Targeting a 100% renewable energy system: The Cases of Brazil and the Canary Islands

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ABSTRACT

This paper presents a methodology for the development of normative energy scenarios. The focus is on cross-sectoral transformation pathways towards a completely renewable energy supply. By using the REMix energy model, which is temporal and spatially highly resolved, the least-cost power supply structure is assessed. The model also calculates additional storage and grid capacity necessary for the target year 2050. By analyzing the interactions of different technologies and sectors we provide a basis for the backcasting of a transformation pathway. This is carried out by a simulation model within the MESAP-PlaNet environment, covering the heat, transport & power sectors. We present and compare feasible transformation pathways towards a 100% renewable energy supply for two case studies, the Canary Islands and Brazil.[1]

KEYWORDS

Normative energy scenario, Energy system modelling, Renewable Energy, Canary Islands, Brazil, REMix, MESAP-PlaNet

INTRODUCTION

To achieve the goals defined in the Paris Agreement, greenhouse gas emissions need to decline by 70-95% until 2050 [1]. It is evident that this demands a decarbonisation of the global energy system. Due to investment cycles for energy infrastructure, long term planning for an emission free energy system is a prerequisite in order to achieve the proposed emission reduction. Renewable Energy (RE) sources are a proven option to reduce greenhouse gas (GHG) emissions. However, the integration of RE provides major challenges such spatial and temporal variability of the energy supply and a high uncertainty in the future technical and economic development of comparatively new technologies such as wind and photvoltaic (PV) [2]. Several studies have targeted a 100% renewable energy system, focusing mostly on European countries [3-8]. While European countries are well developed and strongly interconnected, both in economic and technical respect, facilitating the RE integration into the system [9], other regions (e.g. newly developing countries) face additional challenges, such a lack of infrastructure, amplified by a strong growth in demand.

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[1] The case studies were partially funded by Greenpeace Brazil and Greenpeace International respectively

Our paper therefore targets 100% renewable energy systems under more difficult conditions such as an isolated power system or a strong growth in energy demand due to economic and population growth. We present a methodology for model based scenarios of a completely RE energy supply. It includes a cross-sectoral assessment of the provision of electricity, heat and mobility and can be easily adapted to other countries. The methodology presented below is applied in two case studies which address the additional challenges mentioned above: On the one hand we target the Canary Islands, which are rather remotely located in the Atlantic. And on the other hand we focus on Brazil, a newly industrialized country, ranking 5th in population and 9th in gross domestic product (GDP) globally.

METHODOLOGY

We developed scenarios for a 100% RE supply by 2050, using a combination of energy system models. The two energy system models MESAP-PlaNet [10] and REMix [9] were coupled as presented in
Figure 1 and described in the next section. The scenarios are based on a target-oriented, so-called backcasting approach.

Energy System Models

MESAP-PlaNet [10] provides the framework for our bottom up accounting model. With our model we calculate energy system balances from demand to primary energy supply. MESAP-PlaNet simulates the development of the energy system from today's state to a target year 2050 based on annual energy balances. The calculations are carried out in five year steps. Population and economic development serve as central drivers of the energy demand, based on national and international projections. Within this tool we balance demand and supply for industry, residential & services, and transport separately. The model features comprehensive techno-economic data of the currently available fossil and renewable technologies considered to cover this demand. Efficiency potentials are taken into account as well as restrictions by the potentials of RE technologies.

