Carbon neutral archipelago – 100% renewable energy supply for the Canary Islands

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Highlights:

- A pathway to a 100% renewable energy supply for the Canary Islands is presented
- Hourly system operation is analysed, considering flexibility options and sector linkage
- Results show feasibility of a carbon neutral energy supply with local resources
- High resolution power system model highlights importance of grid connections

Abstract:

As many other small islands and archipelagos, the Canary Islands depend to a high degree on energy imports. Despite its small surface, the archipelago has a high potential for renewable energy (RE) technologies. In this paper, we present a scenario pathway to a 100% RE supply in the Canary Islands by 2050. It relies on a back-casting approach linking the bottom-up accounting framework Mesap-PlaNet and the high resolution power system model REMix. Our analysis shows that locally available technology potentials are sufficient for a fully renewable supply of the islands' power, heat, and land transport energy demands. To follow the pathway for achieving a carbon neutral supply, expansion of RE technology deployment needs to be accelerated in the short-term and efforts towards greater energy efficiency must be increased. According to our results, an extended linkage between energy sectors through electric vehicles as well as electric heating, and the usage of synthetic hydrogen can contribute notably to the integration of intermittent RE power generation. Furthermore, our results highlight the importance of power transmission in RE supply systems. Supply costs are found 15% lower in a scenario considering sea cable connections between all islands.

Abbreviations:

BAU – Business-As-Usual, BEV – Battery Electric Vehicle, CCGT – Combined Cycle Gas Turbine, CHP – Combined Heat and Power, CSP – Concentrating Solar Power, DC – Direct Current, DR – Demand Response, GDP – Gross Domestic Product, GHG – Greenhouse Gases, PSH – Pumped Storage Hydro, PV – Photovoltaic, RE – Renewable Energy, TES –Thermal Energy Storage

1 Introduction

The need to mitigate anthropogenic global CO_2-emissions increasingly focuses on the current energy system, which produced 78% of global greenhouse gas (GHG) emissions between 1970 and 2010 [1]. Policy already addresses the transformation of the existing system towards a more sustainable energy supply on a large scale [2] and local action plans aim at an increased use of renewable energies. The integration and balancing of large fluctuating renewable energy supply with the future demand represents major challenges for national and continental energy systems. For Island systems these challenges are even more pronounced. Owing to their remote situation, islands are often dependent on fossil fuel imports, which are typically expensive due to transport costs [3, 4]. Remoteness and size lead to small isolated markets, with few actors and a low diversity of technologies [5]. Island economies often rely strongly on tourism, with a strong impact on structure and variability of the energy demand [4].

Renewable energy (RE) technologies provide solutions for a more sustainable and self-sufficient energy supply [6, 7]. However, the possibilities to balance fluctuations in power generation and demand through interregional electricity transmission are typically very limited or not available at all in island systems. Consequently, other flexibility options must be employed, including storage, demand response (DR) as well as synthetic fuel production [6, 7]. Considering this, island solutions can act as role models for future energy transition in larger systems.

Supply systems predominantly or fully reliant on RE technologies have been studied for various countries and islands. On a European level, the impact of different balancing technologies on electricity supply and costs has been assessed previously for RE shares of up to 80% [8]. In this work, grid could reduce costs at high RE shares, whereas storage was not cost-efficient. For Portugal, a 100% RE power supply system has been designed before, treating the country as an island system with no international electricity exchange [9]. The possibility of a fully renewable power supply has been evaluated as well for France, showing a significant need for flexibility options along with imports and DR [10]. For the United Kingdom, an analysis of the future power supply in high temporal and spatial resolution found that for more than an 80% RE share to be economically feasible, large-scale storage, significantly more power imports, or domestic dispatchable renewables must be available [11]. These studies were limited to power supply and did not consider energy demands of other sectors. For Ireland, is has been shown that electricity, heating, and transport demands can be completely supplied by RE [12]. Owing to the abundant availability of biomass, intermittent technologies played only a minor role in this work. With the analysis relying on the application of a detailed energy system model, it did not provide any cost assessment. In a subsequent study, the cross-sectoral transition towards 100% RE supply in Ireland has been described in more detail, including an economic assessment [13]. There, wind power was rated most important future energy source, whereas photovoltaics (PV) and ocean energy were not considered. Considering the whole energy system, a 100% RE supply has been designed for Denmark as well [14]. All these national studies did not evaluate internal power transmission.

Specifically for island energy systems, the RenewIsland methodology introduced in [15], provides a framework for mapping demand and supply of energy and water as well as the development of scenarios. Amongst other, it has been applied to Cozumel/Mexico, Porto Santo/Portugal, and Mljet/Croatia [16]. The model relies on a merit order approach and does not optimise the layout and operation of the system components. Based on high resolution data, potential supply cost reductions that can be achieved by RE technologies have been identified on almost 1800 small islands globally [17]. However, this analysis was limited to the power sector and did not consider other balancing technologies than battery storage and diesel generators. A more detailed comparison of electricity demand and RE potentials has been provided for Salina/Italy [18]. Similarly, it has been shown that up to 90% of the electricity demand of Dia/Greece can be supplied by RE technologies [19]. This work proposed to use surplus generation from intermittent resources for seawater desalination. By adjusting their operation to the availability of intermittent RE, desalination plants can enable supply cost reductions [20]. Applying a power system model in hourly resolution to the island of Lesbos/Greece, it has been found that a grid connection to the mainland can reduce supply costs and enable higher wind shares [21]. The importance of energy storage in island systems has been highlighted in a cross-sectoral case study for an imaginary island, [22]. All these studies are limited to the assessment of energy demand and RE potentials, but do not provide a scenario of how to transform the energy supply system.

The available studies on sustainable energy systems and islands are limited mostly to the power sector, and do not reflect the advantages of linking power, heat, transport, and water supply. Furthermore, previous works did neither consider the supply potentials across the large bandwidth of RE technologies, nor provide pathways towards a 100% RE supply system. Instead, they focused either on the final or intermediate stages of the system transformation. Our paper closes this gap by providing a novel approach to the development of cross-sectoral transformation pathways towards a 100% RE system, focusing on a potential supply structure for the future local energy demand. We therefore combine a long-term outlook on transformation pathways with a detailed insight in the interdependencies of an interconnected energy system based mostly on fluctuating power sources. Additionally we focus on connecting neighbouring island power systems to provide insight beyond existing research. We apply this approach to the Canary Island archipelago, which represents an example for a remote island system of relevant size [23]. The archipelago with 2.2 million inhabitants is situated west of the African coast and politically part of Spain. Starting with Lanzarote and Fuerteventura, situated 100 km west of Morocco, the archipelago stretches out more than 300 km to the west across seven islands. Gran Canaria and Tenerife at the centre are the largest islands with a population of 0.85 million and 0.89 million people, respectively. Further to the west the archipelago extends to the smaller islands La Gomera, La Palma, and El Hierro. Tourism is the main economic sector and concentrated in the four larger islands. It is strongly developing, with guest-nights increasing from 11 million in 2010 to 14 million in 2014 [24], putting additional pressure on the energy system. The Canary Islands are part of a cluster of near tropical islands, featuring high solar irradiation, low precipitation with high seasonality. The seven islands feature low PV and wind generation costs at high generation rates and represent a large variety in population density and land availability[23]. As for many other islands and archipelagos, so far the Canary Islands' energy supply depends almost totally on oil imports [25]. Alternatives are being assessed or promoted, including RE sources, natural gas imports and an improved grid connection between the islands [25, 26]. While transformation scenarios are already available on national level for Spain [27], they cannot directly be transferred to the remote Canary archipelago. One of the few previous studies dedicated to the archipelago's energy supply proposed a wind powered pumped hydro system for the island of Gran Canaria [28]. Furthermore, the complementarity of natural gas and renewables in the Canary Islands has been evaluated, suggesting that both supply risks and costs are lowest in a balanced mix of both [5]. So far, no comprehensive long-term study of a sustainable energy supply in the Canary Islands is available. Starting from the current energy system, we elaborate a transformation pathway towards a 100% RE supply in the year 2050, considering RE and efficiency potentials as well as interdependencies between power, transport, and heating sectors.

The present paper is structured as follows: Section 2 gives an overview over the current energy system in the Canary Islands. Section 3 introduces the two applied models Mesap-PlaNet for long-term modelling and REMix for optimisation with high resolution as well as their calibration and linkage for this study. The model input data is described in Section 4. Model results including supply structures and impacts on CO_2 emissions are presented in Section 5 and discussed in Section 6. Finally, the main conclusions from the results are drawn in Section 7.

2 The Canary Island energy system

The Canary Island’s government provides detailed statistics on the local energy system [25]. Currently this system is characterised by a heavy dependence on oil imports, delivering 99% of primary energy. Oil is used for power generation, heat production and land transportation. Road traffic accounts for 45% of internal final energy consumption, such as the residential, service, and commerce sectors, while industry plays a minor role (6%). Renewables are still in the beginning of their development, providing 7% of power and 2% of heat supply. However, a broad range of renewable technologies is already available, including PV, wind energy, hydropower, and solar thermal collectors.

Table 1 shows the recent development of the main energy-economic indicators in the archipelago, which saw considerable variations during the last years. Energy intensity in the power sector is higher than in the Spanish mainland, nonetheless efficiency improvements are targeted by the government by subsidies, as a means to reduce CO_2-emissions [25].

Table 1: Energy intensity and per capita demand in the Canary Islands [25].

	primary energy	final energy	Intensity (primary energy)	Intensity (final energy)	per capita
	PJ	PJ	GJ/€	GJ/€	GJ/cap
2011	207	151	4.96	3.60	71
2012	235	147	5.66	3.53	69
2013	221	137	5.47	3.39	65

The energy sector is the main GHG emitter in the Canary Islands. Starting at about 8 kt CO_2-equivalents (eq) in 1990, total emissions peaked between 2005 and 2008 about 16 kt CO_2-eq, of which 90-92% resulted from the energy sector. Since then, emissions have been decreasing by 10-15%, coinciding with the economic crisis. In the same period, emissions from the energy sector even declined by 25%. Per capita emissions are also declining, adding up to 6.3 t CO_2-eq/cap in 2012.

These figures show that efforts for decreasing emissions are increasingly effective. Still, it is a long way towards a sustainable energy system for the archipelago. Applying our modelling approach, we are shaping a scenario for a potential pathway towards a more sustainable energy supply, integrating efficiency and RE potentials.

