Utilities Policy 55 (2018) 158–166

Contents lists available at ScienceDirect

Utilities Policy

journal homepage: www.elsevier.com/locate/jup

Exploring sustainable energy future in Reunion Island

Sandrine Selosse[a,*], Olivia Ricci[b], Sabine Garabedian[b], Nadia Maïzi[a]

[a] MINES ParisTech, PSL Research University, CMA - Centre for Applied Mathematics, Rue Claude Daunesse, 06904, Sophia Antipolis, France

[b] Université de la Réunion - CEMOI Centre for Economics and Management in Indian Ocean, 15 avenue René Cassin, BP 7151, 97715, St-Denis, La Réunion, France

ARTICLE INFO

Keywords:
Long-term modelling (TIMES)
Power system
Island renewable energy transition

ABSTRACT

To cope with dependency of imported fossil fuels, high shares of renewable energy sources are expected to expand in electricity production in Small Islands. The case of Reunion Island that aims at having an electricity generation based to 100% on renewable energies by 2030 is analyzed using a bottom-up cost-optimization TIMES model. Future production mixes are providing according to different scenarios focusing on alternatives renewable energy sources. The case of Reunion Island provides a good example for the definition of an energy policy fostering renewable technologies to supply electricity and highlighting the crucial role of incentives policies.

1. Introduction

In most islands regions, energy needs are still heavily dependent on imported fossil fuels even though domestic renewable energy sources can meet their energy needs (Dornan, 2015; Gorrie, 2012; Levanti, 2008). This is the case for example for Fiji, Mauritius or Vanuatu, with their abundant solar, geothermal, wind and bioenergy resources (IRENA, 2013). Not only this situation can lead to energy security problem but also the high and fluctuating cost of imported energy has hindered social and economic development in Small Island Developing States (SIDS) (Mishra et al., 2009; ESCAP, 2008). In this way, several islands have started developing ambitious program to redesign the entire energy system in the sense of a renewable energy transition in line with their vision of a clean energy future (Bundhoo Zumar, 2018; Wolf et al., 2015).

As many other small island states, Reunion Island, a 2512 km^2 French overseas territories and collectivities (as Mayotte, Martinique, Guyana, Guadeloupe, Saint Pierre and Miquelon) located between Mauritius and Madagascar in the Indian Ocean, is facing a three-fold challenge combining demographics, the environment and energy. More precisely, energy-independent to meet its electricity needs in the early 1980s, Reunion Island became increasingly dependent on supplies of fossil fuels during the following decades under the pressure of demographic, economic and sociological changes. Indeed, in 1982, the island was self-sufficient since almost all local electricity needs, 99%, were covered by local production, through hydroelectric generation. From the mid-1980s, population growth, one the fastest observed in the world and comparable to Singapore or Hong-Kong (Bénard-Sora and Praene, 2016), and improved comfort (air conditioning, televisions, freezers, etc.) forced the island to resort to imports of oil and coal. From 1970 to 1982, the population increased from 450,000 to 515,814, then reached an estimated level of 843,500 inhabitants in 2015. According to a demographic projection of INSEE Indian Ocean published in November 2017, the symbolic threshold of one million inhabitants could be crossed in 2037. This demographic dynamics, in a context of economic growth, has led to profound changes in the local energy landscape, such as this high dependence on imported fossil fuels. Between 2000 and 2012, primary energy consumption increased by 3.1% per year and final energy consumption by 2.5% per year (Selosse et al., 2014). The rate of electrical independence has steadily deteriorated, reaching barely 36% in 2006. In 2015, petrol, coal and gas represented 86.1% of primary energy consumption and 64% of the island's electricity was generated by fossil fuel (coal and oil) power plants (OER, 2016). To limit its heavy dependence on imported fossil fuels, Reunion Island aims to achieve electricity autonomy by 2030 based on greater energy efficiency and renewable energy alternatives. Moreover, not only motivated by rising fuel costs but also by the impact of global warming, the French territory sets the ambitious goal to be energy-independent to meet all its energy needs and then, wants to use renewable energy sources to power all of its transport by 2050.

Based on the analysis of a 100% renewable power system applied to Reunion Island in 2030, this paper aims to discuss how the island can first envisage the future of its power system to assure supply security, and, in the same time, participate in the greening of the energy system as a part of the ambition to uphold and advance the Paris Agreement. In this sense, the autonomy objective by 2030 of Reunion Island is

* Corresponding author.
E-mail address: sandrine.selosse@mines-paristech.fr (S. Selosse).

https://doi.org/10.1016/j.jup.2018.10.006
Received 1 March 2018; Received in revised form 11 October 2018; Accepted 14 October 2018
Available online 19 October 2018

consistent with the stake of deploying solutions that will build future economies with net zero greenhouse gas emissions, in an effort to limit the rise of global temperatures to 2 °C (or even 1.5 °C) above pre-industrial levels, and "*ensuring access to affordable, reliable, sustainable and modern energy for all*" by 2030 as strived by the seventh United Nations Sustainable Development Goal (SDG).

