Methodology Report

Methodology and assumptions for the Brazil Energy [R]evolution: Scenarios for a future energy supply

Sonja Simon, Hans Christian Gils, Tobias Fichter

German Aerospace Center
Institute for Engineering Thermodynamics
Stuttgart, Germany

DLR Deutsches Zentrum für Luft- und Raumfahrt

1 Introduction to the scenario approach

A pathway toward a more sustainable energy system requires a low risk and low carbon energy supply. Action against climate change requires a long-term perspective. Energy infrastructure takes time to build up; new energy technologies take time to develop. Policy shifts often also need many years to take effect. A transition towards a predominatly renewable energy system, however, promises tremendous economic benefits in the long term, due to much lower consumption of increasingly expensive, rare or imported fuels. Any analysis that seeks to tackle energy and environmental issues therefore needs to look ahead at least until mid of the century.

Scenarios are a necessary tool to describe possible development paths, to give decision-makers a broad overview and indicate how far they can shape the future energy system. In order to evaluate the boundaries of the future energy system, we are developing two scenarios here to show the wide range of possible pathways for a future energy supply system:

- a **Reference scenario**, reflecting a continuation of current trends and policies and
- the **Energy [R]evolution** scenario, designed to achieve a set of environmental policy targets resulting in an optimistic but still feasible pathway towards a widely decarbonised energy system until 2050 in close relation to basic framework assumptions of the Reference scenario.
- This basic Energy [R]evolution scenario is supplemented by **two sub scenarios for the power sector**, analysing interdependencies between Brazilian regions, including grid and storage infrastructure.

1.1 Scenario storylines and main premises

The **Reference scenario** (REF) follows an explorative approach. It is based on the previous report[1] and was revised by national experts[2]. It only takes into account existing international energy and environmental policies. Additionally, general development trends for the region Latin America from the global Energy [R]evolution report 2015[3] were taken into account as well as the Current Policies scenarios published by the International Energy Agency (IEA) in World Energy Outlook 2014[4]. The Reference scenario does not include additional policies to reduce greenhouse gas emissions.

This provides a baseline for comparison with the Energy [R]evolution scenario. Compared with the previous Reference scenario of the Energy [R]evolution study published in 2013, it includes an increase in population and new market trends for renewable energy technologies.

The **Energy [R]evolution scenario** (E[R]) is a target-oriented scenario. It is based on an update of the E[R] scenario published in 2013, which followed the key target to reduce worldwide carbon dioxide emissions from energy use down to a level of around 4 Gigatonnes per year by 2050 in order to hold the increase in global temperature under +2°C. A second objective is the global phasing out of nuclear energy. The new E[R] scenario aims at much stronger efforts towards a almost 100% renewable energy supply. It takes into account developments between the former base year 2010 and the new base year 2014. In addition,

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[1] Teske, S., R. Baitelo, S. Sawyer, T. Pregger, S. Simon, et al. (2013). Energy [R]evolution - a sustainable Brazil energy outlook. Amsterdam, Greenpeace International, European Renewable Energy Council (EREC), Global Wind Energy Council (GWEC), Deutsches Zentrumfür Luft- und Raumfahrt (DLR),.

[2] Jannuzzi, G. M. and H. Jantim (2016). Revolução Energética 2016 - Eficiência Energética. Relatório 1, Relatório 2 - Potenciais de Conservação de Energia e Relatório 3 - Cenário Transição para Renováveis, International Energy Initiative (IEI), Programa de Pós-Graduação em Planejamento de Sistemas Energéticos da Universidade Estadual de Campinas (UNICAMP).

[3] Teske, S., S. Sawyer, O. Schäfer, T. Pregger, S. Simon, et al. (2015). Energy [R]evolution - A sustainable world energy outlook 2015. S. Teske, S. Sawyer and O. Schäfer, Greenpeace International.

[4] IEA (2014). World Energy Outlook 2014. Paris, International Energy Agency, Organisation for Economic Co-operation and Development.

pathways for the deployment of renewable energies and efficiency measures are revised reflecting technology trends of the last years and new estimations of Brazilian potentials and investment costs leading to partly different technology mixes. Furthermore, the possibilities to implement new technologies until 2020 are now more limited than in 2013 due to the required development time of new power plants and other infrastructures. The scenario still includes significant efforts to fully exploit the large potential for energy efficiency, using currently available best practice technology. At the same time, various proven renewable energy sources are integrated to a large extend for heat and electricity generation as well as the production of biofuels and hydrogen. The general framework parameters for population and GDP growth remain unchanged from the Reference scenario.

Due to higher efficiencies of new vehicle concepts and the assumption of much higher modal split changes compared to the previous E[R], the resulting final energy demand for transportation is lower. However, this scenario requires more fundamental changes of mobility patterns and behaviour as well as infrastructural needs to compensate for the high energy losses associated to the production of synthetic fuels based on renewable electricity. Also in the heating sector, electricity plays a larger role substituting remaining fossil fuels. Therefore, electricity generation from renewable energy sources is supposed to be the main "primary energy" of the future.

The scenario building for the Energy [R]evolution scenario follows a framework of targets and main premises that strongly influences the development of individual technological and structural pathways for each region and each sector. The main premises considered for this scenario building process are described in the following.

Strong efficiency improvements and dynamic expansion of renewable energies in all sectors are the main strategies to meet the overall target of CO_2 emissions reduction. CCS technologies are not implemented and nuclear power and coal power plants are phased out quickly. In particular, a shorter operational lifetime for coal power plants, of 20 instead of 35 years, is assumed in order to allow a faster uptake of renewable energy. Based on current knowledge about potentials, costs and recent trends of renewable energy deployment (see next section on ‘Scenario approach and background studies’) a dynamic further growth of capacities for renewable heat and power generation is assumed.

The quantities of biomass power generators and large hydro power remain limited in the Energy [R]evolution scenarios, for reasons of ecological sustainability. Wind power and solar power (both photovoltaics and concentrating solar power (CSP)) are expected to become important pillars of future power supply, complemented by smaller contributions ocean energy and the further expansion of small and medium sized hydro power. The scenarios follow the strategy to limit the share of fluctuating power generation and to maintain a sufficient share of controllable, secured capacity.

Sustainable biomass potentials are assumed to be limited to less than 500 PJ for power production[5] and below 5,5 EJ for primary energy[6] according to according to background studies. Traditional biomass use is largely replaced by state-of-the-art technologies, primarily high-efficient cogeneration plants. In the residential sector with a high share of traditional biomass use an implementation of improved cooking stoves is assumed.

Efficiency savings in the transport sector are a result of modal shift, new highly efficient vehicle concepts such as electric vehicles but also assumed changes in driving patterns and the implementation of efficiency measures for combustion engines.

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[5] Portugal-Pereira, J., R. Soria, R. Rathmann, R. Schaeffer and A. Szklo (2015). "Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil." Biomass and Bioenergy 81: 521-533.