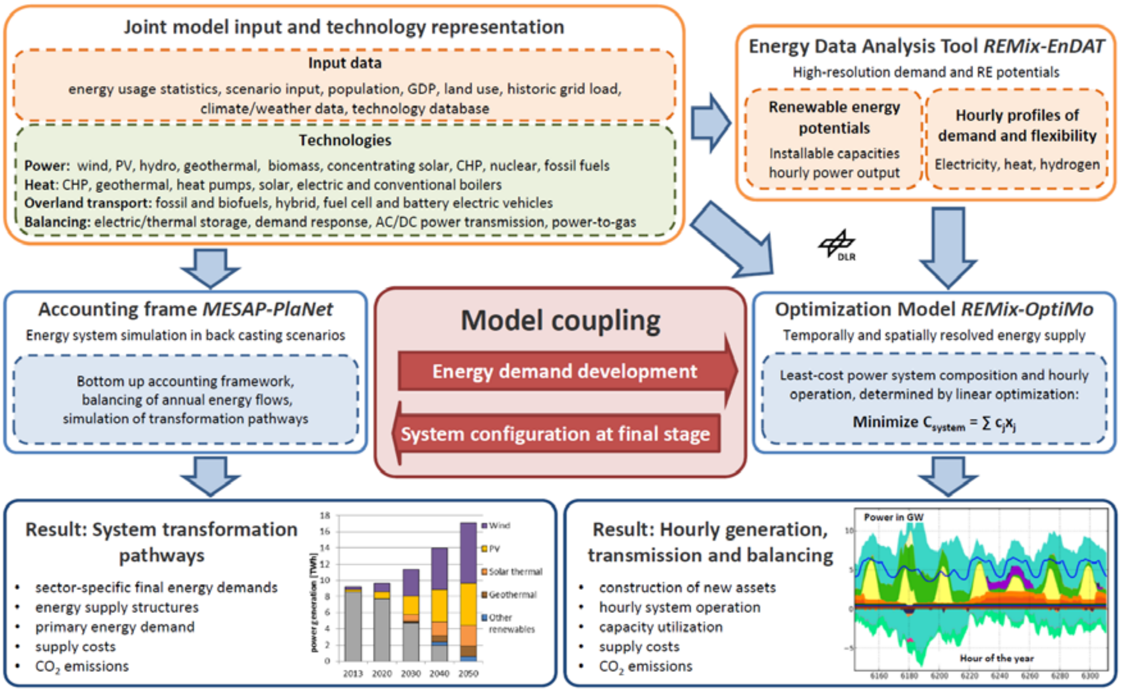

Figure 1. Model coupling between MESAP-PlaNet and REMix [18]

An insight into the application of MESAP-PlaNet is provided by earlier studies on transformation scenarios on global level [11, 12]. Detailed descriptions of technology data can be found in [13].The resulting power demand, including electric mobility and electric heating, from the MESAP-PlaNet model for 2050 serves as an input into the optimization model REMix. It identifies least-cost power system configurations that satisfy the electricity, heating and synthetic fuel demand on hourly basis. The model takes into account the installable services and the hourly availability of RE. REMix provides a simplified representation of the power supply system, including sector coupling. This includes cogeneration, electrical heat generation, electric vehicles, industrial load management, as well as storage, power transmission and, where appropriate, reconversion of synthetic fuels. A detailed model description is contained in [9]. Our case studies particularly focus on the model-endogenous addition of new infrastructures for the target year 2050. This covers new renewable power plants such as wind turbines and solar power plants, but also the need for additional power transmission lines and storage. REMix applications with different geographic and technological focus have been described in previous publications, including [9, 14, 15].

The REMix results are fed back to the MESAP-PlaNet model, serving as a target for 2050 and thus the baseline for backcasting the transformation pathways. First, it validates the power supply system in MESAP-PlaNet with regard to an hourly balance of demand and supply. Second, it allows for adapting the transformation pathways towards minimum power costs. Finally, REMix provides information about additionally necessary storage and network infrastructure, which is not covered by the MESAP-PlaNet model.

Data and Scenarios

We apply our scenario methodology to the Canary Islands and Brazil. A comprehensive documentation of the respective model input data can be found in [16] for the Canary Islands and in [13, 17] for Brazil. The following overview summarizes the central assumptions: Basic projections of future energy demand follow the current policy development of the intensities in industry, transport and other sectors for the respective region or country of the IEA World Energy Outlook [18]. National projections for population, GDP and energy efficiency were used to adapt the energy demand scenarios of the case studies. Efficiency potentials were derived from [19] and [20] and were transferred to regional level. The RE potentials were assessed by the global resource analysis module REMix-EnDAT [21] on high spatial resolution and additionally backed up by national assessments. The hourly resolution of power demand is based on metered profiles of the grid load.

