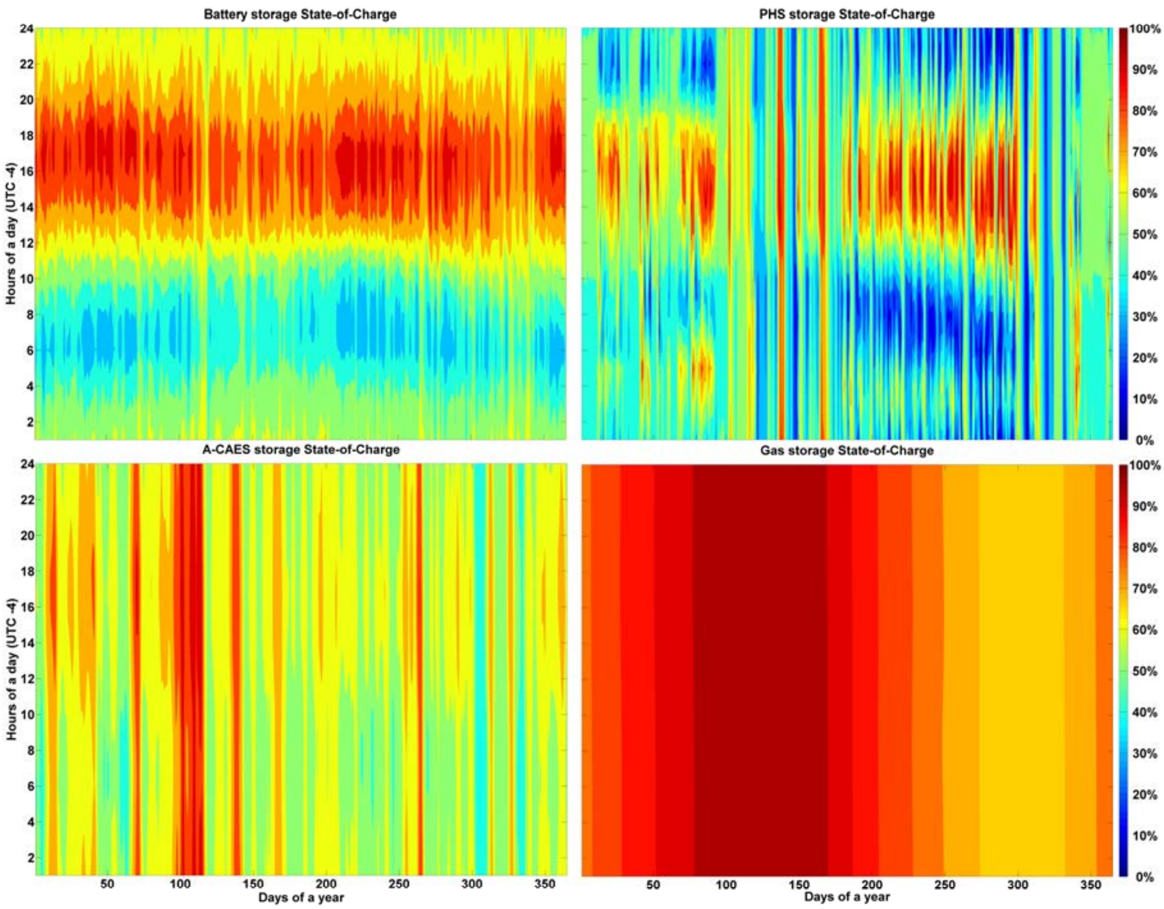
Appendix K.

K.1. Overview on storage capacities, throughput and full cycles per year for the four scenarios for Brazil.

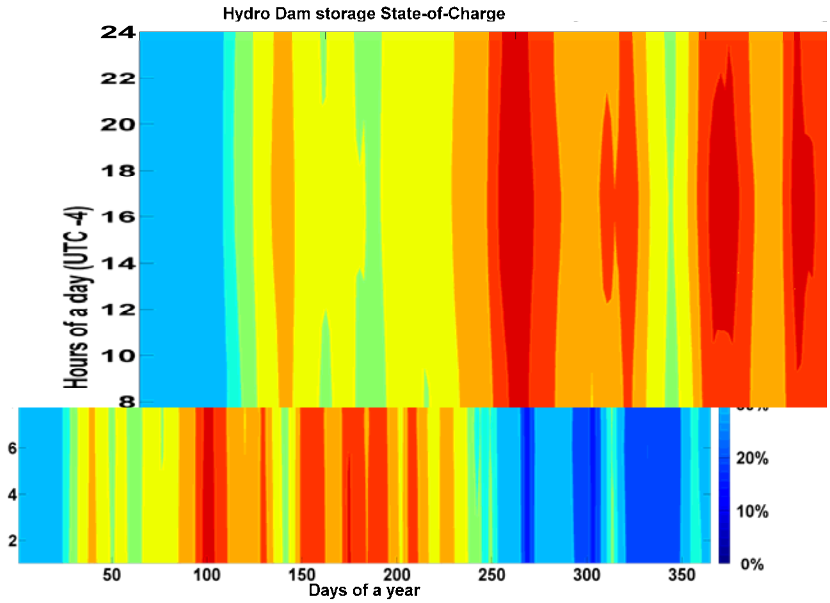
			Country wide	Integrated
Storage capacities	**Battery SC**	[GWh_{el}]	243.5	243.6
	Battery system	[GWh_{el}]	0.2	0.3
	PHS	[GWh_{el}]	1.1	1.2
	A-CAES	[GWh_{el}]	23.1	32.4
	TES	[GWh_{el}]	1.4	3.7
	Gas	[GWh_{th}]	72233.2	89314.9
	Battery SC	[TWh_{el}]	77.0	77.0