3 Methodology

For the analysis of a 100% RE system in the Canary Islands, we enhance our modelling approach by linking the long-term energy system balancing tool Mesap-PlaNet with our deterministic high-resolution energy system optimisation model REMix (Figure 1). Both models are introduced in the following as well as the link between them and the scenario approach for assessing future development pathways for the energy system.

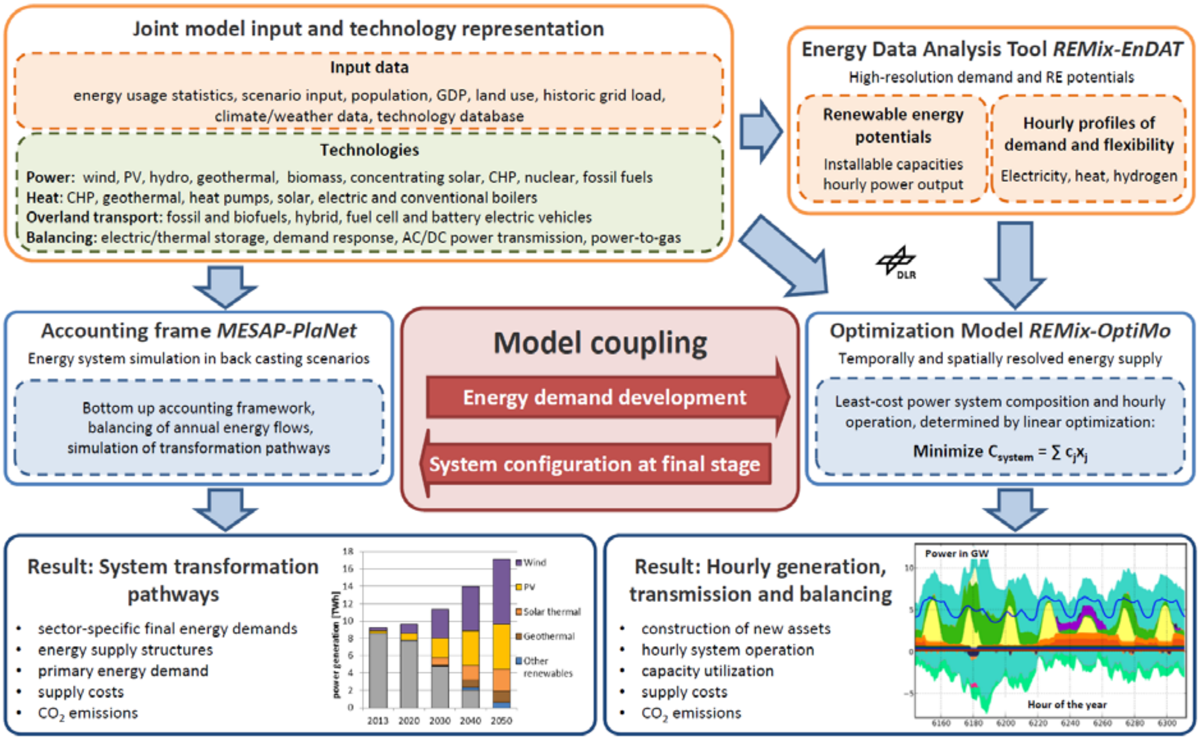

Figure 1: Modelling approach

3.1 Scenario approach and model coupling

The development of the future energy demand is assessed in an explorative scenario approach. Based on that, we apply a normative scenario approach to evaluate the restructuring of the energy supply system. Starting with a target of a 100% RE system in 2050, we develop a transformation scenario in a back-casting process, evaluating the steps that are necessary to achieve the target.

The long-term outlook performed with the Mesap-PlaNet model is technology driven and focuses on interdependencies of the sectoral transformation in the long-term as well as diversification of the energy system. The model is balancing the annual energy demand and supply for the whole archipelago in 5-year steps. While this method provides annual energy balances for heat, transport, and power sectors, it lacks a detailed insight in the complex interrelations of intermittent power generation and demand curves, respectively their geographical interconnection via power grids and the temporal balancing via storage. For this reason, the cross-sectoral approach is back-filled with detailed optimisation of the power sector for the year 2050 with REMix. The model assesses least-cost composition of generation, grid, and storage capacities in high spatial resolution, and provides an evaluation of the hourly system dispatch. By using REMix, we analyse three sub-scenarios for a 100% renewable system, focusing on different balancing options for variable renewable power (Section 4.5).

To combine the two models, we apply an iterative modelling approach.

1. Development of a business-as-usual energy demand scenario and assessment of efficiency potentials within the industrial, transport, and other sectors.

2. Determination of the least-cost power supply technology mix for the year 2050 and 100% RE, including secondary power demand from transport and heat production with REMix.

3. Development of the transformation pathway for the whole energy system with Mesap-PlaNet, using the REMix results of energy outputs, installed capacities, and load factors

3.2 Mesap-PlaNet model

The overall energy system of the Canary Islands is represented within the Mesap-PlaNet energy simulation model [29, 30]. This bottom-up accounting framework can be applied for the calculation of annual energy system balances [31, 32]. The Mesap-PlaNet flow calculation uses a set of linear equations, which are solved sequentially. The model requires a consistent exogenous definition of feasible developments for each sector and technology.

Starting with externally defined drivers such as GDP and, the model first calculates the demand for energy services via intensities, including electricity consumption per capita and industrial heat demand per unit of GDP. As a result, useful heat demands as well as electricity demands are determined for three sectors: industry, transport, and “Other Sectors”, which comprise residential, agriculture, service, and commerce. Each sector is represented by set of available technologies, both renewable and fossil. Backbone of the model is a technology database, defining parameters for intensity, efficiency, fuel input, CO_2 emissions, full-load hours, and – in the case of power technologies also investment costs and life time.

By using assumptions and background information about technical and structural development options for the energy system transformation, and considering potential barriers and limits such as RE potentials, consistent development paths are defined and integrated into the model database (Section 4). This scheme allows for the integrated calculation of energy flows from demand drivers to primary energy consumption. Eventually, the model calculates future energy balances with primary energy consumption, sectoral CO_2 emissions, and power generation cost in five year steps until 2050.

3.3 REMix model

REMix provides a simplified representation of the power system, including demand, renewable and conventional generation as well as storage, DR, and power transmission[1]. The model is not limited to the power sector, but also contains demand and supply of heat as well as synthetic fuels, and electric mobility. The model input comprises techno-economic technology parameter, scenario parameter (e.g. installed power plant capacities) as well as spatially resolved climate and weather data for each hour of the year. The latter is used in the energy data analysis tool REMix-EnDAT for the calculation of hourly wind and solar power production profiles. Relying on this input data and using linear optimisation, REMix-OptiMo assesses the least-cost composition and operation of the energy system during one year. The minimised costs comprise all expenditures arising from the installation of new assets and the operation of all assets, thus capital costs, fuel costs as well as other variable operational costs. Model results comprise the installation of new assets, the hourly operation of all

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[1] This paragraph relies on [33, 34]

assets, supply costs, and CO_2 emissions. 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 asset. The model relies on a perfect foresight modelling approach and optimises over the overall time horizon.

Within REMix, each technology class is represented by an independent module, containing parameters, variables, equations, and inequalities required for the representation of respective technical and economical characteristics. The model application presented in this work uses the technology modules of intermittent RE, concentrating solar power (CSP), geothermal power, conventional power plants, combined heat and power (CHP), electric and thermal storage as well as direct current (DC) power transmission, DR, hydrogen production, electric heating, and electric mobility. Mathematical descriptions of these modules can be gathered from [33-35].

4 Data

The calculation of the target-oriented scenarios is based on the development of detailed input data sets considering efficiency and RE potentials as well as technical parameters of power, heat, and synthetic fuel production technologies.

In a first step, the general Mesap-PlaNet model was adapted, calibrating model inputs and results for the starting year against statistical data for the Canary Islands for 2013 [25]. Where no data was available, the calibration was based on IEA energy balances for Spain for 2013 [36]. Technology data is based on previous model applications for the EU-28 [37] and adapted according to Section 4.3.

4.1 Projection of the final energy demand

Economic development and population growth are important drivers for the future of the final energy demand [31, 38]. Future population development is an important factor because population growth affects the size and composition of the energy demand, directly and through its impact on economic growth and development.

Population

The population projection is based on the Spanish projection for population development and the long-term trend of Canary Islands' share in Spanish population [24] (Table 2). Tourism as a major economic factor is also projected by using a simplistic approach based on available statistics of tourist numbers, average and total cost of stays [39], and the availability of hotel beds [40]. We calculate that guests currently represent an equivalent of about 10% of the population (cap eq.), increasing by one forth during the last four years. For trend projection we assume a slowdown of the current trend of increasing tourism, resulting in a doubling of guest nights by 2050.

Table 2: Population development projections in the Canary Islands (based on statistics [19–21] **and own assumptions)**

		2013	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Population	**Mio. cap**	2.12	2.12	2.15	2.17	2.18	2.19	2.21

Tourism	**Mio. cap eq.**	0.21	0.23	0.24	0.27	0.31	0.37	0.39

Economic growth

For projection of future economic development we apply growth trends for Europe from previous studies, calibrated with current statistical data for Spain and the Canary Islands. GDP in Europe (EU-28) is assumed to grow by about 1.6% per year over the projection period until 2050 [37]. For the Canary Islands GDP, we apply the same growth rate, allocating a constant share of 3.9% of the Spanish GDP to the archipelago as between 2007 and 2011 [41].

Final energy demand

GDP and population drive the final energy demand scenario until 2050, applying the same improvements in energy intensities for industry, transport, and other sectors as for EU-28 [37]. Based on population, GDP and intensities, Mesap provides a projection for electricity and fuels in each sector for a Business-as-usual (BAU) case. To address local developments in the Canary Islands, the resulting final energy demand is then adapted with local information: Short-term development of electricity demand include projections for the archipelago by the Spanish government [26]. Mid-term prospects until 2030 for the electricity demand are based on the trends described in a Spanish energy scenario study [27].

Energy efficiency potentials

Efficient use of energy is a precondition for a sustainable energy system and a major driver to reduce the energy demand. Potentials for a more efficient energy use are yet largely to be exploited, but the markets for efficiency measures is developing strongly [42]. Efficiency potentials for the industrial and other sectors have been assessed in [43]. Details about assumptions for energy efficiency improvement in industries and other sectors can be found in [44]. Based on the above described BAU scenario we apply these efficiency potentials in industry and other sectors in the Canary Islands gradually until 2050, starting from 2020. BAU scenario and efficiency scenario for the final energy demand are both presented and compared in Section 5.1.