Canary Islands. Population, GDP and thus energy demand for the Canary Islands was adapted from national projections for Spain (see [16]). Efficiency potentials are based on [22]. Aviation and navigation are assessed separately and are not part of this paper[2]. Due to the limited biomass potential and the low share of high temperature process heat demand in industry and services the transformation pathways were adjusted with higher shares of solar thermal heat and power-to-heat applications as well as higher shares of electric mobility as described in [23]. This electrification of the heat and transport sectors led to a specific focus on the power sector of the islands. Due to strong land use competition on the Canary Islands, total installable capacity of PV, concentrated solar power (CSP) and wind is strongly limited. However, high solar irradiation and wind speeds during the year lead to high quality RE potential. Wave energy and wind power can be exploited in the near-coastal waters [24, 25],

[2] System boundaries for aviation and navigation data are not consistent with the described approach.

even though the depth of the sea bed requires floating installations. The expansion of water, wave and geothermal power plants, as well as biomass cogeneration was exogenously predetermined, as the potentials are very limited. In contrast, capacity of wind, PV and CSP power plants were output of the optimization. For balancing the variable renewably energy (VRE), several options were considered: The numerous existing water storage facilities on the islands offer some potential for the installation of pumped hydro storage [26]. Due to the relatively short distance between the islands of a maximum of about 160 km, the construction of submarine grid connections is in principle conceivable and partly already realized. Still, the sea depths and the difficult sea bottom pose a particular challenge for grid connections between most of the islands. Current technology only allows for connections between Lanzarote and Fuerteventura, between Gran Canaria and Fuerteventura, as well as between Tenerife and La Gomera. To consider the current power transport on the islands, the two largest - Tenerife and Gran Canaria - were divided into two regions in the REMix model (see Figure 3).

Brazil. Only few countries in the world can draw on such a vast potential of different RE resources as Brazil. This includes not only hydropower and biomass, the current pillars of energy supply, but also wind and solar power. Consequently, the focus of the scenario development was less on the question of whether a completely renewable supply is possible at all, but rather how RE can be implemented cost-effectively. Demand projections were based on national data for population and GDP development (for details compare [13]), while efficiency potentials were taken from the Latin American region from [19]. Based on the high biomass availability [27], only a low electrification of the transport sector was assumed.

In order to assess the regional distribution of power plants and the necessary grid expansion, demand and production were allocated to seven regions in Brazil. In addition, three network nodes at large hydroelectric power stations, as well as three network junction points were considered (see Figure 7). Today's existing hydropower plants were expected to be available in the future, just like the existing facilities already under construction. A model-endogenous addition of hydroelectric power plants was possible within the current plans for hydro dams [17]. A detailed outline of the power system model input is provided in [28]. Additional constraints for the power sector included the political target of 100 GW of PV plants near the demand centres in Brazil [29].

Scenarios. For each case study we developed a demand scenario driven by population and GDP based on a business-as-usual approach, adding efficiency potentials as well as the potential for electrification in all demand sectors, all according to the above described assumptions. In order to evaluate the role of individual central technologies separately, different supply scenarios were calculated: In the scenario RE Base the REMix model optimized power supply without additional constraints. For the Canary Islands we additionally analyzed a scenario Grid +, which assumed that complementary grid connections can be established between the islands. Additional power scenarios are presented in [16] for the Canary Islands and in [28] for Brazil.
In the next section we first present the development of energy demand in both analyzed regions, focusing on the resulting power demand. Next, we focus on the various options the REMix scenarios depict for a secure supply and finally present transformation pathways and emission effects.

RESULTS

Energy demand

GDP and population growth were expected to increase final energy demand in both regions by more than 40% compared to today (under "business-as-usual" conditions) during the complete time horizon. For 2050 this resulted in a final energy demand of around 130 PJ in the Canary Islands and 12.9 EJ in Brazil (see
Figure 2). In the Canary Islands the residential, service & commerce sectors were the main drivers of consumption, as was the industry for Brazil. Our simulation showed that a consequent implementation of efficiency potentials until 2050 can reduce projected final energy demand by half. Increased electric mobility and substitution of inefficient fossil & biomass heat use by modern renewable technologies and power are supporting this efficiency improvement. In the RE Base scenario final energy demand in 2050 dropped to 58 PJ in the Canary Islands and to 6.8 EJ in Brazil.