2. Reunion Island energy landscape and policies

2.1. Towards an autonomous and sustainable power system

French colony from 1642 to 1946, Reunion Island became then the 87th French department but the evolutions were slow, reforms and changes were long overdue, and Reunion remained a forgotten department, under the pretext of the excessive cost of social measures and the equality between the metropolis and the "old colonies" (Combeau and Fontaine). The development and the electrification of the Reunion Island really start in the 1960s with the commissioning of the hydroelectric plants of Langevin and Takamaka. Then, the law No. 75–622 of 11 July 1975 on the nationalization of electricity in the French overseas territories nationalizes the production, the transmission, the distribution, the import and export of electricity. The production, transportation and the distribution is then transferred to the French Public Utility Company, Electricité de France (EDF). Electricity sales tariffs (high and low voltage) in the overseas departments had consequently to be progressively aligned with those of the Metropolis event if energy prices are higher than in continental countries because of high fuel transportation costs but also of the lack of economies of scale. Indeed, islanders benefit from "tariff equity" to virtue of the principle of territorial equity, so electricity is sold at the same price throughout all territories of the French state. More precisely, the cost of producing a megawatt of electricity is around 200 euros in Reunion Island and, the sales price being the same here as in France, electricity is sold at half price. The difference is paid by all the other customers thanks to a tax, the CSPE (Contribution to the Public Electricity Service), representing around 6% of the individuals' bills and allowing not only funding this equalization tariff, but also supporting the development of renewable energies, cogeneration, and the basic necessity tariff that provides access to inexpensive electricity to low-income households. "*Electricity is therefore considered to be a right to which every citizen must be allowed access*" (Bouly de Lesdain, 2015).

Thus, at the end of the 1980s, the electricity production of the island was mainly based on hydraulic resources, sufficiently developed and exploited to meet the needs of the Island. Thereafter, among the profound changes in the landscape, the development of a fossil energy supply can then be explained by a constantly increasing demand for electricity (Bénard-Sora et al., 2018; Bénard-Sora and Praene, 2016). Indeed, to the previously mentioned significant demographic growth must be added an improved standard of living. Bouly de Lesdain (2015) specifies that since 1990, comfort has been especially improved through the generalization of sanitary facilities. "*Hot water has been the fastest spreading facility: only 38% of Reunion homes had hot water in 1990, 60% in 1999, and 82% in 2008. This access to consumption (cooker, refrigerator, television, hot water, etc.) requires electricity.*" This important phenomenon of catching lifestyles compared to the French Metropolis, in terms of greater comfort and better equipment in homes, led to a 205% increase in household electricity consumption between 1980 and 2005 (Savidan et al., 2008). The electrical system had to be developed in order to meet this increasing demand, like the import and use of fossil fuel to generate electricity.

However, Reunion island possesses significant potential in terms of renewables, such as, not only hydropower, but solar, wind, biomass, geothermal and marine energy (Praene et al., 2012). As for some other islands, renewable energy sources are thus sufficiently abundant to explore opportunities for an autonomous, sustainable power system (DESA, 2010; Weisser, 2004). In this context, since the beginning of the 2000s, under the impetus of public policies, essentially fiscal, a new dynamic is initiated and Reunion is committed to the development of renewable energies, mainly photovoltaic (Savidan et al., 2008). Notably, a regional energy agency (ARER) was established, now SPL Energies Reunion, as a tool to develop the island's resources and educate the public (Sawatzky and Albrecht, 2017). Since 2007, Reunion has adopted a strategy for sustainable development that aims to achieve energy autonomy by 2030 based on renewable energy alternatives (ARER, 2009; Robert, 2013). As a first step, the GERRI project, Green Energy Revolution Reunion Island, an economic and social development program centered on the sustainable development of Reunion Island and resulted from the "*Grenelle Environment*" French environment roundtables, was implemented (CGDD, 2009). It was established in the law "*Grenelle 1*" No. 2009-967, with several measures designed to help the island achieve its goal of satisfying all of its heating and cooling needs with renewable resources. Notably, all new constructions in overseas departments must install solar water heating. The GERRI project was dissolved in 2013, but electricity and (then) energy autonomies remain a challenge and a goal to reach, enshrined by the Energy Transition for Green Growth Act launched in France in 2015 which sets the objectives, draws the framework and puts in place the necessary tools to build a new French energy model. So, over the past decade the electricity sector of Reunion has experienced significant changes and reform, much of it driven by the adoption of these ambitious renewable energy targets, such as the substitution of the fossil fuels consumption.