Transport demand

Concerning transport demand, the Canary Islands differ strongly from a mainland system in two major aspects. On the one hand, road transport in the islands covers comparatively small distances with its longest island Fuerteventura stretching just about 100 km. Therefore a main constraint in the mainland – the still low range of battery electric vehicles (BEV) – does not apply in the archipelago, making a quick introduction of electric mobility technically feasible. On the other hand, due its remote situation the archipelago relies strongly on aviation and navigation for goods and people to reach the islands. The importance of tourism in the island economy is further increasing the dependency on aviation. Thus a modal shift towards more efficient means of transport such as ships and rail is not feasible. As there is no data available for a disaggregation of air and ship traffic between mainland and interisland traffic, we restricted our scenario to the land transport demand in the Canary Islands.

Transport assumptions are based on a study for the EU-28 [32, 37]. Starting with the BAU transport demand, we assume a demand reduction in light duty vehicles by about 20% and heavy duty vehicles by about 10% by 2050, achieved by efficient transport planning and modal shifts towards non-fuel transport. A shift to more efficient power trains and a gradual switch to highly efficient electric and fuel cell engines provide additional potentials. Based on the EU-28 transport scenario, by 2050 up to 63% of light duty vehicles will rely predominantly on electric propulsion and 37% on hydrogen fuel cells. For heavy duty vehicles, we apply shares of 25% for electric and hybrid vehicles, and 75% for fuel cell propulsion based vehicles.

4.2 Model regions considered

In REMix, the Canary Island electricity system is not considered as a whole, but subdivided to nine model regions. The islands of El Hierro, La Palma, La Gomera, Fuerteventura, and Lanzarote are represented as one model region each, whereas the two biggest islands Gran Canaria and Tenerife are split into a northern and a southern part at latitude 27°57’ and 28°15’, respectively (Figure 2). This regional subdivision allows for an analysis of the contribution of grid interconnections to the balancing of RE fluctuations and achievement of supply cost reductions.

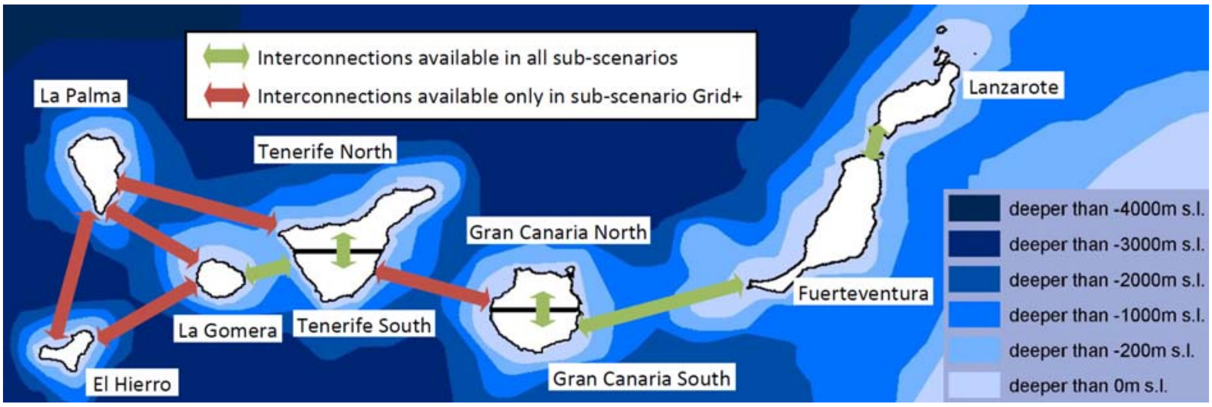

Figure 2: Model regions, sea depth, and possible grid connections. In scenario RE Base and DR-, only the green connections can be built, whereas in scenario Grid+ the red ones are available as well.

4.3 Renewable energy potentials and power plant capacities

Owing to the small island surface, RE potentials are fairly limited in the Canary Island archipelago. This applies to the installable capacities of hydro and biomass power in particular, but also to solar and wind power. However, the latter are available with a fairly good resource quality compared with other regions in Europe. Given the volcanic activity, there is also some potential for geothermal power generation.

Previous studies provide detailed assessments of the potentials for PV [45, 46], onshore wind power [47, 48], floating and fixed foundation offshore wind power [49], geothermal energy [50], biomass energy [51, 52], and wave energy [53-55]. Wave power can be used close to all islands except for La Gomera. While PV, wind and biomass are available in all islands, geothermal energy is only available in Tenerife and Gran Canaria. The hydrological plans for the islands of La Palma and Tenerife [56] include information of currently operating and planned run-of-river hydro power stations. However, these are very limited in their capacity, and additional potentials are not identified.

We evaluate the potential for CSP by using REMix-EnDAT. Its application relies on the resource data and technology characteristics documented in [57, 58]. The model identifies installable capacities of CSP only in the easternmost islands of Fuerteventura, Lanzarote, and Gran Canaria. We furthermore apply REMix-EnDAT for the calculation of region-specific hourly power generation profiles of CSP, PV, and wind power plants. They are calculated from weather data of the year 2001, which exhibited an average annual availability for wind and solar power compared with other years in the considered period 1984-2004. The normalised hourly load profiles rely on metered data of the year 2013.

According to the scenario development premises, we assume that all available RE sources will be exploited in the future. In the REMix analysis for the year 2050, we evaluate the least-cost mix of the RE technologies with highest potential – CSP, PV, and wind power. This is done by providing the maximum installable capacities as input and considering a model-endogenous capacity expansion. For wind energy, we model three different technologies: onshore, floating offshore, and fixed foundation offshore. Available potentials of CSP, PV, and wind power are summarised for each technology and region in Table 3.

Table 3: Maximum installable generation capacities of PV, CSP, and wind power.

	PV	CSP	Wind onshore	Wind offshore fix	Wind offshore floating
	MW	MW (th)	MW	MW	MW
El Hierro	39	0	58	107	342
Fuerteventura	477	8892	1824	846	2592
Gran Canaria N	882	406	269	33	151
Gran Canaria S	1323	1117	627	299	1359
La Gomera	67	0	106	139	696
La Palma	224	0	116	171	771
Lanzarote	581	2157	512	589	1660
Tenerife N	1438	0	155	86	283
Tenerife S	1438	0	233	342	1131
Total	6468	12572	3900	2612	8985

Owing to their limited potential and low technology development, respectively, we assume that run-of-the-river hydro power, geothermal power, and wave energy provide only small amounts of electric energy. For this reason, their power generation capacities are not endogenously determined, but provided as input to the model. The same applies to biomass and fuel cell CHP units, which supply heat to industrial and commercial loads. Table 4 contains the considered power generation capacities.

Table 4: Installed capacities in the year 2050 according to the available potentials.

	Run-of-the-river	Geothermal	Wave	Biomass CHP	Fuel Cell CHP	Pumped storage hydro	
	MW	MW	MW	MW	MW	MW	MWh
El Hierro	0	0	3	0.14	0.02	12	84
Fuerteventura	0	0	19	1.82	0.32	0	0
Gran Canaria N	0	0	3	8.36	1.52	131	788
Gran Canaria S	0	100	0	3.34	0.69	910	5462
La Gomera	0	0	0	0.29	0.05	0	0
La Palma	1.2	0	9	1.11	0.21	200	1200
Lanzarote	0	0	16	2.31	0.41	0	0
Tenerife N	2.0	50	12	8.91	1.61	699	5381

Tenerife S	0.3	50	0	3.51	0.71	305	1831
Sum	3.5	200	62	29.79	5.53	2322	15133

The techno-economic specifications of power generation as well as storage technologies are summarised in Table 6 in the Appendix. Data sources are reported in detail in previous publications of REMix analyses [35, 59].

4.4 Transmission, storage, and demand response

Most RE potentials in the Canary Islands rely on solar irradiation and wind, and are thus of fluctuating nature. The balancing of their temporal variation in power generation poses the major challenge to a 100% RE supply. This may include both spatial balancing by the power grid and temporal balancing by energy storage and DR.

Currently, only Lanzarote and Fuerteventura are electrically connected through a seabed cable. The transmission system operator Red Eléctrica de España plans to install additional connections between La Gomera and Tenerife as well as between Fuerteventura and Gran Canaria [26]. Given the great sea depth and rough seabed (Figure 2), connections between all other islands are much more difficult to realise and currently not considered. In the REMix optimisation, DC cables between neighbouring model regions can be endogenously installed. Whether this includes all connections between all islands or only that already available or planned depends on the sub-scenario (Section 4.5). According to [60], we assume DC transmission losses of 0.27%/100 km in sea cables. An additional loss of 0.7% occurs at conversion from and to alternating current. Investment costs amount to 2000 k€/km and 150 000 k€ for each converter station. All components have an amortization time of 40 years and annual fixed operational costs equivalent to 0.6% of the investment.

In the present study, we consider three different electricity storage technologies: pumped storage hydro (PSH), vanadium redox-flow batteries, and hydrogen tank storage. Given the mountainous surface of most islands and the availability of many water reservoirs, significant potential for an installation of PSH is available in the Canary Islands. It is quantified based on the hydrological plans for each island [56] and considered as being exploited by 2050. The resulting installed capacities concentrate in the islands of Tenerife and Gran Canaria as listed in Table 4.

In contrast to PSH, capacities of battery and hydrogen storage are endogenously optimised by REMix and not subject to any upper limit. Owing to the usage of hydrogen in CHP, industry and transport, the model input considers some electrolyser capacities. We assume that these are equipped with a storage dimensioned to store 12 hours of hydrogen production. To use hydrogen for dispatchable power generation, additional storage, and electrolyser capacity can be added by the model. For re-electrification, these must be complemented by an investment in hydrogen-fired gas turbines or combined cycle gas turbines (CCGT). The REMix assessment also considers thermal energy storage (TES). To allow some adjustment of their operation to the available intermittent RE, we assume that all CHP and electric heat production technologies are equipped with a TES designed to store four hours of peak heat supply.