Electrification in industry, transport, residential & other sectors led to an over proportionate increase in power demand to 12 TWh in the Canary Islands and 860 TWh in Brazil (both for 2050). The massive electrification of road traffic raised electricity demand from practically zero to 1.8 TWh on the Canary Islands, covering more than 50% of road transport. While electric transport was less pronounced in Brazil, it still required 126 TWh in 2050. Here the massive electrification in industry also increased demand growth significantly, resulting in an overall industrial power demand of 320 TWh in 2050. This sectoral power demand served as an input for the REMix optimization.

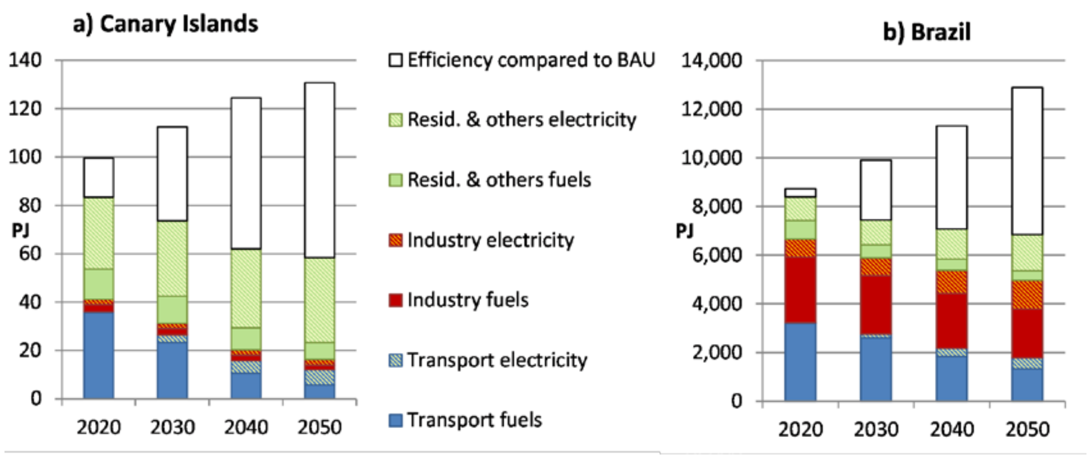

Figure 2: Final energy demand development by sector in the 100% RE Base scenario (RE Base), disaggregated by fuels and electricity

Power supply scenarios

The results of the REMix modeling showed the cost-minimized capacity for electricity generation in the target year 2050. Further results can be found in [13, 16, 17, 28]. Due to the different availability of RE potentials, supply systems were structurally different for the two case studies and are described separately in the following.

Canary Islands. With hydropower and biomass being very limited available, the power supply in the Canary Islands was mainly based on wind and solar energy (see Figure 3 and Figure 4).

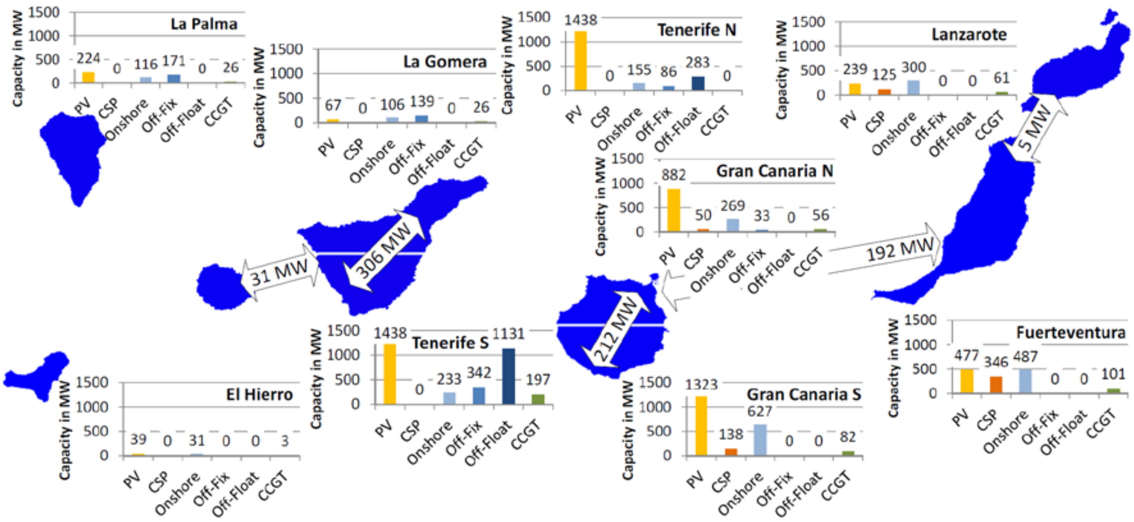

Figure 3: REMix results for installed capacity of power plants and transmission grids on the Canary Islands, scenario RE Base [16]