2.2. The energy challenges

Far away from any European or continental territories, Reunion is not link to any energy production network. This characteristic obliges it to import fossil fuels in order to supply the thermal power station of the Port which ensures the security of the supply of electricity. The island is more precisely equipped with two thermal power plants which operate on a coal/bagasse co-firing system (at the Gol sugar refinery and at Bois Rouge). So, the electricity generation relies primarily on imported coal and heavy fuel oil, during peak, diesel powered engines allowing meeting energy demands. The number of hours per year that the latter can run is however limited for environmental reasons by prefectural order (Sawatzky and Albrecht, 2017). The Reunion Island also disposes hydroelectric power (the island's main renewable operational renewable resource) and biomass (with a considerable potential). Hydroelectricity accounted for 17.2% of the island's power generation in 2012 with 133.6 MW of installed capacity and the bagasse (fibrous residue of sugarcane obtained after grinding) resulting from the sugar cane industry is entirely energy-valued. Other renewable energies contribute to the generation of more than 18% of the island electricity, with bagasse representing around 9%. Moreover, 60% of households on the island are equipped with solar powered hot water tanks.

As for all French Non Interconnected Zone (ZNI) to the continental transport network, the maximum share of intermittent generation is legally limited to 30% within the island's electricity grid, due to reliability reasons. The reliability of supply is defined as the ability of the power system to lock back into steady-state conditions after sudden disturbances (e.g. load or production fluctuations). Indeed, the major drawback of the supply of electricity based on renewable energy is that the production of electricity varies highly according to the availability of the resource (wind, solar, wave, etc.). This causes a real problem for non-interconnected electrical grid where intermittent renewable energies should be limited to a maximum level. Note that this question of reliability is also considered in other modelling exercises done for islands ambitioning to integrate larger shares of renewables, as it is the case for Cyprus reaching a share of 30% of intermittent sources to generate electricity of the island (Taliotis et al., 2017a,b). In the case of Reunion Island, this limitation is imposed by Electricity of France (through the Decrees of March 13, 2003, Article 15, and April 23, 2008)

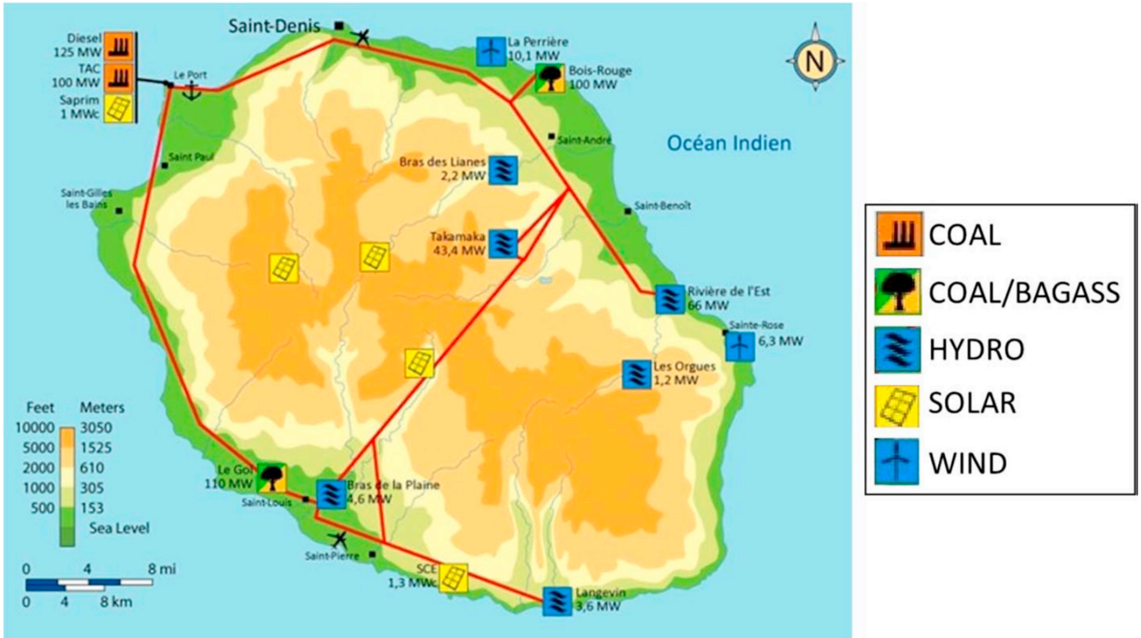

Fig. 1. The Reunion power system as operated in 2008.

based on its capacity to keep the reliability of the network. This aspect is of tremendous importance, especially when high shares of renewable energy sources, and in particular intermittent energy sources, are expected to be integrated in electricity production.

Over the last ten years, a large increase of photovoltaic (PV) installations has been observed, mainly comprising stand-alone systems especially in isolated mountain places that couldn't easily be connected to the grid. The southeast and northeast regions of the island are suitable for wind power generation but, the island being exposed to violent cyclones, special wind turbines insured for cyclonic conditions (pull-down technology) have to be installed, with extra cost. Moreover, the investment is also limited by the non-exploitation during cyclonic winds. Fig. 1 presents the Reunion power system as operated in 2008.