DR is considered for desalination, BEV charging, cement production, cooling, and air conditioning as well as the flexible operation of hydrogen electrolysis. Uncontrolled load shedding is not considered in the model. This implies that all other demand must be covered in every hour of the year. The analysis of desalination in the Canary Islands relies on [61-64]. We assume that desalination can be used for electric load shifting, which is technically possible for plants applying reverse osmosis. However, it requires a more generous plant capacity layout compared to today as well as the availability of freshwater storage. We consider a dimensioning, which allows for an annual production within 5000 full-load hours. Load shifting is possible within a time period of up 48 hours, and storage for twelve hours of average production is assumed to be available in all plants. We apply an increase in the electricity demand of 0.5% per hour of load shift. We estimate DR potentials of cement production, air conditioning as well as cooling in industry and the commercial sector according to the methodology presented in [65]. Additional data sources include [25, 66]. The duration of load interventions is limited to one hour for air conditioning, six hours for cooling and 48 hours for cement production. For BEV, we assume that the charging capacity equals 1.5 times the maximum demand at uncontrolled charging (details on modelling and data are reported in [33]). Here, a delay in charging by up to eight hours is considered. Table 5 provides the maximum load reduction potential of all considered DR options. BEV charging, heat demand and hydrogen demand profiles are considered according to [33].

Table 5: Average load reduction potential of the available DR measures.

	Desalination	Cooling	Air Conditioning	BEV	Cement	Electrolysers
	MW	MW	MW	MW	MW	MW
El Hierro	1.9	0.05	0.3	0.5	0	3.9
Fuerteventura	14.2	1.73	4.6	5.5	0	48.7
Gran Canaria N	46.9	2.83	12.2	32.9	1.5	102.0
Gran Canaria S	46.9	2.81	9.4	10.5	0	69.1
La Gomera	2.0	0.15	0.5	1.1	0	35.4
La Palma	11.8	0.45	1.9	4.3	0	36.8
Lanzarote	16.0	1.99	5.1	7.2	0	41.9
Tenerife N	35.0	3.52	14.3	34.2	0	135.1
Tenerife S	35.0	2.90	8.6	11.1	1.2	169.8

4.5 Scenario variations in the REMix assessment

To assess the importance of different balancing technologies in least-cost supply structures, we analyse three sub-scenarios with REMix. They differ in the availability of DR and the feasibility of grid connections.

- **RE Base:** Grid connections between islands are limited to those currently available, planned or considered as technically feasible. This implies a possible exchange between Gran Canaria, Fuerteventura, and Lanzarote as well as between Tenerife and La Gomera. In contrast, El Hierro and La Palma cannot be connected to any other island and a connection of the two major islands of Tenerife and Gran Canaria is not possible (Figure 2).
- **DR-:** Scenario DR- relies on the same grid connections as the RE Base scenario, but sets aside load shifting of desalination, BEV charging, cement production, cooling, and air conditioning.
- **Grid+:** This scenario includes an enhanced grid extension. In contrast to the RE Base scenario, grid connections are assumed feasible between all islands, thus providing one integrated

power system over the entire archipelago. DR is considered as in the RE Base scenario.

5 Results

In the following, we present scenario results along the modelling chain. Starting with the evaluation of the final energy demand and potential efficiency gains (Section 5.1), we then present the results of the REMix optimisation for 2050, focusing on the optimised mix of power plants and their regional disaggregation (Section 5.2). Finally, we provide an overview of the transition pathway for the whole archipelago (Section 5.3). Additional results are reported in [67].

5.1 Energy demand

GDP and population growth can be expected to drive the final energy demand from 92 PJ in 2012 to about 131 PJ in 2050 under BAU conditions, representing an increase of 42% (Figure 3). Main drivers are the residential and commercial sector, aggregated under other sectors. This development reflects the expected increase in tourism (Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). The final energy demand in land transport remains stable, as the increased transport demand is compensated by higher efficiency. The same holds true for the industry sector.

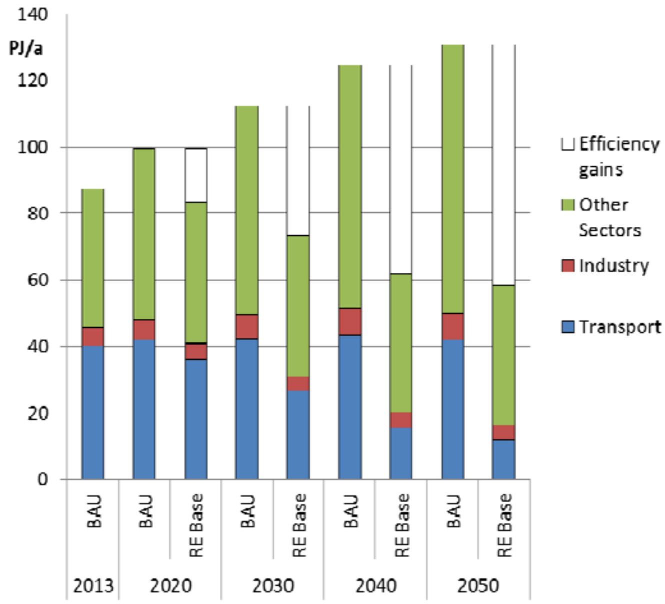

Figure 3: Final energy demand by sector under the BAU and the 100% renewable energy scenario (RE Base) disaggregated by sectors

If efficiency measures are consequently applied across all sectors, a decrease in energy demand can be achieved. In the 100% RE scenario (RE Base), the final energy demand drops to 58 PJ/a by 2050. However, electrification of heating and transport increases the power demand from 8.7 TWh in 2013 to 15.6 TWh in 2050. Improved living standards (e.g. additional appliances for cooling and additional water desalination), and electric heating lead to higher power demands in industry (+26%) and other sectors (+17%).

5.2 The power sector in 2050

REMix provides the least-cost composition of the power supply structure in 2050 as well as the hourly system operation. Overall power generation capacities reach 11.3 GW in scenario Grid+, 12.1 GW in RE Base, and 12.2 GW in DR-, equivalent to between 320% and 350% of the annual peak load.

All sub-scenarios are dominated by solar PV, which accounts for approximately half of the installed capacity. Second highest capacities are found for wind power with shares between 28% and 37%. Figure 4 shows that the possibility to connect all islands reduces the overall size of the power plant park, and also changes its composition: Floating offshore wind turbines are not applied at all, and fixed offshore wind turbines are reduced. These reductions are compensated by a higher installation of CSP, which is almost twice as high as in the other scenarios, and onshore wind. The model-endogenous installation of hydrogen-fired CCGT reaches between 424 MW (Grid+) and 613 MW (DR-), which is about 5% of the total generation capacity.

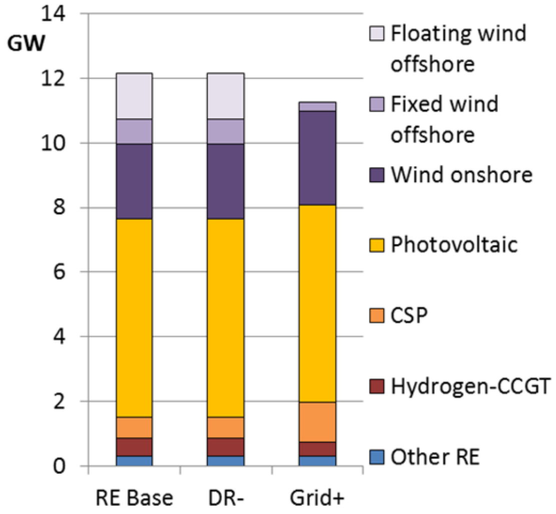

Figure 4: Total installed power generation capacity in the three sub-scenarios. *Other RE* contains geothermal, biomass, hydro and wave power as well as fuel cells (Table 4).

The regional allocation of power generation capacities is shown for scenario RE Base and Grid+ in Figure 5 and Figure 6, respectively. The results of scenario DR- are very similar to those of scenario RE Base. In all scenarios, onshore wind, PV and, and CCGT are applied on all islands, whereas CSP and offshore wind show regional concentrations. CSP is installed on all islands with a technical potential – Lanzarote, Gran Canaria, and Fuerteventura. The capacity on the first two islands is not affected by the availability of grid and DR, whereas in Fuerteventura it is more than doubling in scenario Grid+. In scenario RE Base and DR-, about 91% of the offshore wind capacities are located in the subsystem composed of the islands of Tenerife and La Gomera, the remaining 9% in La Palma and Gran Canaria. With the additional grid available in scenario Grid+, remaining offshore wind capacities are found in Tenerife (60%), Gran Canaria (13%), and La Palma (27%). The technology shift from offshore wind to onshore wind and CSP enabled by the availability of more grid connections causes a significant shift of generation capacities from La Gomera and Tenerife to Fuerteventura.

Comparing the model-endogenous capacity installation with the available potentials (Table 3) it appears that PV potentials are fully exploited in all scenarios and model regions except Lanzarote. Onshore wind potentials are also exploited mostly, except for those in Lanzarote, Fuerteventura, and El Hierro. Offshore wind power capacities reach their limits almost exclusively for fixed turbines, in the scenarios with limited grid expansion and in Tenerife, La Gomera, and La Palma. CSP potentials are fully exploited in Gran Canaria in all scenarios, but not in Lanzarote and Fuerteventura in any of the scenarios. The comparison of potentials and required capacities reveals that additional renewable power generation would be possible in most islands. However, for the least-cost technologies of PV, onshore Wind and, and CSP, remaining potentials are almost exclusively found in the easternmost islands of Lanzarote and Fuerteventura.