[6] Teske, S., R. Baitelo, S. Sawyer, T. Pregger, S. Simon, et al. (2013). Energy [R]evolution - a sustainable Brazil energy outlook. Amsterdam, Greenpeace International, European Renewable Energy Council (EREC), Global Wind Energy Council (GWEC), Deutsches Zentrumfür Luft- und Raumfahrt (DLR),.

Assumptions for the transport sector are based on a separate study by Brazilian experts.[7]

Efficiency in use of electricity and fuels in 'industry' and 'other sectors' have also been re-evaluated by national experts, who provided a independent demand scenario for both the Reference and the Energy [R]evolution scenario. In consequence, specific energy use for all applications and in all regions is assumed to decrease significantly.

The Energy [R]evolution scenarios also foresee a shift in the heat sector towards an increasing direct use of electricity, thanks to the enormous and diverse potential for renewable power and the limited availability of renewable fuels for high temperature process heat in industry. In addition a fast expansion of the use of district and solar heating is assumed, supplemented by an introduction of geothermal heat pumps. This all leads to an increasing electricity demand which partly compensates for the efficiency savings in these sectors.

The increasing shares of fluctuating renewable power generation – above all by wind farms and photovoltaics – implicitly require the implementation of smart grids, a fast expansion of transmission grids, an extension of storage or other load balancing capacities. Other infrastructural needs result e.g. from an increasing role electric mobility.

Therefore, the two sub-scenarios for the power sector provide additional information concerning the least-cost power supply system, as well as the impact of a reduced water inflow to hydro power stations.

- The basic Energy [R]evolution scenario includes PV installations of 100 GW by 2050 as a precondition, according to the planing of the Brazilian government.

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[7] LTC/PET/COPPE/UFRJ (2016). Revolução Energética Cenários para os Transportes no Brasil em 2050. Relatório Final., Laboratório de Transporte de Carga (LTC) do Programa de Engenharia de Transportes (PET/COPPE) da Universidade Federal do Rio de Janeiro (UFRJ).t einfügen

- In contrast to the basic Energy [R]evolution scenario, the PV-Opt scenario includes no predefined PV installations. Instead, it assesses the least-cost capacity of PV, such as for wind and CSP (see also chapter 2.2)
- The Red-Inflow scenario represents a case in which the water inflow to hydro power plants is reduced by one quarter all across Brazil. This scenario addresses risks of increasing water scarcity for the Brazilian energy system.

The Energy [R]evolution scenarios by no means claims to predict the future; they simply describe and compare potential development pathways out of the broad range of possible ‘futures’. The Energy [R]evolution scenarios are designed to indicate the efforts and actions required to achieve their ambitious objectives and to illustrate the options we have at hand to change our energy supply system into one that is truly sustainable. They may serve as a consistent basis for further analyses of possible ways and concepts to implement pathways to the energy transition.

1.2 Scenario approach and background studies

The Energy [R]evolution scenarios in this report were commissioned by Greenpeace Brazil from the Systems Analysis and Technology Assessment department of the Institute of Engineering Thermodynamics, part of the German Aerospace Center (DLR). The scenarios are based on a series of studies developed for previous Energy [R]evolution versions[8].

The Energy [R]evolution scenarios are target-oriented scenarios. Therefore, they must not be interpreted as a "forecast" of the future development of the energy systems. The scenarios are developed using a primarily “bottom-up” approach (technology driven). Assumed growth rates for population, GDP, specific energy demand and the deployment of renewable energy technology are important

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[8] Teske, S., R. Baitelo, S. Sawyer, T. Pregger, S. Simon, et al. (2013). Energy [R]evolution - a sustainable Brazil energy outlook. Amsterdam, Greenpeace International, European Renewable Energy Council (EREC), Global Wind Energy Council (GWEC), Deutsches Zentrumfür Luft- und Raumfahrt (DLR),.

drivers. Based on these drivers new energy demand projections were developed by national experts[9] based on an analysis of the future potential for energy efficiency measures until 2050.

The supply scenarios were calculated using the Mesap/PlaNet simulation model adopted in the previous Energy [R]evolution studies[10]. This model requires a consistent exogenous definition of feasible developments in order to meet the targets. Quantified targets for transforming the energy systems set the framework for its design. For the power sector sub scenarios, a new methodology was applied at DLR. It consists of the coupling of the standard energy system modelling approach with MESAP/PlaNet simulation model with a high-resolution optimization model (see also the modeling approach in chaper 2)

Structure and initial parametrization of the energy system is extracted from the extended energy balances published in 2014 by International Energy Agency (IEA)[11]. For the base yeat 2014 statistical data is based on national statistics[12].

The dynamic expansion of renewable energies defined in the scenarios is based on recent technology trends[13], current knowledge about regional renewable

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[9] Greenpeace Brazil; Jannuzzi, G. M. and H. Jantim (2016). Revolução Energética 2016 - Eficiência Energética. Relatório 1, Relatório 2 - Potenciais de Conservação de Energia e Relatório 3 - Cenário Transição para Renováveis, International Energy Initiative (IEI), Programa de Pós-Graduação em Planejamento de Sistemas Energéticos da Universidade Estadual de Campinas (UNICAMP).

[10] Teske, S., S. Sawyer, O. Schäfer, T. Pregger, S. Simon, et al. (2015). Energy [R]evolution - A sustainable world energy outlook 2015. S. Teske, S. Sawyer and O. Schäfer, Greenpeace International.

Teske, S., T. Pregger, S. Simon, T. Naegler, M. O'Sullivan, et al. (2012). Energy [R]evolution - a sustainable world energy outlook - 4th edition 2012. S. Teske, J. Muth and S. Sawyer, Greenpeace International, Global Wind Energy Council (GWEC),.

[11] IEA (2014). Energy balance of non-OECD countries (2014 edition). IEA energy statistics (Beyond 20/20). Paris, International Energy Agency.

[12] Empresa de Pesquisa Energética (2015). Balanço Energético Nacional 2015. Brasília: EPE, Ministério de Minas e Energia, Governo Federal Brasil.

[13] REN 21 (2015). Renewables 2015 Global Status Report.
EWEA (2015). The European offshore wind industry - key trends and statistics 2014, European Wind Energy Association.

energy potentials and costs for their deployment[14], market development projections of the renewable energy industry[15].

The future development pathway for cars and other transportation technologies is based on a special report produced for this scenario by COPPE[16].

Assumptions on fossil fuel resources and planned and ongoing investments in coal, gas and oil on a global and regional basis are based on a study by the Ludwig Bölkow Systemtechnik Institute, commissioned by Greenpeace for the Energy [R]evolution study of 2012. Technology and cost projections for the heating sector are adopted from a background study commissioned by EREC from DLR about the current renewable heating technology markets, market forecasts, cost projections and state of the technology development. Details can be found as well in the global Energy [R]evolution study of 2012.