Reunion Island is very often a territory conducive to experimentations in the field of energy, especially for new renewable energies (Praene et al., 2012). The geography of the island (climate, sunshine, pluviometry, etc.) facilitates the establishment of an original electrical mix combining hydroelectricity, photovoltaics, wind and bagasse. Furthermore, beyond the development of the energy cane, marine renewable but also geothermal energies are subject to numerous discussions. Research projects on marine energies are under development and ocean thermal energy conversion (OTEC) could have to be largely deployed as well as wave energy. Geothermal energy also has significant potential thanks to a high thermal gradient with the Piton de la Fournaise volcano. However, this potential is still under study as the volcano is located in a protected natural zone. In this regard, the ministerial decree of 19 October 2016 authorizes research of geothermal deposits at high temperature in the circuses of Salazie and Cilaos.

The net energy delivered to the network amounted to 2944 GWh in 2016, up 4.73% from 2012. Electricity production still comes from 66% of primary fossil energies (coal and oil) and 34% from renewable energies. Moreover, although the consumption of coal continues its decrease in 2016, from −1.9% between 2015 and 2014 to −2.4% between 2016 and 2015 (due to an optimization of the electricity production), the valorized local resources have decreased by 2.7% between 2015 and 216; while the consumption of heavy fuel oil has increased by 17.8%. The increase in heavy fuel oil consumption is explained by the greater solicitation of the Port power station to compensate for the drop in local production and coal, and the increase in consumption (OER, 2017). Although endowed with many types of renewable energy sources and a strong ambition to reach an energy autonomy, reaching a 100% renewable electricity mix is not easily achievable and will involve many structural changes in electricity production in a relatively short time-frame.

This paper aims to discuss different pathways and the key issues that the high penetration of renewable energies in the power mix can raise in Reunion Island. To address these issues, we have conducted a prospective analysis of the Reunion Island electricity system examining the changes in current production patterns in order to move toward a 100% renewable mix by 2030.

3. Model and energy autonomy scenarios

This analysis is conducted with the bottom-up optimization model TIMES-Reunion specifically built to evaluate Reunion Island's power system development until 2030 (Drouineau, 2011). In order to provide plausible options for the long-term development of power systems, TIMES models are useful and widely used tools as they offer a technology-rich representation of the electricity system where each process is defined by a set of economic and technological attributes (i.e. investment costs, variable costs, lifetime, availability factor, residential capacities, etc.) and different primary energy sources are depicted with a detailed description (Fig. 2). The bottom-up optimization model TIMES minimizes the total system cost under constraints (i.e. technical, demand fulfillment, capacity and activity boundaries) over a time horizon. Typically for Reunion Island, the time horizon of the model ranges from 2008 (reference year) to 2030. Then, the model aims to supply energy services at minimum global cost by simultaneously making decisions on equipment investment and operation, and primary energy supply. It computes a total net present value of the stream of the total annual cost, discounted at 7% to the selected reference year 2008. The total annual cost includes investment and dismantling costs (capital costs) that are annualized using hurdle rates, annual fixed and variable operation and maintenance costs, and costs incurred for exogenous imports and domestic resource production.

The model is calibrated for the reference year 2008 when 2546 GWh of electricity was generated according to a mix dominated by fossil fuels, although hydroelectricity and bagasse are well represented.

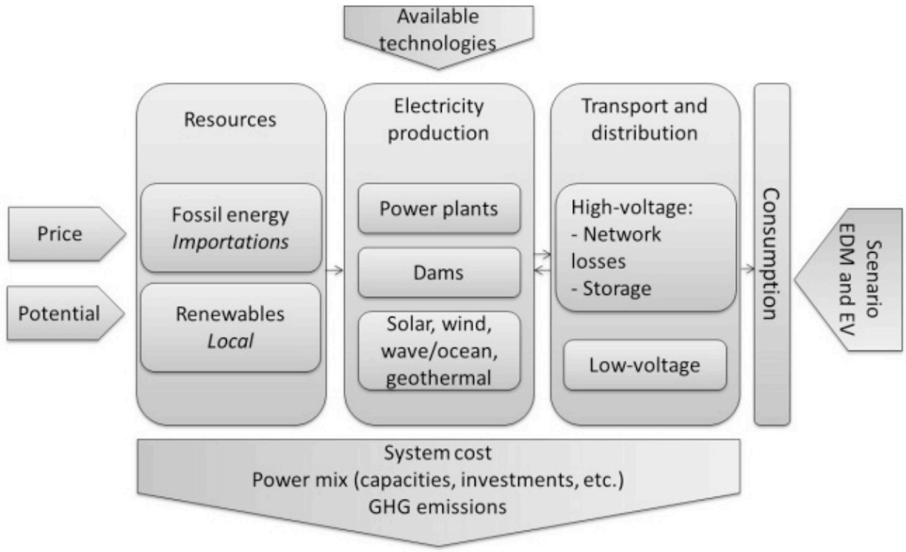

Fig. 2. Reunion Island reference power system (Drouineau, 2011).