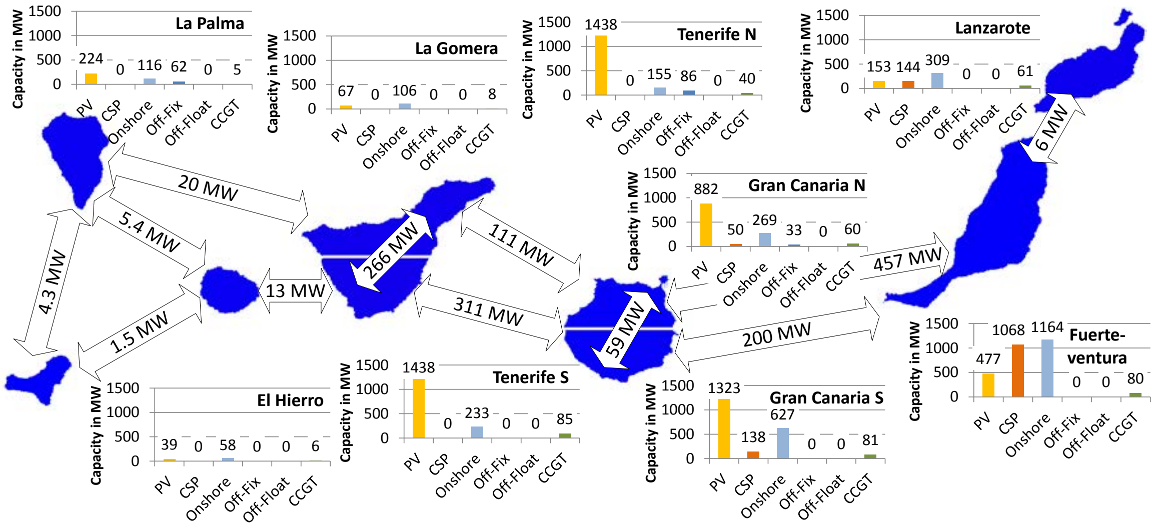

Figure 4: REMix results for installed capacity of power plants and transmission grids on the Canary Islands, scenario Grid+ [16]

To supply the increased demand, the potential for PV and onshore wind power was fully exploited on almost all islands. In order to securely supply power throughout the year, additional offshore wind plants and reconversion of hydrogen were necessary. The other technologies - geothermal energy, wave energy, run-of-river power and biomass cogeneration - contributed only very little to the power supply (see Figure 7) and were externally specified. VRE were compensated for by pumped hydro storage, battery storage, controlled charging of battery electric vehicles, as well as flexible hydrogen electrolysers, seawater desalination plants and electrical heat generation. Additional grid connections could tap significant, cost-effective CSP potentials, reducing expensive floating offshore wind installations (see Figure 3 and Figure 4). Especially the grid connection between the two largest islands of Tenerife and Gran Canaria was essential. This led to substantial reduction in the supply costs, reducing electricity generation costs from 19.5 €ct/kWh in scenario RE Base to 16.6 €ct/kWh in Grid+, whereas other options such as load management had a minor effect on the cost structure. [16].

Figure 5 illustrates the role of different load balancing options (a) and power transmission (b). In all scenarios about 15% of annual power was supplied by storage options or shifted by load management. Scenario Grid+ had only a minor effect on load management and pumped storage, but could replace battery storage completely and also two-thirds of hydrogen back-up. While the totally transmitted power increased only slightly, Grid+ significantly redirected power production from Tenerife to Fuerteventura, which then exported around 25% of total power demand of the archipelago.