1.3 Main scenario assumptions

1.3.1 Demand development

Population development and economic growth are the main drivers for the development of the energy demand. Since 1971, each 1% increase in global Gross Domestic Product (GDP) has been accompanied by a 0.6% increase in

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[14] Pietzcker, R. C., D. Stetter, S. Manger and G. Luderer (2014). "Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power." Applied Energy 135: 704-720.
Deng, Y. Y., M. Haigh, W. Pouwels, L. Ramaekers, R. Brandsma, et al. (2015). "Quantifying a realistic, worldwide wind and solar electricity supply." Global Environmental Change 31: 239-252.
IRENA (2015). Renewable Power Generation Costs in 2014, International Renewable Energy Agency.
DLR (2016): REMix Endat modelling results provided by the German Aerospace Center, Institute of Engineering Thermodynamics

[15] EPIA (2014). Market Report 2013, European Photovoltaic Industry Association.
GWEC (2014). Global Wind Statistics 2013, Global Wind Energy Council.
WEC (2015). World Energy Resources - Charting the Upsurge in Hydropower Development 2015, World Energy Council.

[16] LTC/PET/COPPE/UFRJ (2016). Revolução Energética Cenários para os Transportes no Brasil em 2050. Relatório Final., Laboratório de Transporte de Carga (LTC) do Programa de Engenharia de Transportes (PET/COPPE) da Universidade Federal do Rio de Janeiro (UFRJ).

primary energy consumption. The decoupling of energy demand and GDP growth is therefore a prerequisite for an Energy [R]evolution

Population development

Future population development is an important factor in energy scenario building, affecting size and composition of energy demand, directly and through its impact on economic growth and development. For the Energy [R]evolution scenarios, we applied the United Nations Development Programme (UNDP) projections for population development up to 2050[17].

Table 1: Population development projections (based on UNDP development projections, medium variant)

Mio.cap	2014	2020	2025	2030	2040	2050
Brazil	200	218	223	227	230	231

Table 1 shows that the Brazilian population is expected to grow by 0.4% per year on average over the period 2014 to 2050, from 200 milllion people in 2014 to about 231 million by 2050. The updated projections show a slight increase in population estimates by 2050 of around 7 million compared to the UNDP 2010 edition which was used for the Energy [R]evolution 2013. Satisfying the energy needs of a growing population in an environmentally friendly manner is the fundamental challenge to achieve a global sustainable energy supply.

Economic growth

Economic growth is a key driver for energy demand. Prospects for GDP growth have decreased considerably since the previous study, due to the economic crisis in Brazil. GDP growth is expected to slow gradually over the coming decades.

National GDP development for Brazil was provided by Greenpeace Brazil.

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[17] UNPD. (2015). "World Population Prospects: The 2015 Revision."   Retrieved 1.2.2016, 2016, from http://esa.un.org/unpp/.

Demand scenarios and efficiency potentials

For the Brazilian Energy [R]evolution scenario 2016 national experts developed a Reference energy demand scenario based on the economic development[18]. Resulting energy intensities for industries and other sectors were compared and reviewed on the basis of regional values from the global Energy [R]evolution scenario 2015.

1.3.2 Oil and gas price projections

The recent dramatic fluctuations in global oil prices have been significant and with influence on price projections. Under the 2004 ‘high oil and gas price’ scenario from the European Commission, for example, an oil price of just $34 per barrel was assumed in 2030. More recent projections of oil prices by 2040 in the IEA’s WEO 2014 range from $\$_{2013}$100/bbl in the 450 ppm scenario up to $\$_{2013}$155/bbl in the Current Policies scenario.

Since the first Energy [R]evolution study was published in 2007, the oil price has seen repeated fluctuation highs ($140/bbl July 2008) and lows (40- 60 $/bbl in 2015) due to the global economic situation and market reasons. Taking into account expected growth in global energy demand in mid-term and long-term projections, the Brazilian Energy [R]evolution scenario 2016 assumed fossil fuel price projections according to the World Energy Outlook 2014. In contrast to the previous E[R] editions this results in different assumptions for the Reference scenario compared to the Energy [R]evolution scenarios.

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[18] Greenpeace Brazil; Jannuzzi, G. M. and H. Jantim (2016). Revolução Energética 2016 - Eficiência Energética. Relatório 1, Relatório 2 - Potenciais de Conservação de Energia e Relatório 3 - Cenário Transição para Renováveis, International Energy Initiative (IEI), Programa de Pós-Graduação em Planejamento de Sistemas Energéticos da Universidade Estadual de Campinas (UNICAMP).

Table 2: Development projections for fossil fuel and biomass prices in $2012 for Brazil based on assumptions for Latin America

	Scenario	unit	2014	2020	2030	2040	2050
Crude Oil	REF and E[R]	$/GJ	13.5	18.8	22.5	25.1	24.3
Hard coal	REF	$/GJ	4.6	4.6	5.0	5.3	5.6
	E[R]	$/GJ		3.8	3.4	3.3	3.3
Lignite	REF and E[R]	$/GJ	1.6	1.9	2.1	2.2	2.5
Natural Gas	REF	$/GJ	12.3	15.7	17.0	18.1	19.1
	E[R]	$/GJ		14.2	13.2	12.5	11.9
Biomass	REF and E[R]	$/GJ	1.5	1.5	2.1	2.8	3.0

As the supply of natural gas is limited by the availability of pipeline infrastructure, there is no world market price for gas. In most regions of the world the gas price is directly tied to the price of oil. For Brazil fossil fuel prices are based on the assumptions for Latin America from the global Energy [R]evolution study 2015[19].

1.3.3 Cost projections for efficient fossil fuel generation and CO_2 emissions

Specific investment and operation costs of coal, gas, lignite and oil power plants are assumed according to WEO 2014 Special report on investments[20]. Because

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[19] Teske, S., S. Sawyer, O. Schäfer, T. Pregger, S. Simon, et al. (2015). Energy [R]evolution - A sustainable world energy outlook 2015. S. Teske, S. Sawyer and O. Schäfer, Greenpeace International.

IEA (2014). World Energy Outlook 2014. Paris, International Energy Agency, Organisation for Economic Co-operation and Development.

[20] IEA (2014). IEA World Energy Investment Outlook 2014- Power Generation in the New Policies and 450 Scenarios - Assumed investment costs, operation and maintenance costs and efficiencies. Paris, International Energy Agency, Organisation for Economic Co-operation and Development.

they are at an advanced stage of technology and market development, the potential for cost reductions is limited. More details can be found in the global Energy [R]evolution edition of 2012.

Prospects for establishing an effective global carbon emissions trading system across all world regions are currently at best unclear. In contrast to the previous Energy [R]evolution scenario, the 2016 revision sets aside CO2 pricing altogether. Cost comparisons between the scenarios thus only rely on investment, operation & maintenance and fuel costs. Table 3 summarises our assumptions on the technical and economic parameters of future fossil-fuelled power plant technologies. Based on estimates from WEO 2014, we assume that further technical innovation will not prevent an increase of future investment costs because raw material costs and technical complexity will continue to increase. Also, improvements in power plant efficiency are outweighed by the expected increase in fossil fuel prices, in which would make electricity generation costs increase significantly.