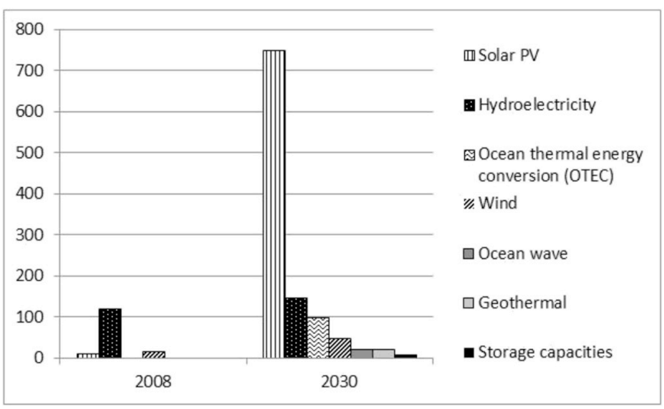

Fig. 3. Renewable installed capacities in 2008 and potentials by 2030 (MW).

Indeed, 64% of electricity production was supplied by fossil primary energy comprising some oil but mostly coal, and 36% by renewables. Hydroelectricity represented close to 25% of the power generation and 69% of renewable electricity. Around 550,000 tons of bagasse were produced and recovered in the two power plants by year, representing 10% of electricity generation sources. In 2008, intermittent energies, solar and wind were insignificant sources of electricity generation (PPI, 2009). 76% of the installed capacities in 2008 concern thermal power plants, representing 476 MW. Hydropower represents 20% of the installed capacities distributed between dams for 109.4 MW and run of river for 11.6 MW. The remainders of the installed capacities are constituted by wind power representing 16.8 MW, solar power representing 10 MW, and municipal waste with 2 MW. Biomass energy sources generated 260 GWh of the island's electricity in 2008. They are supposed to have the potential to generate 460 GWh by 2030. The potential of additional hydroelectricity is assumed to be 147 MW for a production of 542 GWh. The other renewable energies of the Island are assumed to have the potential to reach by 2030 (Fig. 3): 50 MW for wind, 750 MW for solar PV, 100 MW for OTEC, 20 MW for ocean wave, 20 MW for geothermal sources. 1 MW of storage capacity has been installed in 2009 and is assumed to increase until 10 MW.

This technological model is driven by an exogenous demand. The overall evolution of electricity consumption by sector was taken from the planning report produced by EDF (Drouineau et al., 2015). In the reference scenario, the demand on the time horizon corresponds to the Median scenario of electricity demand where the latter increases from 2318 GWh in 2008 to 3732 GWh in 2030. In this reference scenario, no specific energy policy is assumed. There is no particular objective to integrate renewable energy into the mix. This scenario outlines some key patterns in the evolution of the electricity system and serves as the starting point of the analysis. In the different investigated scenarios, we assume that energy demand management will be put in place and that the increase in demand will be lower than in the reference scenario. In this case, the electric demand increases from 2318 GWh in 2008 to 2957 GWh in 2030. Indeed, since 2010, an inflection of the consumption curve has been taking shape and can be explained in particular by the energy demand control actions carried out by local players (Regional Council of Reunion, ADEME, EDF) which contributed to mitigate this energy consumption growth year after year. For example, investments by EDF, of the *Agir Plus* offerings (majority of individual customers) for the year 2016 were as follows (from the *OpenData Platform* of EDF):

- Installation of 6311 individual solar water heaters;
- Sale of 42,839 LED lights via promotions in supermarkets;
- Distribution of 54,754 free LEDs to tenants of social landlords;
- Serving (off-peak hours/peak hours) of 2163 electric water heaters;
- Laying of 72,434 m^2 of insulation in the residential sector and 69,879 m^2 in the commercial sector;
- Installation of 3746 efficient air conditioners on the professional market.

Electric mobility is also a relevant practice for a region like the island where the vast majority of daily trips are less than 100 km. We also expect the deployment of electric car by 2030 with an electricity demand from these vehicles representing 1400 GWh in 2030.

Different scenarios for a completely “green” power system have been implemented in order to analyze possible alternative development pathways of the future autonomous energy system. More precisely, in the green scenarios, the importation of fossil fuels is forbidden in 2030. So, in a first scenario of autonomy, *the Autonomy scenario*, fossil fuel is no longer present in the electricity mix and Reunion Island has to substitute fossil resources by its renewable and local energy sources to reach electricity self-sufficiency by the end of the time horizon.