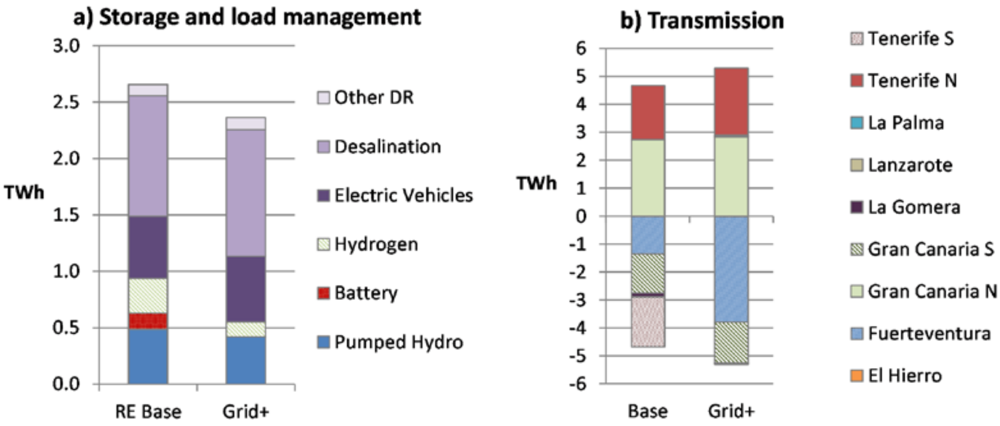

Figure 5. REMix results for (a) storage and load management and (b) regional power imports (positive) and exports (negative)

Brazil. The second case study of Brazil started from a completely different situation, supplying 80% of its power from hydro. Also in the long term, hydropower and biomass dominated a cost-effective generation mix. Still, the currently dominant hydroelectric power decreased to only about 45% of the electricity supply in the target year 2050 (Figure 6). The scenario could secure supply throughout the year, balancing wind and PV by hydro, biomass and CSP.

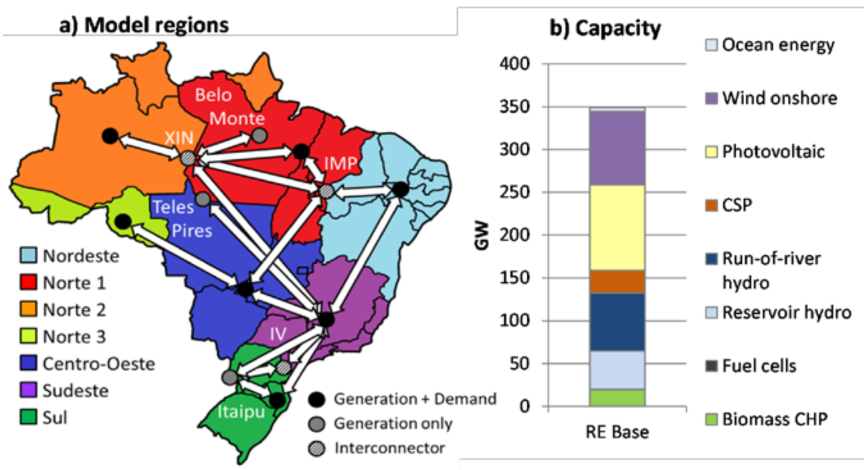

Figure 6. Model regions (a) and REMix results for power capacity for Brazil in 2050

Biomass contributed only about 7% of electricity generation and was applied rather in the heat and transport sector (see Figure 8). In RE Base the current capacity and the predefined 100 GW of PV were mainly supplemented by about 90 GW of wind power. The endogenous installation of CSP power plants accounted for 26 GW.

Specific generation costs of the electricity system were calculated at about 7 €ct/kWh. The costs are well below the level of the Canary Islands, with its additional infrastructure demand. In contrast to the Canary Islands, load management and storage in Brazil were only used to a very limited extent. Fluctuations in demand and generation of RE are largely offset by hydro dams, biomass and the grid.

Transformation pathways

The REMix results served as a basis for backcasting the energy supply system, which is presented next. We used the RE Base case in both regions to analyze the necessary development towards a 100% RE supply by 2050. Figure 7 shows the evolution of power generation until 2050 in the MESAP-PlaNet model. In both regions the transformation required a strong expansion of wind and PV already in the next years. CSP will become increasingly important from 2030 on. This would allow for phasing out oil power plants on the Canary Island, cutting the capacity by half until 2030. A completely RE supply by midcentury needed a quadrupling of capacity on the archipelago. This will not only provide for the increased power demand but will also completely substitute energy imports for heat, power and local transport supply.