Table 3: Development of efficiency and investment costs for selected new power plant technologies; exemplary data for OECD Europe (based on WEO 2014 and own assumptions)

		2014	2020	2030	2040	2050
Coal fired condensing power plant	efficiency (%)	36	36	36	36	36
	investment costs ($\$_{2012}$/kW)	1290	1270	1240	1210	1190
Gas fired power plant	efficiency (%)	41	41	41	41	41
	investment costs ($\$_{2012}$/kW)	870	870	870	870	870
Gas fired combined cycle CHP plant	efficiency (%)	61	64	71	78	86
	investment costs ($\$_{2012}$/kW)	910	910	890	870	870

1.3.4 Cost projections for renewable energy technologies

The different renewable energy technologies available today all have different technical maturity, costs and development potential. Whereas hydro power has been widely used for decades, other technologies, such as the gasification of biomass or ocean energy, have yet to find their way to market maturity. Some renewable sources by their very nature, including wind and solar power, provide a variable supply, requiring a revised coordination with the grid network. But although in many cases renewable energy technologies are 'distributed' - their output being generated and delivered locally to the consumer – in the future we can also have large-scale applications like offshore wind parks, photovoltaic power plants or concentrating solar power stations.

It is possible to develop a wide spectrum of options to market maturity, using the individual advantages of the different technologies, linking them with each other, and integrating them step by step into the existing supply structures. This approach will provide a complementary portfolio of environmentally friendly technologies for heat and power supply and the provision of transport fuels.

Many of the renewable technologies employed today are at a relatively early stage of market development. It is expected, however that large cost reductions can come from technical advances, manufacturing improvements and large-scale production, unlike conventional technologies. The dynamic trend of cost developments over time plays a crucial role in identifying economically sensible expansion strategies for scenarios spanning several decades.

To identify long-term cost developments, learning curves have been applied to the model calculations to reflect the how cost of a particular technology change in relation to the cumulative production volumes. Assumptions on future costs for renewable electricity are based on the cost assumptions of the global Energy [R]evolution scenario 2015.

They are integrating information form learning curve studies, for example by Lena Neij[21], from the analysis of technology foresight and road mapping studies, including the European Commission funded NEEDS project (New Energy Externalities Developments for Sustainability)[22] or the IEA Energy Technology Perspectives 2008, projections by the European Renewable Energy Council published in April 2010 ("Re-Thinking 2050") and discussions with experts from different sectors of the renewable energy industry.

For the Brazilian Energy [R]evolution scenario 2016 cost decreases due to recent market developments are taken into account, leading to changes in own cost assumptions above all for photovoltaics and solar thermal power plants (including heat storages). Cost assumptions for 2050 were reviewed by national experts from COPPE from the University of Rio de Janeiro[23].

Photovoltaics

The worldwide photovoltaics (PV) market has been growing at 25% per annum in recent years, reaching 40 GW of new installed capacity in 2014[24] and is starting to make a significant contribution to electricity generation. Photovoltaics is important because of its decentralised/centralized variability, its flexibility for use in an urban environment and huge potential for cost reduction. The PV industry has been increasingly exploiting this potential during the last few years, with installation prices more than halving in the last few years. Current development is focused on improving existing modules and system components by increasing their energy efficiency and reducing material usage. Technologies

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[21] Neij, L. (2008). "Cost development of future technologies for power generation—a study based on experience curves and complementary bottom-up assessments." Energy policy 36(6): 2200-2211.

[22] NEEDS. (2009). "The NEEDS Life Cycle Inventory Database." The European reference life cycle inventory database of future electricity supply systems, from http://www.needs-project.org/needswebdb/index.php.

[23] Soria, R., M. Imperio, C. Viviescas, F. Guedes, B. Scola, et al. (2016). Data input and comments for Energy [R]evolution Scenario Brazil, Energy Planning Program (COPPE), Universidade Federal do Rio de Janeiro.

[24] EPIA (2014). Market Report 2013, European Photovoltaic Industry Association.

like PV thin film (using alternative semiconductor materials) or dye sensitive solar cells are developing quickly and present a huge potential for cost reduction. The mature technology crystalline silicon, with a proven lifetime of 30 years, is continually increasing its cell and module efficiency (by 0.5% annually), whereas the cell thickness is rapidly decreasing (from 230 to 180 microns over the last five years). Commercial module efficiency varies from 14 to 21%, depending on silicon quality and fabrication process.

The learning factor for PV modules has been fairly constant over the last 30 years with costs reducing by 20% each time the installed capacity doubles, indicating a high rate of technical learning. Based on global installations in the Energy [R]evolution scenario we can expect generation costs of around 4-6 cents/kWh. PV has already become competitive with retail electricity prices in some parts of the world, and will become competitive with fossil fuel costs soon.

Concentrating Solar Power (CSP)

'Concentrating' solar thermal power stations can only use direct sunlight and therefore depend on very sunny locations. Solar thermal technologies have good prospects for further development and cost reductions. Because of their more simple design, 'Fresnel' collectors are considered as an option for additional cost trimming. The efficiency of central receiver systems can be increased by producing compressed air at a temperature of up to 1,000^{0}C, which is then used to run a combined gas and steam turbine.

Thermal storage systems are a way for CSP electricity generators to reduce costs and to provide flexible and firm capacity. The Spanish Andasol 1 plant, for example, is equipped with molten salt storage with a capacity of 7.5 hours. A higher level of full load operation can be realised by using a thermal storage system and a larger collector field. Although this leads to higher investment costs, it reduces the cost of electricity generation.

An additional option are hybrid power plants, combining a CSP plant with small to medium storage with a back up biomass power plant. Especially for the

Brazilian case these hybrid CSP plants provide an economic option for dispatchable power.

Depending on the level of irradiation and mode of operation, it is expected that long term future electricity generation costs of 5-10 cents/kWh can be achieved. This presupposes rapid market introduction in the next few years.

Wind power

Within a short period of time, the dynamic development of wind power has resulted in the establishment of a flourishing global market of over 50 GW in 2014[25]. In Europe, favourable policy incentives were the early drivers for the global wind market. However, since 2009 more than three quarters of the annual capacity installed was outside Europe and this trend is likely to continue. The boom in demand for wind power technology has nonetheless led to supply constraints and stagnating markets. As a consequence, the cost of new systems has increased. The industry is continuously expanding production capacity, however, so it is already resolving the bottlenecks in the supply chain and in 2014 market development again gained speed and increased by 6-10 GW compared to the years before. Taking into account market development projections, learning curve analysis and industry expectations, investment costs for wind turbines are reduced in the scenario by 20% for onshore installations by 2050.