Then, we implement a sensitivity analysis specifying different targets for renewables, with particular focus on solar, ocean energy, geothermal and sugarcane. A second scenario, the *Solar scenario*, assumes that 300 MW of solar has to be installed by 2030 (EDF, 2017).

Next, we explore the impact on the system of strong political choices such as a large incentive on the development of marine energies. In this case, 50 MW of wave energy has to be installed by 2030 and 100 MW of thermal marine energy by 2030. In this *Ocean scenario*, photovoltaic will significantly also be supported and deployed. In these scenarios, there is no objective to integrate more bagasse in the electricity mix.

Another scenario consists in achieving the 100% renewable target with large scale deployment of bagasse and geothermal energy. Indeed, a significant difference between Reunion Island and many other islands is its biomass potential to reach its renewable targets (Praene et al., 2012) as opposed to a frequent focus on intermittent energy sources (Sawatzky and Albrecht, 2017). So, in this *Biomass scenario*, the exploitation of geothermal energy can be expanded in the protected natural area and the sugarcane resource produced on the island is only devoted to energy. The challenge of biomass availability is integrated in the assumed potential (Drouineau, 2011). More precisely, for the calibration of the year 2008, it was considered that the production of sugar cane mobilizes 25,000 ha of plantations in Reunion Island. Each year, the sugar industry generates around 500,000 tons of bagasse producing around 260 GWh of electricity. New sugarcane varieties were implemented, as proposed by teams at eRcane (Centre for trials, research and training), where yields of sugar cane per hectare are higher – they can increase by 20% in 2020 compared to the production of 2008, or even 30% in 2030 – and where the fiber rate in the sugar cane is higher, allowing to increase the production yield of electricity. These changes can attain a production level of 460 GWh in 2030. The available areas and energy resources were also considered (according to ARER/Energies Reunion) for fiber cane with 1500 ha in 2020, and 7500 ha in 2030, plus a 100% cane energy option with 25,000 ha. The 100% energy cane option would correspond to the abandonment of the sugar industry, this option is not on the agenda but it is an ambitious and political scenario to analyze.

Based on the intermittent nature of solar and wind energy, and the fact that the electrical grid is characterized by a single distributor, without external connections and limited storage facilities, as specified previously, French government set in 2008 a legal limit of 30% of instantaneous electricity production from intermittent sources for its overseas territories, including Reunion Island. In order to handle these reliability issues and avoid any risk for the network, the limitation concerns more precisely solar, wind, wave energy and run of river. However, given the success of the experiment conducted since 2010 by EDF with its storage system, a sodium-sulfur battery (NaS) with a capacity of 1 MW, we assume a higher limitation in the exploitation rule, i.e. a first level of 32% of intermittent sources in the grid. In a second time, through a sensitivity scenario, we assume that intermittent energy sources in the grid are limited to a maximum of 35%, this level corresponding to the threshold targeted in 2018 by EDF (EDF, 2016).

On the basis of these different orientations, we analyze the changes in current electricity production patterns to move toward a system capable of achieving the electricity challenge of Reunion Island by 2030.

4. Results

In the reference scenario, the production of electricity increases from 3069 GWh in 2008 to 4688 GWh by 2030. The electricity mix is dominated by fossil fuels during the entire time horizon, and especially by coal, the quantity of electricity produced from this source doubling from 2008 to 2030 (including co-firing power plants whose contribution decreases relatively in favor of coal-only plants). The share of renewable energy in the production of electricity stabilizes at around 35%, close to the level observed in 2008 (36%). This evolution indicates that without a constraint to promote electricity autonomy, the most economical solution for producing electricity is based on imported fossil fuels, notably coal. Furthermore, the stable contribution of renewables, even if in value it increases by 14% between 2008 and 2030, underlines that on the one hand, the level of renewable energy in the current system is close to the maximum level of integration from a purely economic point of view, and on the other hand, the transition to a 100% renewable cannot be reached without an effective incentive system or regulatory constraint. Indeed, the fact that Reunion Island is endowed with abundant and varied sources of renewable suggests that a green plan for the power sector is feasible but it must rely on substantial commitments and supports by public policy-makers. Much of the academic literature on renewable energy deployment in small islands highlights the institutional policies necessary for their development. Be geographically small has obviously economic and policy implications for renewable energy development, small consumer markets constraining the ability of energy suppliers to benefit from economies of scale in power generation (Dornan and Shah, 2016). The development of innovative technologies can be backed by financial or tax incentives but non-financial obstacles have also to be unblocked. Moreover, it is essential for the private sector to be supportive (Khoodaruth et al., 2017; Shirley and Kammen, 2013). In the framework of the Reunion Island's energy plan, i.e. the Regional Schema for Climate, Air, Energy (SRCAE), the regional government established an Energy Governance Committee (EGC) gathering regional, local and state government actors as well as private stakeholders (energy and waste companies) and the public. Its objective is to evaluate the current energy situation and determine appropriate future directions for energy development (Sawatzky and Albrecht, 2017).