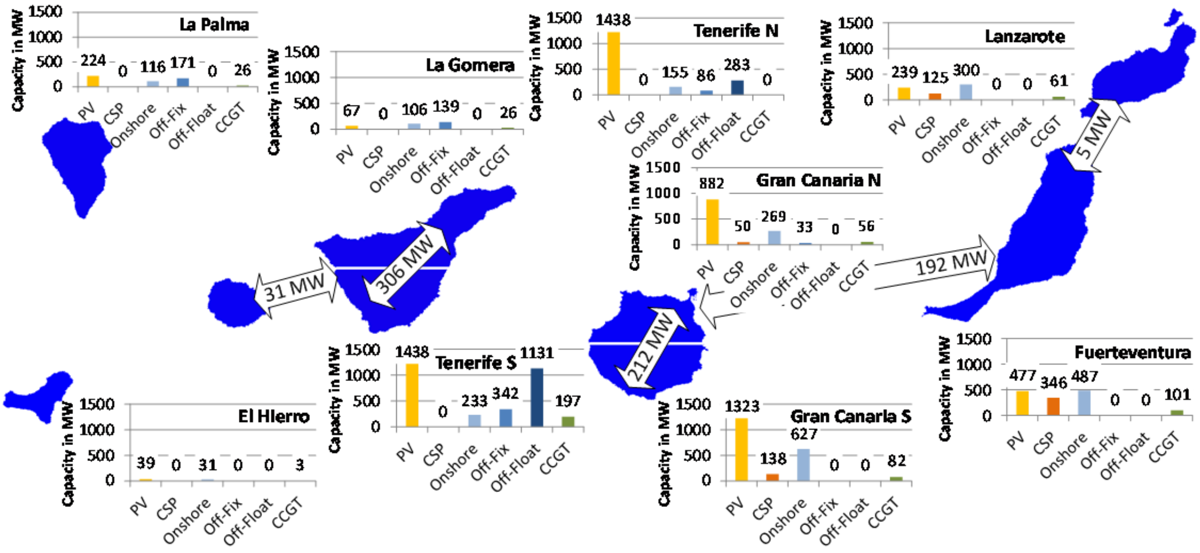

Figure 5: Power plant and grid capacities in scenario RE Base.

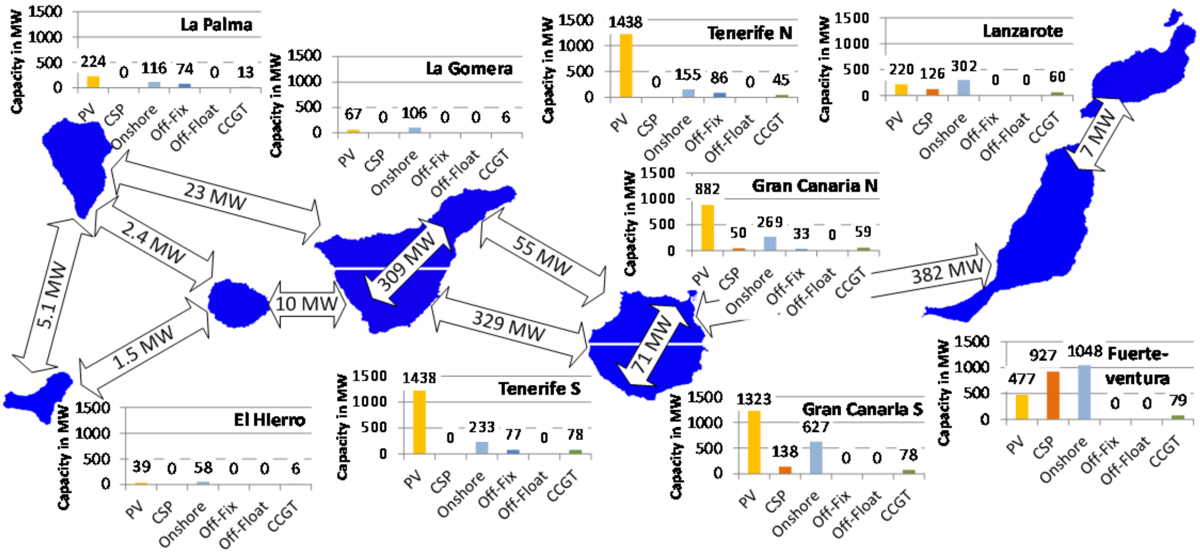

Figure 6: Power plant and grid capacities in scenario Grid+.

Figure 5 and Figure 6 compare the model-endogenous installation of power connections between model regions and scenarios. Overall transmission capacities reach 746 MW in scenario RE Base, 763 MW in DR- and 1195 MW in Grid+. A possible connection of all islands increases the grid capacity by about 450 MW, and decreases the required generation capacity by twice this amount. The REMix results displayed in Figure 6 highlight that the most important connections are those between the three major islands Gran Canaria, Tenerife, and Fuerteventura as well as within Tenerife.

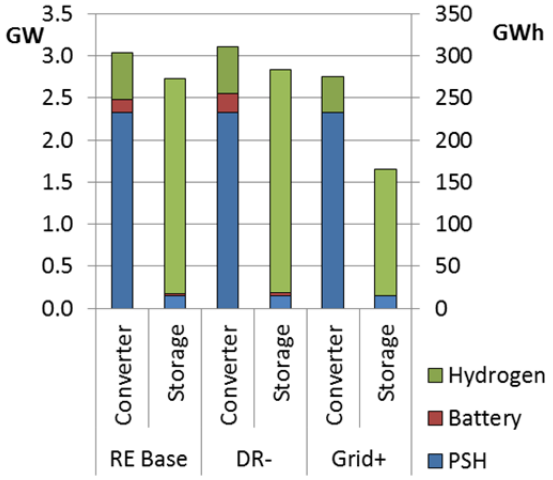

Figure 7: Total installed storage capacity in the three sub-scenarios: generation capacity (left scale) and energy content (right scale).

Figure 7 shows the necessary storage demand under the three scenarios. It reaches up to 3 GW of converter capacity and 300 GWh of energy content, which are equivalent to about 85% of peak load and 2% of the annual power demand, respectively. The converter capacity is dominated by PSH, whereas the energy capacity is highest for hydrogen storage. Additional grid connections in scenario Grid+ reduce the required hydrogen storage almost by half and eliminate all battery storage demand. On the contrary, more battery and hydrogen storage is needed if no DR can be realised. Hydrogen re-electrification in CCGT is used in all islands (Figure 5 and Figure 6), whereas battery storage is installed only in La Gomera and southern Tenerife.

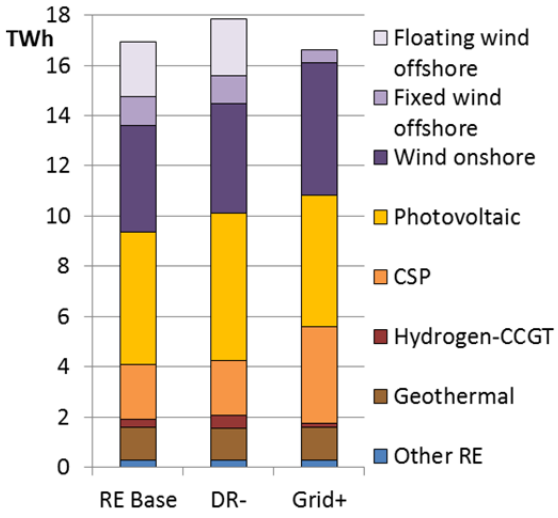

Figure 8: Total power generation in the three sub-scenarios. *Other RE* comprises biomass, hydro, wave power, and fuel cells.

Figure 8 shows the power generation structure in the three sub-scenarios. According to potentials and capacities, it is dominated by wind and solar power. In the scenarios RE Base and DR-, wind and solar provide about 45% of the overall generation each. Two thirds of solar power is generated by PV, one third by CSP. Additional grid connections available in scenario Grid+ enable a significant shift from offshore wind to CSP generation. Both overall generation and dispatchable CCGT operation are significantly higher when DR and transmission are not available. Owing to additional storage losses, the overall generation is by more than 1 TWh higher in scenario DR- than in scenario Grid+. Furthermore, the contribution of hydrogen-fired CCGT to power supply reaches less than 1% in scenario Grid+, and almost 3% in DR-. The operation of all other technologies is influenced only to a minor extent by the scenario assumptions. Geothermal power generation contributes about 1.3 TWh, which is equivalent to 8% of the total generation. Annual generation of other technologies are much lower at about 160 GWh for biomass CHP, 70 GWh for wave power, 40 GWh for fuel cells,, and 15 GWh for hydro run-of-river power.

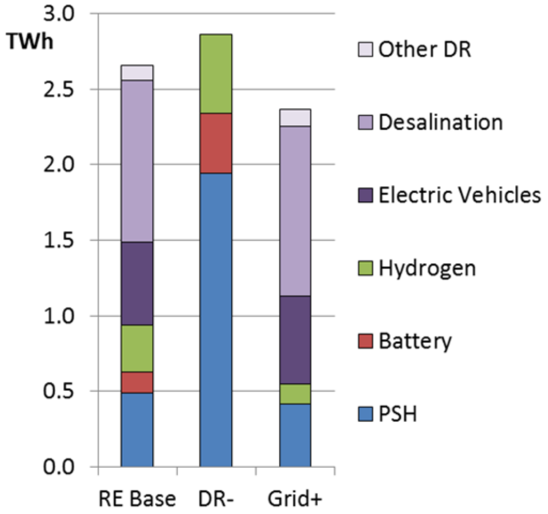

Figure 9: Annual storage output and load shifting in the three sub-scenarios. Hydrogen storage output reflects the power generation in CCGT.

According to the REMix results, electricity storage and DR contribute significantly to the balancing of fluctuations in wind and solar power generation (Figure 9). Annual storage output reaches 0.6 TWh in scenario Grid+, 0.9 TWh in RE Base, and 2.9 TWh in DR-, which is equivalent to between 3% and 16% of the overall power generation (Figure 7). When available, DR is used extensively for shifting electric loads, especially by modifying the charging of BEV and operation of reverse osmosis desalination plants. Overall load shifting accounts for about 1.8 TWh in both scenarios RE Base and Grid+. Maximum load reduction by desalination reaches 0.21 GW, the BEV charging load varies between 0−0.43 GW. In scenario DR-, load shifting is completely substituted by PSH, battery, and hydrogen storage. Additional balancing is provided by flexible operation of electrolysers and electric heating. During the year, their electricity demand varies between 0−1.85 GW and 0−0.21 GW, respectively.

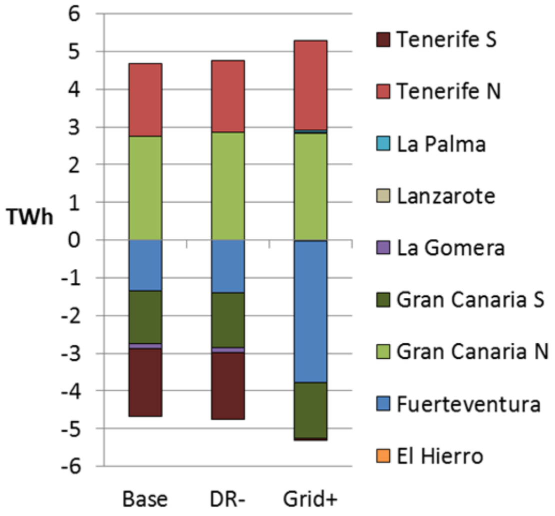

Figure 10: Annual electricity exchange between the model regions in the three sub-scenarios. Values greater than zero imply a net import, those smaller than zero a net export of electricity.