Biomass

The crucial factor for the economics of using biomass for energy is the cost of the feedstock, which today ranges from a negative for waste wood (based on credit for waste disposal costs avoided) through inexpensive residual materials to the more expensive energy crops. The resulting spectrum of energy generation costs is correspondingly broad. One of the most economic options is the use of bagasse in combined heat and power (CHP) plants. Gasification of solid biomass,

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[25] GWEC (2014). Global Wind Statistics 2013, Global Wind Energy Council.

on the other hand, which has a wide range of applications, is still relatively expensive. In the long term it is expected that using wood gas both in micro CHP units (engines and fuel cells) and hybridization of CSP power plants will have the most favourable electricity production costs.

Brazil has been a leading country in converting crops into biofuels, which also globally have become increasingly important in recent years –although climate benefit especially of first generation biofuel is disputed. Processes for obtaining synthetic fuels from biogenic synthesis gases will also play a larger role in the future.

A large potential for exploiting modern technologies exists in Brazil either in stationary appliances or the transport sector. In the long term biomass use will mainly have to rely on agricultural and forest residues, industrial wood waste and straw. In Brazil in particular an increasing residue potential will be available.

Ocean energy

Ocean energy, particularly offshore wave energy, is a significant resource, and has the potential to satisfy an important percentage of electricity supply worldwide, thus it also plays a role in the Brazilian Energy [R]evolution scenario. Globally, the potential of ocean energy has been estimated at around 90,000 TWh/year. The most significant advantages are the vast availability and high predictability of the resource and a technology with very low visual impact and no CO_2 emissions. Many different concepts and devices have been developed, including taking energy from the tides, waves, currents and both thermal and saline gradient resources. Many of these are in an advanced phase of research & development, large scale prototypes have been deployed in real sea conditions and some have reached pre-market deployment. There are a few grid connected, fully operational commercial wave and tidal generating plants.

The cost of energy from initial tidal and wave energy farms has been estimated to be in the range of 20-80 €cents/kWh[26], and for initial tidal stream farms in the range of 11-22 €cents/kWh with significant learning prospects. Key areas for development will include concept design, optimisation of the device configuration, reduction of capital costs by exploring the use of alternative structural materials, economies of scale and learning from operation. According to the latest research findings, the learning factor is estimated to be 10-15% for offshore wave and 5-10% for tidal stream. In the long term, ocean energy has the potential to become a competitive and cost effective form of generation. In the next few years a dynamic market penetration is expected, following a similar curve to wind energy. Because of the early development stage any future cost estimates for ocean energy systems are uncertain and assumed comparatively high.

Hydro power

Hydropower is a the major electricity source in Brazil and will remain the backbone of the energy system also in the future It is a mature technology with a significant part of its global resource already exploited. There is still, however, some potential left both for new schemes (especially small scale run-of-river projects with little or no reservoir impoundment), for repowering of existing sites and for establishing pumpes for pumped storage at existing reservoirs. There is likely to be some more potential for hydropower with the increasing need for flood control and the maintenance of water supply during dry periods. Sustainable hydropower makes an effort to integrate plants with river ecosystems while reconciling ecology with economically attractive power generation.

Hydrogen production

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[26] Dalton, G. and T. Lewis (2011). "Performance and economic feasibility analysis of 5 wave energy devices off the west coast of Ireland." Hydraulics and Maritime Research Centre (HMRC), University College Cork, Ireland.

In the Energy [R]evolution scenarios hydrogen is introduced as a substitute for natural gas Brazil with small shares after 2040. Hydrogen is assumed to be produced via electrolysis, resulting in an additional electricity demand which is fully supplied by extra renewable power production capacities mainly from wind, PV and CSP. It thus can serve as backup for fluctuating electricity production from wind and PV, securing electricity supply at all times.

Summary of renewable energy cost development

Table 4 summarises the cost trends for renewable power technologies derived from the respective learning curves. It is important to note that the expected cost reduction is not a function of time, but of cumulative capacity (production of unites), so dynamic market development is required. Most of the technologies will be able to reduce their specific investment costs to between 30% and 60% of current once they have achieved full maturity (after 2040).

Table 4: Assumptions of cost development of renewable power technologies in the Energy [R]evolution scenario (in US$$_{2012}$/kW)[27]

		2014	**2020**	**2030**	**2040**	**2050**
Photovoltaics	US$/kW	2140	1850	1240	930	640
Concentrating Solar Power*	US$/kW	6180	5560	2370	2150	1950
Wind onshore	US$/kW	1390	1210	1200	1160	1110
Wind offshore	US$/kW	5160	3550	2810	2540	2220
Biomass	US$/kW	3880	3810	3450	2860	2470

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[27] Fraunhofer ISE (2015): Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study on behalf of Agora Energiewende

Danish Energy Agency and Energinet.dk (2012). Technology data for energy plants.

Nitsch, J., et al. (2012). Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global.

Ocean energy	US$/kW	4310	4310	4310	3580	2470
Hydro** small	US$/kW	3080	3080	3200	3170	3140
Hydro** large	US$/kW	2680	2600	2520	2450	2380
Hydrogen production	US$/kW	770	770	700	530	400
	Efficiency %	67	68	71	71	71

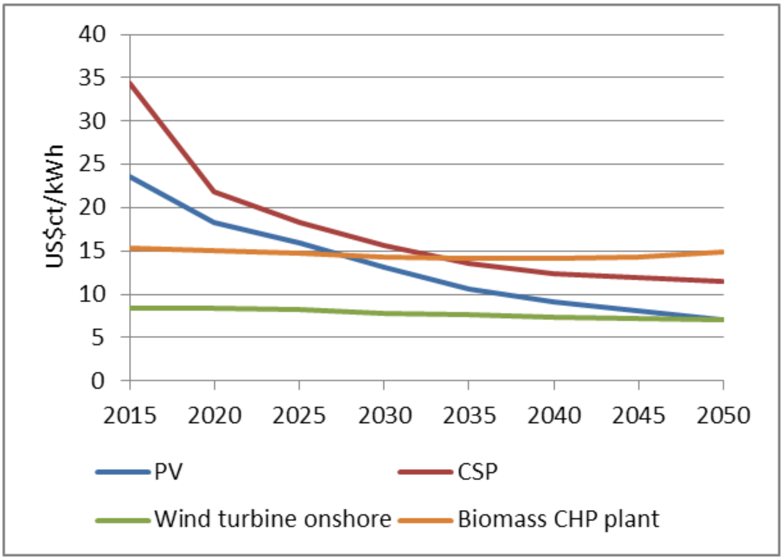
*Costs for a system with solar multiple of two and thermal storage for eight hours of turbine operation

**Values apply to both run-of-the river and reservoir hydro power.

The optimization model runs for 2050 additionally applied costs for medium hydro at 2580 US$/kW and the option of additionally enhancing existing hydro reservoirs by pumped storage at 790$/kW.

Reduced investment costs for renewable energy technologies lead directly to reduced heat and electricity generation costs, as shown in Figure 1. In the long term, full costs are expected to converge at around 6-12 US$cents/kWh, except for biomass with about 15 US$cents/kWh (calculated without heat credits for CHP). These estimates depend on site-specific conditions such as the local wind regime or solar irradiation, the availability of biomass at reasonable prices or the credit granted for heat supply in the case of combined heat and power generation.