Then, to tend towards a system able to answer the autonomy challenges, the current electricity production modes need first to be modified. Given the varied potential of renewable resources that Reunion Island could deployed, such as wind, solar, biomass, ocean or geothermal energy, we analyze the impact on the electricity system of different focus expressing specific supports. The question is to determine how fossil fuel generation of electricity could be substitute by a mix of different renewable sources and how renewable could be deployed if a resource is specifically supported. Table 1 presents the electricity mix according to the different investigated scenarios.

In the *Autonomy scenario*, without specific support on particular

Table 1
Electricity mix under the 100% renewable scenarios (GWh).

Scenario	Period	Coal	Coal/Biomass	Oil	Hydro	Biomass	Ocean	Solar	Wind	Waste biogas	Geothermal	Total
Autonomy	2020	698	412	798	843	340	77	98	71	32		3,368
	2025	693	74	141	870	1,845	77	98	103	16	112	4,028
	2030				870	2,820	666	72	110		112	4,649
Solar	2020	452	539	795	882	305	25	235	103	32		3,369
	2025	419	155	324	882	1,634	42	298	103	16	149	4,021
	2030		25		882	2,748	368	386	110		149	4,649
Ocean	2020	455	488	793	870	442	25	235	30	32		3,369
	2025	478	395		870	1,362	305	579	30	16		4,034
	2030		131		870	2,293	582	755				4,630
Biomass	2020	592	466	788	948	254	25	235	30	32		3,369
	2025	601	85		948	2,004	53	298	30	16		4,034
	2030				948	3,256	77	368				4,649

renewable resources, biomass is largely deployed from 2025. It then represents 46% of the electricity mix and reaches 61% in 2030. In the *Biomass scenario* where this resource is particularly supported, notably by the development of cane-energy, biomass represents 50% and 70% of the power generation in 2025 and 2030 respectively. In the *Solar* and *Ocean scenarios*, it is interesting to note that, despite that solar and marine energy have been greatly encouraged, biomass is the main substitute to fossil fuels.

The fact that electricity from biomass has advantageously replaced electricity from coal can be explained by the use of new varieties of sugarcane and the opportunity to develop a sugarcane variety solely devoted to the energy production. Biomass is developed by 2020, due to, on the one hand, the availability of energy-dedicated sugarcane, with higher efficiency, and on the other hand, significant investments in bioplants. Massive investments are moreover made in biomass gasification plants in 2025. As highlight Arshad and Ahmed (2016), energy production through bagasse cogeneration is very efficacious and presently established in many sugarcane producing countries such as Brazil, Mauritius and India. This option appears particularly promising with regards to the objectives of Reunion Island and its potential. But actions on the sugar industry can be expected to be developed. The sugarcane industry has a long history and is an important pillar of the Reunion but it is based on subsidies from the European Union that allowed favorable prices. The end of these commercial privileges in the coming years pushes to rethink the industry or, at least, to make the scenario more realistic. The sugar industry could be called to re-engineered itself to support the bio-refinery concept. Production of biofuel for the electricity sector, even bio-ethanol for the transportation sector, could be promoted.

As regards geothermal energy, it is slightly developed in 2025 and 2030 to meet the target, about 3–4%, in the *Autonomy* and *Solar* scenarios. In the *Biomass scenario*, geothermal option is not developed, although the exploitation in the protected natural zone is possible in this scenario. Wind power is not particularly deployed whatever the scenario as other investments are supported. It is interesting to note, beyond the choice of substitution, that while coal still produced electricity in 2025 whatever the green scenarios, oil disappears of the electricity mix after 2020 in *Ocean* and *Biomass* scenario. The share of hydroelectricity decreases at the end of the time horizon, whatever the scenario, the level of electricity generation remaining relatively unchanged in all scenarios, between 833 and 944 GWh of produced electricity. The potential of other abundant renewable sources, such as tidal and wave, can be tapped in the future but, in these scenarios, investments in these options have not been very significant; their future appears conditional on resolving some uncertainties about the technologies and their cost, and specific support will have to be provided.

The sensitivity analysis which was conducted with a 35% limit of intermittent energy sources in the grid instead of 32%, did not have a significant impact on these results and the choice of investments in the scenarios we analyzed. Higher level of intermittent sources can be integrated if storage systems are implemented in association with. Investments are then to be done in this sense, just like demand response measures should be more investigated (Drouineau et al., 2015; Bouckaert, 2013, 2014; Maïzi et al., 2017). Provided appropriate investment storage allows a higher share of variable intermittent plants, demonstrators and pilot sites have been developed in Reunion Island in that sense. This is also the case of the island of Ireland with it storage pilot scheme for notably reliability consideration (Eirgrid, 2017). Considering demand response to respect this objective, it will first of all be necessary that the local population really appropriates the energy object, then that the necessary means continue to be put in place in order to respect these targets. In this context of increasing the proportion of electricity produced by intermittent renewable energy sources, vehicle-to-grid system can also provide an important benefit for the peak shaving, participating in the grid frequency control and maintaining the balance between generation and demand on the grid.