Throughput of storages	**Battery system**	[TWh_{el}]	0.05	0.05
	PHS	[TWh_{el}]	0.2	0.2
	A-CAES	[TWh_{el}]	0.2	0.3
	TES	[TWh_{el}]	0.1	0.1
	Gas	[TWh_{th}]	55.3	1.4
Full cycles per year	**Battery SC**	[-]	316.4	316.4
	Battery system	[-]	229.1	163.6
	PHS	[-]	1470	181.5
	A-CAES	[-]	9.3	10.7
	TES	[-]	71.9	35.7
	Gas	[-]	0.8	0.02

K.2. Aggregated state-of-charge for the storages in the integrated scenario: battery (top left), PHS (top right), A-CAES (bottom left) and gas storage (bottom right).



K.3. State-of-charge for hydro dams in the integrated scenario.



References

[1] Agora Energiewende, 2014. Comparing the cost of low-carbon technologies: what is the cheapest option? report by Prognos AG on behalf of Agora Energiewende, p. 10-13. Available online at: www.prognos.com/fileadmin/pdf/publikationsdatenbank/140417_Prognos_Agora_Analysis_Decarbonisationtechnologies_EN.pdf [accessed: 19.12.2015]

[2] Agora Energiewende, 2015. Current and Future Cost of Photovoltaics – Long-term Scenarios for Market Development System Prices and LCOE of Utility-Scale PV Systems. Report by Fraunhofer Institute for Solar Energy Systems on behalf of Agora Energiewende. Available online at: www.fvee.de/fileadmin/publikationen/weitere_publikationen/15_AgoraEnergiewende-ISE_Current_and_Future_Cost_of_PV.pdf [accessed: 19.12.2015]

[3] Barasa M, Bogdanov D, Oyewo S, Breyer Ch, 2016. A Cost Optimal Resolution for Sub-Saharan Africa powered by 100 Percent of Renewables by the Year 2030, 32nd EU PVSEC, Munich, June 20-24.

[4] Barbosa LSNS, Bogdanov D, Vainikka P, Breyer Ch, 2016. Hydro, wind and solar power as a base for a 100% Renewable Energy supply for South and Central America. submitted.

[5] BEN, 2015. Brazilian Energy Balance. Empresa de Pesquisa Energética (EPE). Available online at: https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2015.pdf [accessed: 20.01.2016]

[6] Bogdanov D and Breyer Ch, 2015. Eurasian Super Grid for 100% Renewable Energy power supply: Generation and storage technologies in the cost optimal mix, ISES Solar World Congress 2015, Daegu, Korea, November 8-12.

[7] Bogdanov D and Breyer Ch, 2016. North-East Asian Super Grid for 100% Renewable Energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. Energy Conversion and Management, 112, 176-190.

[8] Breyer Ch, Gerlach A, 2013. Global Overview on Grid-Parity, Progress in Photovoltaics: Research and Applications 21, 121-136.

[9] Caldera U, Bogdanov D, Breyer Ch, 2016. Local cost of seawater RO desalination based on solar PV and wind energy – A global estimate, Desalination, Desalination, 385, 207-216.

[10] Carvalho JF, Sauer IL, 2009. Does Brazil need new nuclear power plants?. Energy Policy 37, 1580-1584.

[11] DBFZ, 2009. Regionale und globale räumliche Verteilung von Biomassepotenzialen. German Biomass Research Centre. [in German]

[12] Dii, 2012. 2050 Desert power – perspectives on a sustainable power system for EUMENA. Dii, Munich.

[13] European Commission, 2014. ETRI 2014 - Energy technology reference indicator projections for 2010-2050. EC Joint Research Centre Institute for Energy and Transport, Petten, Netherlands.