Power exchange between the islands is a major factor within all considered scenario variations. Figure 10 shows that between 30% and 34% of the total power demand are transferred over at least one region border. Highest electricity import and exports naturally occur in the Grid+ scenario with about 5.3 TWh. Most important import regions are the northern parts of Gran Canaria and Tenerife, whereas Fuerteventura and the southern parts of Gran Canaria and Tenerife are major exporters of electricity. The high RE potential of Fuerteventura can especially well be exploited in scenario Grid+, where the power generation provides for almost 400% of the island’s demand. The surplus is used mostly in Tenerife and Gran Canaria, substituting the more expensive offshore wind power used in the scenarios without additional grid availability. La Gomera contributes to power supply of Tenerife in scenario RE Base and DR-, but not in Grid+. Lowest net imports of less than 1% of the overall demand are found for Lanzarote. El Hierro and La Palma are restricted to an island supply in scenario RE Base and DR-, in Grid+ El Hierro produces about 18% more as it consumes, whereas La Palma imports about 9% of its demand.

Owing to the high supply share of intermittent RE and limited storage, grid, and DR capacities, more than 30% of the potential solar, wind, and wave power generation remains unused across all scenarios. Curtailments are particularly high during spring and summer (April through August), whereas they are negligibly during the winter (November, December, January).

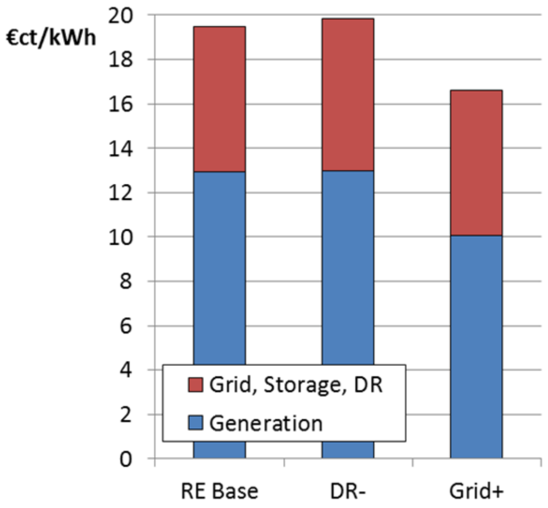

Figure 11: Power supply cost per unit of demand.

Figure 11 relates the overall supply costs to the annual demand. It considers the annual depreciation of capital expenditure as well as fixed and variable operational costs of all power generation, transmission, storage, electric heating, hydrogen electrolysis, and DR technologies. The specific cost of electricity generation reaches about 13 €ct/kWh in scenario RE Base and DR-. Owing to the shift to cheaper technologies enabled by additional grid connections, a significant lower value of 10 €cent/kWh is determined in scenario Grid+. Despite the differences in system operation, the balancing costs arising from storage, grid and DR are almost identical across all sub-scenarios and amount to about 7 €ct/kWh.

The high uncertainty of future costs of rapidly developing storage technology motivates a quantitative sensitivity analysis with REMix. We determine that a reduction of battery storage costs by half can lower the power generation capacity by 4%, and supply cost by 8% relative to scenario RE Base. Nearly the same values are obtained when considering a reduction in investment costs of hydrogen electrolysers and storage by one third, while the effects of additional grid connections in scenario Grid+ are almost twice as high. This implies that even significant reductions in storage costs can lower generation capacity and costs to a much lower extent than the technical possibility to connect all islands of the archipelago. An additional model run reveals that a reduction of hydrogen storage investment costs by 90% would enable a decrease in supply costs by 35%. With currently available technologies, such reduction in seasonal storage costs could only be realized by using underground cavern storage. However, owing to the volcanic activity, this technology is not suited for the Canary Islands.

5.3 Long term transformation pathways

Starting from the optimised power system determined with REMix, the long-term scenario pathway focuses on the RE Base case, without engaging in additional infrastructure installation between the islands. At the end of the transition, PV, wind, and CSP contribute 91% to the total electricity generation (Figure 12). According to the scenario pathway, their supply share increases to 20% and 58% in 2020 and 2030, respectively. The installed capacity of RE technologies reaches 3 GW in 2030 and 12 GW in 2050.

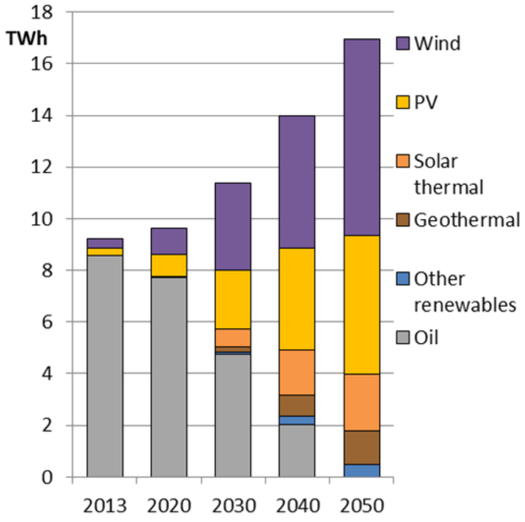

Figure 12: Transition of the structure of power production in the RE Base scenario for a 100% renewable target.

To implement a 100% RE system, electricity also needs to increasingly compensate for fossil fuels in the heating and transport sector. Although efficiency measures help to stabilise the heat demand, a large portfolio of renewable sources is required to provide heat for all applications. Currently, only 2% of the officially recorded heat demand is covered by renewables, mainly by solar collectors. Traditional biomass use is lacking official records. For low temperature heat, e.g. hot water in the residential and commercial sector, the installation of solar collectors and ambient heat in heat pumps are rapidly expanded in the RE Base scenario (Figure 13). Higher temperature levels for process heat are provided by biomass and concentrating solar collectors. From 2040 on, hydrogen and electricity replace the remaining fossil fuels. Solar thermal energy covers 15% of the heat demand in 2030, and 26% in 2050. By then, electricity is the main heat source, covering 36% of the demand. Both options need to be supplemented with heat storage, which can also cover for fluctuations in power production. With additional heat supply from hydrogen (15%), ambient heat (14%), and biomass (8%), 99% of the sectoral demand are covered by RE in 2050.

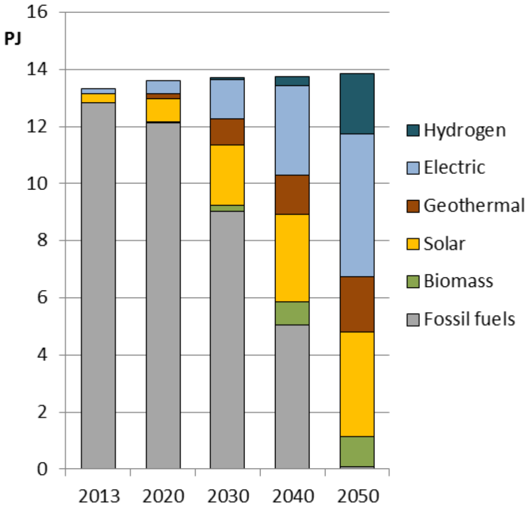

Figure 13: Transition of heat production structure in the RE Base scenario

For road transport, efficiency gains in engines, a modal shift towards busses and the shift in propulsion technology leads to a substantial reduction of transport energy demand by 71% to 12 PJ in 2050 (Figure 14). Biofuels can only serve as transition fuels. Hybrid, plug-in hybrids, and electric power trains gain a significant market share by 2030, covering 12% of the transport energy demand. Fuel cell cars become important just after 2030 especially for heavy duty vehicles. In 2050, 44% of the transport energy demand is covered by hydrogen and 53% by electricity, leaving only 3% to biofuels. The massive electrification of road traffic raises the electricity demand from practically zero to 1.8 TWh in 2050.

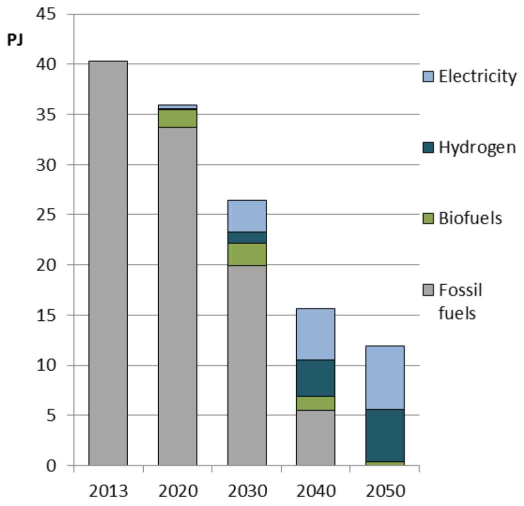

Figure 14: Transition of the transport sector in the RE Base scenario towards 100% renewable

Across all sectors, the RE Base scenario leads to a reduction in total primary energy demand by 55% to 86 PJ in 2050. The main energy source is solar, covering 37% of the demand, followed by wind (31%), geothermal/ambient heat (29%), and biomass (3%). Following the transition pathway, GHG effects of the energy system are reduced already in the near future. Power generation, which currently accounts for half of the CO_2-emissions, will remain the main source of emissions until fossil fuels are eventually replaced by RE after 2040 (Figure 15). Decreasing demand in transport fuels also reduces emissions from conversion, e.g. refineries. Given the increase in RE supply, CO_2-emissions are cut by 48% until 2030. In the RE Base scenario, CO_2 emissions are almost totally eliminated by 2050.