Figure 1: Expected development of electricity generation costs from renewable power generation in the Energy [R]evolution scenarios depending on the assumed development of full load hours per year, example for OECD Europe (US$ct/kWh, biomass CHP costs without heat credits)



1.3.5 Renewable heating technologies

Renewable heating has the longest tradition of all renewable technologies. Although no specific cost calculation for the heat sector was conducted for the Brazilian Energy [R]evolution scenario, the following sections give an overview over relevant technologies and costs. For the previous Energy [R]evolution report 2012 EREC and DLR carried out a joint survey on costs of renewable heating technologies in Europe. The report analysed installation costs of renewable heating technologies, ranging from direct solar collector systems to geothermal and ambient heat applications and biomass technologies. Some technologies are already mature and compete on the market – especially simple heating systems in the domestic sector. However, more sophisticated technologies, which can provide higher shares of heat demand from renewable sources, are still under development and rather expensive. Market barriers slow down the further implementation and cost reduction of renewable heating system. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented as projected in the Energy [R]evolution scenario.

Solar thermal technologies

Solar collectors depend on direct solar irradiation, so the yield strongly depends on the location. In very sunny regions, simple thermosiphon systems can provide total hot water demand in households at around 400 €/m^2 installation costs. In regions with less sun, where additional space heating is needed, installation cost for pumped systems are twice as high. In these areas, economies of scales can decrease solar heating costs significantly. Large scale solar collector system are known from 250-600 €/m2, depending on the share of solar energy in the whole heating system and the level of storage required.

Heat pumps

Heat pumps typically provide hot water or space heat for heating systems with relatively low supply temperature or can serve as a supplement to other heating technologies. They have become increasingly popular for underfloor heating in buildings. Economies of scale are less important than for deep geothermal, so there is focus on small household applications with investment costs from 500-1600 €/kW for ground water systems and higher costs from 1200-3000 €/kW for ground source or aerothermal systems.

Biomass applications

There is broad portfolio of modern technologies for heat production from biomass, ranging from small scale single room stoves to heating or CHP-plants in MW scale. Investments costs show a similar variety: simple log wood stoves can be obtained from 100 €/kW, more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive. Log wood or pellet boilers range from 400-1200 €/kW, with large applications being cheaper than small systems.

Heat from cogeneration (CHP) is another option with a broad range of technologies at hand. It is a very varied energy technology – applying to co-firing in large coal-fired cogeneration plants; biomass gasification combined with CHP or biogas from wet residues. But the costs for heat are often mainly dependent on the power production.

Storage and Grid installations

For the detailed assessment of the power sector in 2050, the REMix model also includes different load balancing options, such as storage, grid and demand side management, which allow for the integration of a higher proportion of fluctuating renewable power. Storage and demand side management allow for a temporal balancing of demand and supply, whereas additional grid connections provide spatial balancing.

Storage options vary from the installation of pumps in existing reservoir hydro stations over battery storage that can deliver decentralized storage options, to hydrogen production. The latter then either is stored locally for power reconversion or can be used as a renewable fuel in the transport and heating sector.

Another option to limit installed capacity and reduce curtailment is the installation of additional power grid connections. In the REMix analysis, a model endogenous installation of additional point-to-point high voltage alternating current (HVAC) and high voltage direct current connections (HVDC) are considered.

Table 5 gives and overview over the assumed investment costs for grid and storage in the REMix model for Brazil. As the cost data is applied for 2050, cost data is still uncertain. Most of the mentioned technologies are still at an early market stage, leaving large variations for future learning effects.

Table 5: Cost assumptions for power storage and power grid[28]

	Storage				H_2 production	HVAC	HVDC	
	Pumps in reservoir hydro	Battery storage		Hydrogen storage	Electro-lyzers	Land cable	Land cable	Converter Unit
Unit	$/kW	$/kW	$/kWh	$/kW	$/kW	$/km	$/km	$
Invest-ment costs	790	371	124	30	397	593.000	279.000	185.000

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[28] Trieb, F., Schillings, C., Pregger, T., O'Sullivan, M., 2012. Solar electricity imports from the Middle East and North Africa to Europe. Energy Policy 42, 341-353

Evans, A., Strezov, V., and Evans, T. J. (2012). Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews, 16(6):4141-4147

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2 The modeling approach

The supply scenarios were calculated using the Mesap/PlaNet simulation model adopted in the previous Energy [R]evolution studies[29]. This model does not use a cost optimization approach for the calculation of energy technology expansion rather it requires a consistent exogenous definition of feasible developments in order to meet the targets. Using assumptions and background information about technical and structural options for the transformation of the energy system, and taking into account – as far as possible – potential barriers and limits, consistent development paths are defined and integrated into the model database. The model as accounting framework then calculates the energy balances of the future for all sectors as well as related investments and costs in the power sector.

For the Brazil Energy [R]evolution scenario this model is complemented by calculations using a deterministic energy system model REMix – developed at the DLR Institute of Engineering Thermodynamics, for a more detailed outlook on the power sector in 2050. A detailed description of the REMix modelling approach is given below. REMix identifies least-cost power system configurations able to satisfy the electricity demand under given constraints. In addition to different renewable technologies, the model simulations consider conventional power plants, storage systems (pumped storage, batteries and hydrogen electrolysis and reconversion) and demand side management. Furthermore, the model allows for a long-range transmission of electricity between defined model regions and compares the costs for local supply against the costs from a strategy that allows transmission of electricity across Islands. Taking into account constraints such as installed capacities or the flexibility of producers and consumers REMix simulates the interaction between all technologies in hourly

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[29] 'ENERGY [R]EVOLUTION: A Sustainable World Energy Outlook', GREENPEACE INTERNATIONAL, 2007, 2008, 2010, 2012 and 2015.

resolution and determines the least-cost design and operation of the power system.

2.1 REMix model

REMix is a deterministic linear optimization program realized in GAMS. It has been developed with the aim of providing a powerful tool for the preparation and assessment of future energy supply scenarios based on a system representation in high spatial and temporal resolution. Starting with renewable energy technologies, different power and heat generation technologies have been included in the model. Previous model applications range from least-cost green-field capacity expansion analysis to validation of long-term scenarios of European power supply and impact assessment of electric mobility, demand response and enhanced sector coupling on renewable energy integration[30]. The model set-up, as well as its input and output are shown in Figure 2.