[14] Farfan J and Breyer Ch, 2016. Structural Changes of the global power generation capacity towards sustainability and the risk of stranded investments, submitted.

[15] Gasch R and Twele J Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb, 6th ed. Wiesbaden : Vieweg + Teubner; 2010, p. 505 [in German].

[16] Gerlach A, Werner Ch, Breyer Ch, 2014. Impact of Financing Cost on Global Grid-Parity Dynamics till 2030. 29th EU PVSEC,

Amsterdam, September 22-26, DOI: 10.4229/29thEUPVSEC2014-7DO.15.4. Available online at: www.researchgate.net/publication/266558306_Impact_of_Financing_Cost_on_Global_Grid-Parity_Dynamics_till_2030 [accessed: 19.12.2015]

[17] Gulagi A, Bogdanov D, Breyer Ch, 2016a. Solar Photovoltaics – A driving force towards a 100% renewable energy system for India and the SAARC region, 32nd EU PVSEC, Munich, June 20-24

[18] Gulagi A, Bogdanov D, Breyer Ch, 2016b. Southeast Asia and the Pacific Rim Super Grid for 100% Renewable Energy Power Supply, submitted.

[19] Hau E Windkraftanlagen – Grundlagen, Technik, Einsatz, Wirtschaftlichkeit. 4th ed. Berlin : Springer-Verlag; 2008, p. 732 [in German].

[20] Heier S Windkraftanlagen – Systemauslegung, Netzintegration und Regelung, 5th edition, Vieweg + Teubner, Wiesbaden; 2009, p. 393-436 [in German].

[21] Hoffmann W, 2014. Importance and evidence for cost effective electricity storage. 29th EU PVSEC, Amsterdam, September 22-26.

[22] IBGE, 2013. Instituto Brasileiro de Geografia Estatística. Available online at: www.ibge.gov.br/home/estatistica/economia/industria/pia/empresas/2013/defaulttabzip.shtm [accessed: 26.02.2016]

[23] IEA, 2014. World Energy Outlook 2014. IEA Publishing, Paris.

[24] IEA, 2015. IEA Statistics. Available online at: www.iea.org/statistics/statisticssearch/ [accessed: 20.08.2015]

[25] Komoto K, Ito M, Van der Vleuten P, Faiman D, Kurokawa K (eds.), 2009. Energy from the desert – very large scale photovoltaic systems: socio-economic, financial, technical and environmental aspects. Earthscan, London.

[26] MME, 2015. Boletim Mensal de Monitoramento do Sistema Elétrico Brasileiro. January. Available online at: www.mme.gov.br/documents/10584/1256627/--+Boletim+de+Monitoramento+do+Sistema+El%C3%A9trico+-+Janeiro-2015_/b6795ba5-2d05-4a27-aafe-cd671b963761 [accessed: 11.02.2016] [in Portuguese].

[27] Narvarte L and Lorenzo E, 2008. Tracking and Ground Cover Ratio, Progress in Photovoltaics: Research and Application, 16:703–714.

[28] Pleßmann G, Erdmann M, Hlusiak M, Breyer Ch, 2014. Global energy storage demand for a 100% renewable electricity supply. Energy Procedia 46, 22-31.

[29] PV Magazine, 2014. Brazilian regions move forward. Available online at: www.pv-magazine.com/archive/articles/beitrag/brazilian-regions-move-forward-_100014704/618/#axzz3ycoLC9bi [accessed: 25.01.2016]

[30] PV Magazine, 2016. Tax exemptions for solar components introduced in Brazil's legislature. January, 8. Available online at: www.pv-magazine.com/news/details/beitrag/tax-exemptions-for-solar-components-introduced-in-brazils-legislature_100022719/#axzz3ycoLC9bi [accessed: 25.01.2016]

[31] REN21, 2015. Global Status Report. Renewable Energy Policy Network for the 21st Century, Paris, Available online at: www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf [accessed: 08.02.2016]

[32] Soito JLS, Freitas MAV, 2011. Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change. Renewable and Sustainable Energy Reviews 15, 3165-77.

[33] Urban W, Lohmann H, Girod K, 2009. Abschlussbericht für das BMBF-Verbundprojekt Biogaseinspeisung. Fraunhofer UMSICHT. [in German].

[34] Vartiainen E, Masson G, Breyer Ch, 2015. PV LCOE in Europe 2015-2050. 31th EU PVSEC, Hamburg, September 14-18; 10.4229/31stEUPVSEC2015-7DO.15.1. Available online at: www.researchgate.net/publication/281939918_PV_LCOE_in_Europe_2015-2050 [accessed: 19.12.2015]