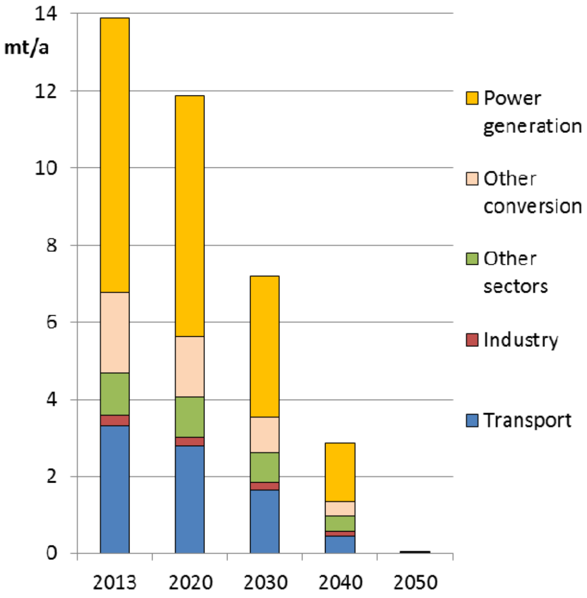

Figure 15: CO_2-Emissions in the RE Base scenario

6 Discussion

The scenario pathway to a 100% RE supply developed in this paper relies on a back-casting approach and provides a breakdown of long-term targets to short-term actions. It can be used as a guideline to a carbon-free energy supply for the Canary Islands, but does not represent a prognosis of the future. The decarbonisation scenario is limited to power, heat, and land transport, whereas aviation and navigation are not included. Owing to the restricted RE potentials in the Canary archipelago, these sectors will be dependent on imported hydrocarbon fuels in the future as they are today.

The scenario shaping methodology introduced in this work can be used for other islands or countries as well. According to [23], the results of its application to the Canary Islands can be helpful for designing supply systems on other islands with similar climatic, and socio-economic characteristics as well. However, their methodology focuses on single islands, and does neither include any cross-sectoral perspective, nor the possibility to connect different islands within an archipelago.

Power supply, electric heating, and synthetic hydrogen production are evaluated for the year 2050 by using a linear optimisation approach. The high temporal and spatial resolution of the applied REMix model ensures a high quality and validity of the results compared with more aggregated approaches. Nevertheless, the temporal resolution of REMix limits its scope to the evaluation of hourly balancing of demand and generation. Therefore, the model does neither account for power system stability requirements, especially the provision of operating reserve, nor does it capture ramping limitations of thermal units. Furthermore, REMix is based on a simplified technology representation and does not fully reflect operational restrictions. This particularly concerns thermal power plants, but also the representation of power transmission. From this follows that our results tend to underestimate the capacity needs for ensuring supply security at lower timescales as well as the operational costs of power supply [68]. More detailed models need to be applied to validate and reinforce our results. A comprehensive discussion of capabilities and restrictions of REMix can be found in [35]. Not only the temporal, but also the spatial resolution of REMix has an impact on the results. Maximum installable capacities and hourly output of RE technologies are likely to vary if a higher resolution is used. Furthermore, potentials of wind turbines, CSP plants, and open space PV depend to a high degree on the available areas and the area specific capacities. The input data used in this study relies on the methodologies and data presented and discussed in the cited publications.

The cost analysis in REMix extends beyond the usual levelised cost of electricity generation (LCOE) approach, as it also accounts for the integration costs arising from the need to balance intermittent RE generation by grid, storage and other balancing technologies [59]. To evaluate these costs, we compare them with LCOE from a predominantly fossil power supply in the Canary Islands in 2050. The detailed analysis reported in [67] shows that in a business-as-usual scenario based on same investment and fuel cost assumptions, overall LCOE reach a value of 23 €ct/kWh. This is about 15% more than the highest value found in the REMix analysis of the present work. From this follows that fuel cost savings can more than overcompensate for the cost of additional infrastructure. A comprehensive cross-sectoral cost-benefit analysis, extending to the assessment of other externalities such as air pollutants is beyond the scope of the present study and should be addressed in future studies.

The data input of the analysis considers substantial future cost decreases and technology developments. Especially the consideration of improved under water cables in sub-scenario *Grid+* is important as it enables a connection of the two major islands. If this technology cannot be realised in the future, offshore wind turbines without fixed foundation are required in the subsystem formed by the islands of Tenerife and La Gomera which then substantially increases the supply costs. Furthermore, the commercialisation of wave energy is currently at an early stage and requires further enhancement and cost reduction. The same applies to the large-scale deployment of hydrogen electrolysis, storage, and re-electrification. BEV are now available from different manufacturers, but charging infrastructures still need to be provided at large scale. Technology costs assumptions have a strong impact on the results of cost-minimising linear optimisation models. Regarding the most important power generation technologies, we expect the following impact of a different cost development: Owing to the almost complete exploitation of potentials, lower or higher PV and onshore wind costs would have a very limited impact on the composition of the system, but will influence the overall supply costs. The same is true for offshore wind power, which is used only to a minor extent. The situation is different for lower or higher CSP costs as these are likely to reduce or increase the usage of PV and onshore wind.

The high curtailment of intermittent RE power generation indicates additional potential for balancing technologies. Additional DR or the appearance of cheaper storage technologies can enable cost reductions by avoiding the usage of the most expensive power generation technologies. The sensitivity analysis shows that a decrease in storage cost could reduce both capacity demand and costs. However, the cost-cutting potential of storage exceeds that of additional grid connections only if long-term storage is available at very low investment cost. If not stored, surplus power generation can be used for an additional electrification of heating, and transport sector as well as industry.

7 Conclusion

This paper provides a novel approach to energy scenario design. It combines a cross-sectoral energy system model in high temporal and spatial resolution with an accounting framework. This modelling framework is able to simulate a consistent pathway towards a fully renewable energy supply and can be applied globally.

Our modelling results highlight the importance of transmission, storage, and flexible demand in energy systems with high share of fluctuating power generation. Furthermore, they show the great potential of an intelligent linkage of power, heating, and transport sectors as well as water supply both for climate protection and cost reduction. A flexible operation of BEV charging, hydrogen electrolysis, reverse osmosis seawater desalination facilities, electric heating, CHP, and electric cooling can contribute significantly to the achievement of high RE shares across all sectors. It must be enabled by an intelligent charging infrastructure as well as thermal, hydrogen, and water storage. Their implementation is particularly important in island energy systems, where there is no or limited possibility to balance power generation fluctuations through the grid. Load shifting of BEV, heating, cooling, and desalination are found to provide cheaper storage function than the considered electric energy storage. These insights can help market actors to optimise their investment decisions and political planners to shape an appropriate regulatory framework, so that new infrastructures are designed accordingly already at their deployment.

With their limitations in space, biomass, and hydro power, small islands represent the most challenging environment for the implementation of a carbon-neutral energy supply. The case study region of the Canary Islands is furthermore characterised by a significant number of inhabitants and increasing tourism, but also by good solar and wind energy potentials. Our modelling results show that these potentials are sufficient for a fully renewable supply of the archipelago’s power, heat, and land transport energy demands. Owing to the very limited potential of biomass, electrification of the heating and transport sector are essential elements of the system transformation. According to our results, the currently projected gas infrastructure can be completely substituted by RE technologies. Such a change, however, requires a redirection of the current and future infrastructure planning. To follow the pathway towards a carbon neutral energy supply by 2050, a broad portfolio of RE technologies needs to be developed already in an early stage of the transformation. A strong increase in the installation of wind and PV capacities is already required in the short-term; a doubling of wind capacity is necessary until 2020 and again by 2025 as well as a tripling of current PV installations by 2020 and doubling again by 2025. Besides these very mature technologies, increased efforts are required for the deployment of dispatchable CSP and PSH plants in the Canary Islands. Additionally, new technologies, including wave energy, floating offshore wind, and stationary fuel cells must be developed further to contribute to a broad power supply technology portfolio in later stages of the transformation. Apart from the gradual deployment of a new supply infrastructure, a strong increase in energy efficiency compared with current improvements is an essential precondition for the implementation of the scenario. Especially in the transport sector, large efficiency gains are achievable. However, they require a complete transformation of transport modes and technologies as well as the deployment of new infrastructures. Higher energy efficiency and reduced overall demand are crucial for keeping supply costs low, as economic RE potentials are to a very high degree exploited in our scenario. If the demand can be reduced to a lower extent, a disproportionate increase in costs will result. We determine that the realisation of sea cable connections between all islands of the Canary archipelago can enable a reduction in supply cost by 15%. Consequently, additional effort is necessary to overcome application limits arising from sea depth and seabed conditions. Another key requirement to keep supply costs low is the activation of the considered DR potential. Despite the considered sector linkage, a significant share of wind and solar power generation has to be curtailed. This implies that there is huge potential for additional flexibility, including new storage options, usage of surplus generation in other sectors, or development of additional DR potentials.

Our modelling results can be used by energy system planners to determine RE capacity expansion pathways for the Canary Islands. Future studies are required to enhance the understanding of challenges and chances of a carbon-free energy supply. Considering different demand and RE generation profiles and performing further technology cost sensitivity analyses, the exact configuration of the supply system and the dimensioning of its elements need to be determined in future works.

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Appendix

Table 6: Techno-economic data of the considered power generation and storage technologies, according to [56–59]**. Abbreviations: PB – Power block, TES – Thermal energy storage, SF – Solar field, Stor. – Storage unit, Conv. – Converter unit**

Technology	η_{net}	**Avail.**	c_{invest}	c_{OMFix}	c_{OMVar}	t_{amort}
	%	**%**	**€[2]/kW**	**% of invest/a**	**€/MWh**	**a**
Solar PV	n.a.	95%	720	1%	0	20
Wind onshore	n.a.	92%	900	4%	0	20
Wind offshore, fix	n.a.	92%	1800	5.5%	0	20
Wind offshore, floating	n.a.	92%	3000	5.5%	0	20
Wave energy	n.a.	92%	2000	5.5%	0	20
CSP	37.0% (PB) 95% (TES)	95%	970 (PB) 250 (SF) 25 (TES)	2.5%	0	25
Geothermal power	13.5%	95%	7220	4.5%	0	20
Run-of-river hydro	n.a.	95%	4000	5%	0	60
Gas turbine	46.5%	95%	400	4%	0.3	25
CCGT	66.5%	96%	700	4%	0.3	25
Biomass CHP	34% (power) 53% (heat)	98%	1100	2%	5	20
Fuel Cell CHP	27% (power) 53% (heat)	98%	1100	2%	5	20
Redox flow battery	81%	98%	100 (Stor.) 300 (Conv.)	3%	0	20
Pumped storage hydro	80%	98%	10 (Stor.) 640 (Conv.)	3%	0	60 (Stor.) 20 (Conv.)
Hydrogen storage	95%	100%	24	2%	0	30
Electrolysers	71%	100%	322	2%	4	20

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[2] € refers to €2012

References

[1] IPCC. Climate change 2014: synthesis Report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. Geneva, Switzerland: Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.); 2014.

[2] EU-Parliament, EU-Council. Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the EuropeanUnion. 2009;L 140:42 ff.