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[30] Scholz, Y. (2012). Renewable energy based electricity supply at low costs : development of the REMix model and application for Europe, Universitätsbibliothek der Universität Stuttgart

Luca de Tena, D. (2014). Large scale renewable power integration with electric vehicles: long term analysis for Germany with a renewable based power supply Dissertation, Universität Stuttgart.http://dx.doi.org/10.18419/opus-2339

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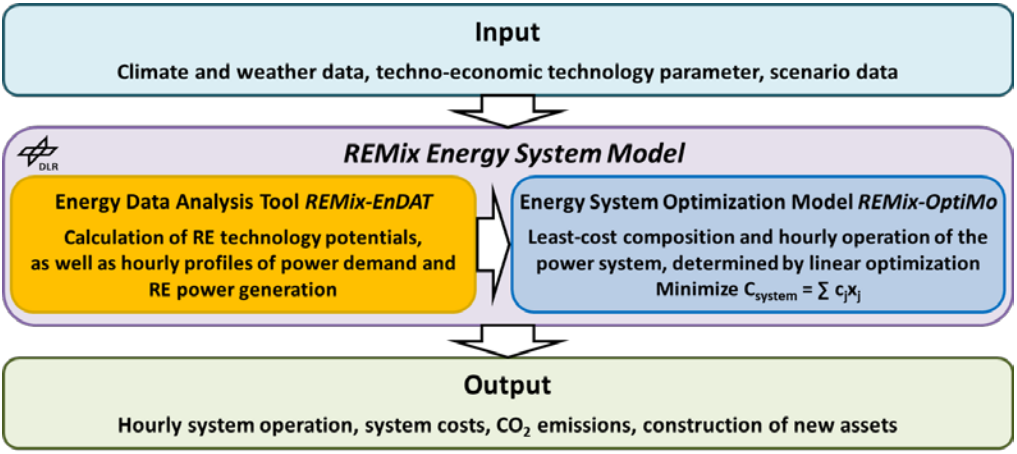
Gils, H. C. (2015). Balancing of intermittent renewable power generation by demand response and thermal energy storage Dissertation, University of Stuttgart.http://dx.doi.org/10.18419/opus-6888

Figure 2: REMix model structure



The model is programmed in a modular structure. Each technology is represented by an independent module, containing parameters, variables, equations and inequalities required for the representation of respective technical and economic characteristics. REMix is a multi-node model. Demand and supply within predefined geographical regions are aggregated to model nodes, which can be connected through electricity grids. Within the nodes, all generation units of each technology are grouped and treated as one single power or heat producer. The model relies on a perfect foresight modelling approach and optimizes over the overall time horizon. REMix is designed to offer a high flexibility concerning geographical or technological focus. All modules can in principle be applied to regions of all sizes, ranging from world regions to single cities.

Most technology modules not only allow for technology dispatch, but optionally also for capacity expansion analyses. Additional power plant, transmission line or storage capacity can be optimized by the model according to the available potentials and system requirements. Investments in new capacities consider the technology costs, as well as an amortization time and interest rate. They allow for the calculation of proportionate capital costs for the chosen optimization interval.

REMix is characterized by its objective function, boundary conditions and constraints. The latter are parametrized using a comprehensive set of input data. Model variables comprise technology-specific power generation, heat production, power transmission and storage in each time step and model region. If a capacity expansion is considered, the additional capacities in each region are furthermore taken into account. The objective function that is minimized is the sum of system costs in the overall investigation area. Its composition depends on the set of active technology modules. In each module, parameters, variables, equations and inequalities required for the representation of respective technical and economic characteristics are defined. Typically, a number of approximations and simplifications need to be done in the modelling process, striking a balance between a true to life mathematical description of technological characteristics and a reduction in the degree of complexity allowing for reasonable computing time. Generation, storage and grid technologies are mostly represented by their available and maximum installable capacity, investment and operation costs, as well as efficiency.

The model application presented in this work uses the technology modules of variable renewable energies, reservoir hydro power, concentrated solar power, conventional power plants, CHP, electricity-to-electricity storage, demand response, hydrogen production, electric mobility, as well as AC and DC power transmission. The mathematical equations of these modules have been introduced in previous publications.[31]

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[31] See previous footnote

2.2 Optimization

For the optimization with REMix a set of technologies was selected that are available in Brazil in the Energy [R]evolution scenario for 2050. These technologies include renewable power plants, power storage and power grid installations as well as electrolyzers for the production of hydrogen. One part of the technologies was given with fixed available capacity, based on the current and planned set of installations available now or in the near future. This mostly concerns hydro power, where based on a comprehensive assessment by COPPE[32] all currently operating and already auctioned power stations are considered as available in 2050. An expansion of hydro power is possible to the extent of the currently identified medium and long term (MT/LT) investment options. In addition to hydro power, a PV capacity of 100 GW is taken into accout in the Energy [R]evolution scenario. Exogenously defined capacities furthermore include smaller amounts of biomass and fuel cell CHP, as well as ocean energy.

Based on these capacities REMix optimizes the power generation in wind, CSP and additional PV and hydro power stations, as well as hydrogen reconversion, grid and storage. Table 6 gives an overview over fixed and optimized technologies in the three sub scenarios.

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[32] Soria, R., M. Imperio, C. Viviescas, F. Guedes, B. Scola, et al. (2016). Data input and comments for Energy [R]evolution Scenario Brazil, Energy Planning Program (COPPE), Universidade Federal do Rio de Janeiro.

Table 6: Overview of the exogenously defined and endogenously calculated system elements

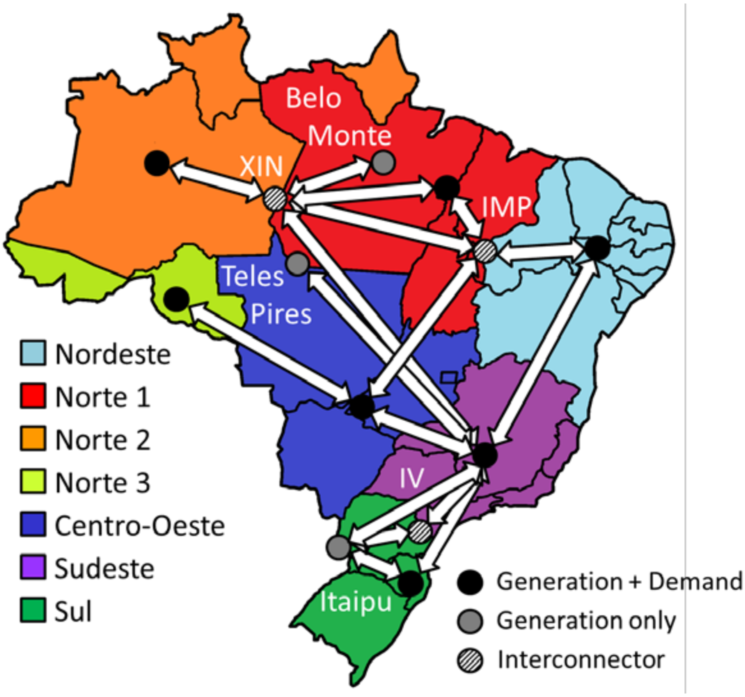
	Exogenously defined capacities	**Endogenously calculated capacities**
Generation	Run-of-river hydro power (existent and under construction) Reservoir hydro power (existent and under construction) Biomass power Biomass CHP Fuel Cell CHP Ocean energy	Run-of-river hydro power (investment options MT/LT) Reservoir hydro power (investment options MT/LT) Photovoltaic Wind onshore Wind offshore Concentrated solar power Hydrogen gas turbine Hydrogen combined cycle
Grid	Existing DC und AC lines	Additional AC and DC lines
Storage	none	Battery storage Hydrogen storage Enhancement of reservoir hydro stations by pumps
Other	Load shifting of: • Electric vehicle charging • Energy-intensive process industries • Cooling in industry and commercial sector Electric heat production in: • Boilers • Heat pumps Hydrogen electrolysis for transport, heating and power generation	