Also in Brazil an accelerated expansion of RE was necessary. The PV capacity then doubled in every subsequent decade, while the addition of wind power plants slowed down after 2030. However, as wind and PV power could be balanced by hydro, the fossil power production was reduced to 1/3 already by 2030.

Heat demand in the scenarios was strongly reduced through efficiency potentials. In the Canary Island it was mainly supplied by power, solar and heat pumps (see Figure 8). From 2040 on biomass and reconversion of RE hydrogen (mainly via CHP-applications) provided the necessary high temperature heat.

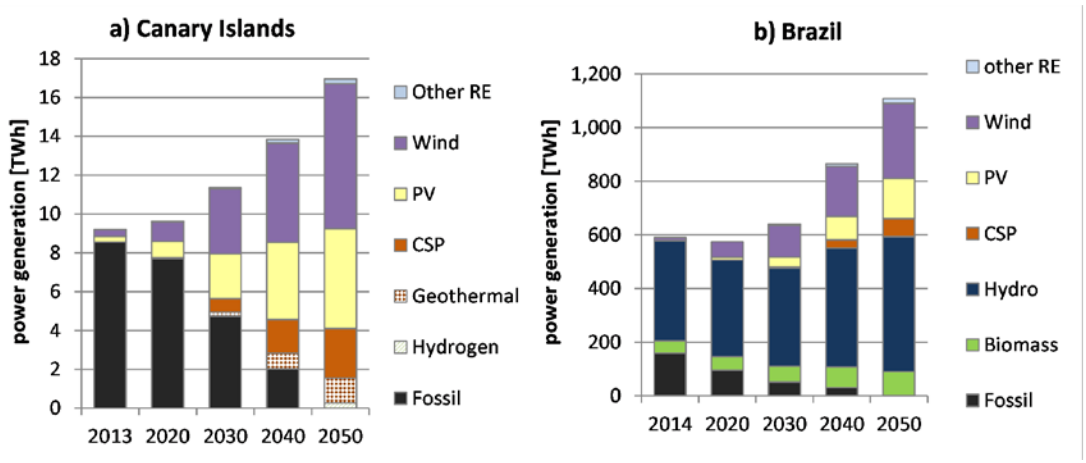

Figure 7: Transformation pathways for power production in the Canary Islands (a) and in Brazil (b)

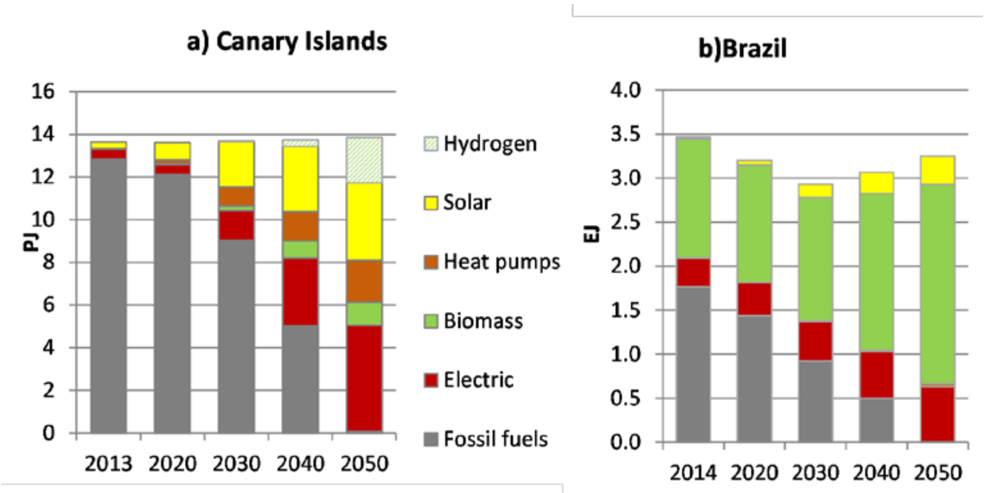

Figure 8. Transformation pathways for heat supply in the Canary Islands (a) and in Brazil (b)