[3] Monteiro Alves LM, Lopes Costa A, da Graça Carvalho M. Analysis of potential for market penetration of renewable energy technologies in peripheral islands. Renewable Energy. 2000;19:311-7.

[4] Riva Sanseverino E, Riva Sanseverino R, Favuzza S, Vaccaro V. Near zero energy islands in the Mediterranean: Supporting policies and local obstacles. Energy Policy. 2014;66:592-602.

[5] Marrero GA, Ramos-Real FJ. Electricity generation cost in isolated system: The complementarities of natural gas and renewables in the Canary Islands. Renewable and Sustainable Energy Reviews. 2010;14:2808-18.

[6] Erdinc O, Paterakis NG, Catalão JPS. Overview of insular power systems under increasing penetration of renewable energy sources: Opportunities and challenges. Renewable and Sustainable Energy Reviews. 2015;52:333-46.

[7] Kuang Y, Zhang Y, Zhou B, Li C, Cao Y, Li L, et al. A review of renewable energy utilization in islands. Renewable and Sustainable Energy Reviews. 2016;59:504-13.

[8] Brouwer AS, van den Broek M, Zappa W, Turkenburg WC, Faaij A. Least-cost options for integrating intermittent renewables in low-carbon power systems. Applied Energy. 2016;161:48-74.

[9] Krajačić G, Duić N, Carvalho MdG. How to achieve a 100% RES electricity supply for Portugal? Applied Energy. 2011;88:508-17.

[10] Krakowski V, Assoumou E, Mazauric V, Maïzi N. Reprint of Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis. Applied Energy. 2016;184:1529-50.

[11] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain’s power system considering costs, emissions and energy security. Applied Energy. 2015;152:83-93.

[12] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Applied Energy. 2011;88:502-7.

[13] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. International Journal of Sustainable Energy Planning and Management. 2014;1:7-28.

[14] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy. 2011;88:488-501.

[15] Duić N, Lerer M, Carvalho MG. Increasing the supply of renewable energy sources in island energy systems. International Journal of Sustainable Energy. 2003;23:177-86.

[16] Duić N, Krajačić G, da Graça Carvalho M. RenewIslands methodology for sustainable energy and resource planning for islands. Renewable and Sustainable Energy Reviews. 2008;12:1032-62.

[17] Blechinger P, Cader C, Bertheau P, Huyskens H, Seguin R, Breyer C. Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands. Energy Policy. 2016;98:674-87.

[18] Andaloro APF, Salomone R, Andaloro L, Briguglio N, Sparacia S. Alternative energy scenarios for small islands: A case study from Salina Island (Aeolian Islands, Southern Italy). Renewable Energy. 2012;47:135-46.

[19] Katsaprakakis DA, Papadakis N, Kozirakis G, Minadakis Y, Christakis D, Kondaxakis K. Electricity supply on the island of Dia based on renewable energy sources (R.E.S.). Applied Energy. 2009;86:516-27.

[20] Segurado R, Costa M, Duić N, Carvalho MG. Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde. Energy. 2015;92, Part 3:639-48.

[21] Kapsali M, Kaldellis JK, Anagnostopoulos JS. Investigating the techno-economic perspectives of high wind energy production in remote vs interconnected island networks. Applied Energy. 2016;173:238-54.

[22] Centeno Brito M, Lobato K, Nunes P, Serra F. Sustainable energy systems in an imaginary island. Renewable and Sustainable Energy Reviews. 2014;37:229-42.

[23] Meschede H, Holzapfel P, Kadelbach F, Hesselbach J. Classification of global island regarding the opportunity of using RES. Applied Energy. 2016;175:251-8.

[24] ISTAC. Estadísticas. Instituto Canario de Estadística, Gobierno de Canarias; 2015.

[25] Gobierno de Canarias. Anuario Energético de Canarias 2013. Consejería de Empleo, Industria y Turismo; 2014.

[26] Ministerio de Industria TeC. Planificacion energetica – Plan de desarrollo de la red de transporte de energía eléctrica 2015-2020, primera propuesta. 2014.

[27] X. Casals JDB, P. Linares Lllamas, and O. López García,. Renovables 2050. Un informe sobre el potencial de las energías renovables en la España peninsular. Informe del Instituto de Investigaciones Tecnológicas de la Universidad Pontificia de Comillas para Greenpeace2005.

[28] Bueno C, Carta JA. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. Renewable and Sustainable Energy Reviews. 2006;10:312-40.

[29] Seven2one. Mesap. 2015.

[30] Seven2one. Mesap 4.11. 2010.

[31] Krewitt W, Simon S, Graus W, Teske S, Zervos A, Schäfer O. The 2°C scenario - A sustainable world energy perspective. Energy Policy. 2007;35:4969-80.

[32] Teske S, Muth J, Sawyer S, Pregger T, Simon S, Naegler T, et al. Energy [R]evolution - a sustainable world energy outlook. In: Alexandra Dawe, Rebecca Short, Aubrey C, editors. Amsterdam: Greenpeace International, European Renewable Energy Council (EREC), Global Wind Energy Council (GWEC), Deutsches Zentrumfür Luft- und Raumfahrt (DLR),; 2012.

[33] Gils HC. Balancing of Intermittent Renewable Power Generation by Demand Response and Thermal Energy Storage: Universität Stuttgart; 2015.

[34] Gils HC. Economic potential for future demand response in Germany – Modeling approach and case study. Applied Energy. 2016;162:401-15.

[35] Gils HC, Scholz Y, Pregger T, Luca de Tena D, Heide D. Integrated capacity expansion and operation modelling for variable renewable energy based power supply in Europe. Energy. 2016;(submitted).

[36] IEA. Energy balance of OECD countries (2014 edition). IEA energy statistics (Beyond 20/20). Paris: International Energy Agency; 2014.

[37] Teske S, Achternberg F, Putte JV, Pregger T, Zittel W. Roadmap for Europe - towards a sustainable and independent energy supply. Greenpeace International; 2014.

[38] Suganthi L, Samuel AA. Energy models for demand forecasting—A review. Renewable and Sustainable Energy Reviews. 2012;16:1223-40.

[39] Gobierno de Canarias. Evolución del gasto turístico. 2015.

[40] Gobierno de Canarias. Oferta alojativa de las Islas Canarias. 2015.

[41] EUROSTAT. Database. European Commission; 2015.

[42] IEA. Energy Efficiency Market Report. International Energy Agency, Organisation for Economic Co-operation and Development; 2015.

[43] Teske S, Zervos A, Lins C, Josche M, Krewitt W, Pregger T, et al. Energy [R]evolution - a sustainable world energy outlook. Amsterdam: Greenpeace International, European Renewable Energy Council (EREC), Deutsches Zentrumfür Luft- und Raumfahrt (DLR), ecofys; 2010.

[44] Kermeli K, Graus WJ, Worrell E. Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. Energy Efficiency. 2014;7:987-1011.

[45] Instituto Tecnológico de Canarias. Mapa Solar de Canarias. 2011.

[46] Schallenberg-Rodríguez J. Photovoltaic techno-economical potential on roofs in regions and islands: The case of the Canary Islands. Methodological review and methodology proposal. Renewable and Sustainable Energy Reviews. 2013;20:219-39.

[47] Schallenberg-Rodríguez J, Notario-del Pino J. Evaluation of on-shore wind techno-economical potential in regions and islands. Applied Energy. 2014;124:117-29.

[48] Instituto Tecnológico de Canarias. Mapa Eolica de Canarias. 2011.

[49] Martín Mederos AC, Medina Padrón JF, Feijóo Lorenzo AE. An offshore wind atlas for the Canary Islands. Renewable and Sustainable Energy Reviews. 2011;15:612-20.

[50] IDAE. Evaluación del potencial de la energía geotérmica. Instituto para la Diversificación y Ahorro de Energía; 2011.

[51] IDAE. Evaluación del potencial de la energía de la biomasa. Instituto para la Diversificación y Ahorro de Energía; 2011.

[52] Santamarta JC, Jarabo F, Rodríguez-Martín J, Arraiza MP, López JV. Analysis and Potential of Use of Biomass Energy in Canary Islands, Spain. IERI Procedia. 2014;8:136-41.

[53] IDAE. Evaluación del potencial de la energía de las olas. Instituto para la Diversificación y Ahorro de Energía; 2011.

[54] Gonçalves M, Martinho P, Guedes Soares C. Assessment of wave energy in the Canary Islands. Renewable Energy. 2014;68:774-84.

[55] Sierra JP, González-Marco D, Sospedra J, Gironella X, Mösso C, Sánchez-Arcilla A. Wave energy resource assessment in Lanzarote (Spain). Renewable Energy. 2013;55:480-9.

[56] Gobierno de Canarias. Planes hidrológicos de las Islas Canarias. 2015.

[57] Pietzcker RC, Stetter D, Manger S, Luderer G. Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power. Applied Energy. 2014;135:704-20.

[58] Stetter D. Enhancement of the REMix energy system model: Global renewable energy potentials, optimized power plant siting and scenario validation: Universität Stuttgart; 2014.

[59] Scholz Y, Gils HC, Pietzcker R. Application of a high-detail energy system model to derive power sector characteristics at high wind and solar shares. Energy Economics. 2016.

[60] Trieb F, Schillings C, Pregger T, O'Sullivan M. Solar electricity imports from the Middle East and North Africa to Europe. Energy Policy. 2012;42:341-53.

[61] Suárez BP. personal communication. Instituto Tecnológico de Canarias2015.

[62] Moser M. Combined electricity and water production based on solar energy: University of Stuttgart; 2015.

[63] Schallenberg-Rodríguez J, Veza JM, Blanco-Marigorta A. Energy efficiency and desalination in the Canary Islands. Renewable and Sustainable Energy Reviews. 2014;40:741-8.

[64] Sadhwani JJ, Veza JM. Desalination and energy consumption in Canary Islands. Desalination. 2008;221:143-50.

[65] Gils HC. Assessment of the theoretical demand response potential in Europe. Energy. 2014;67:1-18.

[66] Enerdata Research Service. Odyssee database on energy efficiency data and indicators. 2012.

[67] de Otto S, Bevaqua M, Ferrán F, Teske S, Simon S, Gils HC. Energy [R]evolution for the Canary Islands - Energy design for sustainable islands. In: García del Vado C, editor.: Greenpeace Espana; 2015.

[68] Deane JP, Drayton G, Ó Gallachóir BP. The impact of sub-hourly modelling in power systems with significant levels of renewable generation. Applied Energy. 2014;113:152-8.