2.3 Scenario regions for REMix

In order to represent restrictions in power transmission between different parts of the country, Brazil is subdivided into ten model regions in REMix (see Figure

3). Three of these regions – Belo Monte, Teles Pires and Itaipu – represent big hydro power stations and do not have any electricity demand. The grid representation furthermore includes three interconnectors without any generation and demand, labelled XIN, IMP and IV in Figure 3, according to the labelling used by the Electrical Energy Research Center (Cepel).

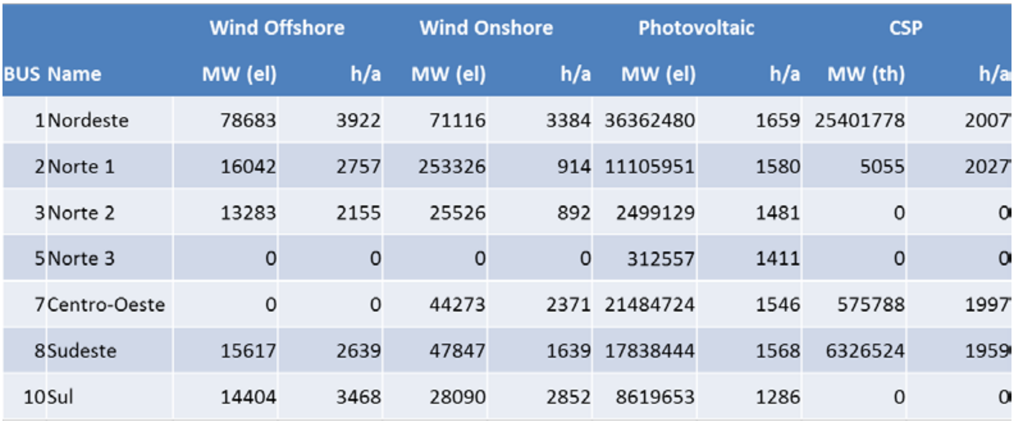
Figure 3: Model regions and grid interconnections represented in REMix.



2.4 Renewable energy potentials

The potentials for renewable energy production is a vital input for the modeling of the energy system. As described above, the modeling therefore relys on internal calculation of potentials of wind and solar power production. For the above described regions the potential is shown in the following table.

Table 7: Potentials of wind and solar power production in Brazil by region

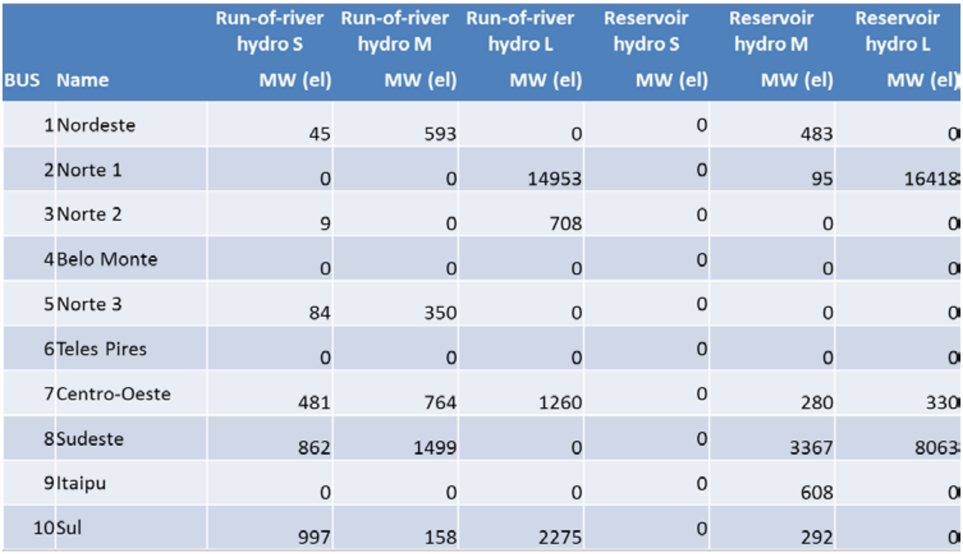


		Wind Offshore		Wind Onshore		Photovoltaic		CSP	
BUS	Name	MW (el)	h/a	MW (el)	h/a	MW (el)	h/a	MW (th)	h/a
1	Nordeste	78683	3922	71116	3384	36362480	1659	25401778	2007
2	Norte 1	16042	2757	253326	914	11105951	1580	5055	2027
3	Norte 2	13283	2155	25526	892	2499129	1481	0	0
5	Norte 3	0	0	0	0	312557	1411	0	0
7	Centro-Oeste	0	0	44273	2371	21484724	1546	575788	1997
8	Sudeste	15617	2639	47847	1639	17838444	1568	6326524	1959
10	Sul	14404	3468	28090	2852	8619653	1286	0	0

Hourly wind and PV power generation profiles as well as CSP heat generation profiles are calculated in REMix-EnDAT based on historic weather data.

Input on hydro power potentials was provided by COPPE as presented in Table 8. Daily water inflow to hydro power plants are based on COPPE data, based on averages over the years 1931-2013.

Table 8: Potentials of hydro power in Brazil by region



BUS	Name	Run-of-river hydro S MW (el)	Run-of-river hydro M MW (el)	Run-of-river hydro L MW (el)	Reservoir hydro S MW (el)	Reservoir hydro M MW (el)	Reservoir hydro L MW (el)
1	Nordeste	45	593	0	0	483	0
2	Norte 1	0	0	14953	0	95	16418
3	Norte 2	9	0	708	0	0	0
4	Belo Monte	0	0	0	0	0	0
5	Norte 3	84	350	0	0	0	0
6	Teles Pires	0	0	0	0	0	0
7	Centro-Oeste	481	764	1260	0	280	330
8	Sudeste	862	1499	0	0	3367	8063
9	Itaipu	0	0	0	0	608	0
10	Sul	997	158	2275	0	292	0

Combining the above described technical and economic data, we calculated the Brazil Energy [R]evolution scenario both in the MESAP/Planet environment as well as in the REMix optimization model. The results have been presented in the Brazil Energy [R]evolution scenario report. For sensitivity we additionally calculated the above documented sub scenarios with REMix, validating the presented Energy [R]evolution scenario under different framing conditions.

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