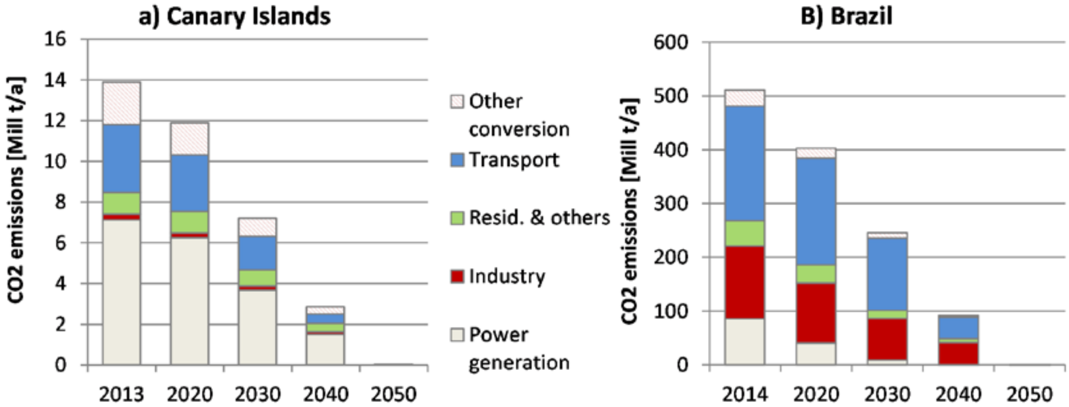

Figure 9. Development of direct CO_2 emissions for (a) the Canary Islands and (b) Brazil

In Brazil, this demand section was completely supplied biomass, which is already a main energy carrier e.g. in the sugar industry. Especially in the residential sector solar and electric heat applications provide for a diversification of the heat supply. Along the described pathways a reduction of direct energy related CO_2 emissions of 50% would be possible by 2030 and a complete elimination by 2050 in both regions, as showed in Figure 9.

DISCUSSION AND CONCLUSIONS

Based on the increased electrification of heat and transport, combined with hydrogen and – in the case of Brazil with biofuels – a complete phase out of fossil fuels is possible by 2050. Our results show, that the thus increased power demand in 2050 can be securely supplied by RE, integrating around 40% of VRE into the power system in Brazil at around 7-8 €ct/kWh. For the Canary Islands 70% of VRE are backed up by CSP and grid extension at costs of around 17-20 €ct/kWh. Here costs for storage and grid infrastructures account for 1/3. For both regions alternative scenarios for the power sector showed only minor differences in generation costs [16, 28].

By coupling two energy system models, we provide an easily adaptable methodology to assess possible transformation pathways, which makes a significant contribution to the improvement of supply scenarios. The REMix modeling with its high temporal and spatial resolution allows to determine storage and grid demand at high shares of RE and can thus quantify the integration costs for fluctuating RE. Further flexibility options such as load management and sector coupling can also be analyzed at hourly level. The high-resolution wind and solar resource assessment in REMix also accounts for their fluctuations and regional differences in full load hours. The MESAP-PlaNet model relies on REMix for validation of the target and complements the perspective by including heat and transport. The results of the case studies represent a feasible transformation toward a completely RE supply in all demand sectors, in the Canary Islands as well as in Brazil.

The case studies represent two rather different pathways towards a complete decarbonisation. According to the resource potential the Canary Island's supply must mainly be based on PV and wind power, which is then transferred to the heat and transport sectors directly or indirectly via hydrogen production. Here the grid extension and sector coupling are central elements for reducing curtailment and system costs, even though installing the necessary infrastructures is ambitious. The REMix calculations for Brazil show that the expansion of wind, PV and CSP is cheaper than the construction of additional hydroelectric power stations. This is favored by the fact that the existing hydroelectric power plants already offer large capacity of dispatchable power to compensate for fluctuations, and thus no additional storage is necessary. Biomass could be the backbone for heat and transport in Brazil. However efficiency improvements in traditional biomass applications should ensure a sustainable exploitation of the biomass potential. Unlike in the Canary Islands, sector coupling and RE hydrogen play a minor role for heat and transport, due to significant biomass potentials. With biomass potentials becoming increasingly exploited and exported globally, however, sector coupling might become increasingly important in Brazil as well.

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