Finally, it is interesting to note that 2.15 Mt of CO_2 are then avoided by 2030 because of the use of renewable energy to produce electricity on the island. By 2020, emissions decrease by half, from 1.99 Mt to about 900 kt in this context. They reach about 490 kt in 2025 (instead of 2.11 kt in the reference scenario). Moreover, as previously indicated, the objective function of the linear optimization model TIMES-Reunion is to minimize the total discounted cost of the power system (comprising fuel, investments, fixed and variable operation and maintenance costs, etc.) on the time horizon, given the assumed demand and technico-economic, political or environmental constraints. The decarbonized transition of the power system incurs higher total discounted system costs due to the additional costs induced by the different incentives to promote certain renewables; some pathways toward the energy autonomy appear more costly than others. Compare to the reference scenario, the increase of the total discounted cost of the Reunion power system under the *Autonomy scenario* is 8%, 11% in the *Solar scenario*, 13% in the *Biomass scenario* and 17%, the most costly, in the *Ocean scenario*.

5. Discussion

For economic, social and environmental reasons, it is imperative for small island like Reunion, and especially SIDS, to get out of their unsustainable scenario in the long-term and to reduce their dependency on fossil fuels and expand the use of renewable resources (Khoodaruth et al., 2017; Dornan and Shah, 2016; Shirley and Kammen, 2013). Recent studies highlight that the design of carbon-neutral energy systems based on renewable energies is technologically achievable (Jacobson et al., 2014; Elliston et al., 2013) and small islands have a key role to play in the greater reliance on renewable energy resources and in lessons that the rest of the world can derive. As highlighted in Maïzi et al. (2017), the increased share of renewable energy sources in electricity production has been widely studied focusing on the various technical and economic challenge: for example, on the one hand, on demand challenges, and more precisely on how to meet future global or regional demand (Jacobson and Delucchi, 2011; Delucchi and Jacobson, 2011), or, on the other hand, on cost optimization criteria to study the feasibility and/or design of solar- and wind-based power system using storage technologies (Plessmann et al., 2014; Aboumahboub, 2012). As many small islands, over the last decades, Reunion Island committed to use their resources in a more sustainable manner. This had led it to seek to exploit renewable energy resources available locally, rather than continue its dependence on foreign oil reserves. Despite this ambitious target, renewable energy sources continue to struggle to be adopted (Ince et al., 2016), the power mix of Reunion island remains dominated by imported fossil fuels and the share of renewable stagnates by 35%.

Establishing renewable targets and recognizing the considerable potential that exists for replacing oil-based power generation with electricity produced by renewable energy technologies, most small islands focused on investments in the electricity sector, and in some cases, targets extend beyond this sector, often with a view to the production of biofuels from domestic crops (Dornan and Shah, 2016). This can be particularly interesting considering the biomass potential of Reunion Island. Indeed, the sustainable transition of the energy system implies to transform electricity sector but also the other sectors, as transport. This analysis focused on the electricity mix but it considered higher demand due to the development of electric vehicles, one of various solutions to decarbonized the transport sector. For all that, further investigation, notably in terms of model development, could be done to consider the energy system of the Reunion Island in its whole and integrate more precisely mobility issues. With electric vehicles and biofuels, hydrogen solutions can also be investigated in that sense. This transition takes time and involves systemic changes notably because infrastructure favors the currently dominant fuels (Shirley and Kammen, 2013). So, even if Reunion Island succeeds to provide 100%

electricity, the challenge of renewable and sustainable transition of the Island is still huge as more electric power is expected to be supply to all other sectors, that have to be decarbonized in order to reach the ultimate objective of achieving total energy self-sufficiency and security (Surroop and Raghoo, 2017; Khoodaruth et al., 2017). In transport particularly, the challenge is of tremendous importance as the Reunion car park is maintained and the public transport network remains undeveloped. The direct consequence is therefore a 39.7% increase in the supply of fossil fuels between 2000 and 2015, i.e. an average of 2.6% per annum (OER, 2016).

Many reasons can be advanced for the lack of renewable development but the higher cost of developing renewable energy and the lack of necessary financial support and incentives can be primarily cited. A deployment of options based on resource availability, maturity and cost effectiveness can be combined with less mature technologies with high potential for development, such as ocean technologies (Khoodaruth et al., 2017). In order to encourage non-public stakeholders to support the burden of financial and investment risk, they could be involved in formulation and implementation of the policy, particularly to help to design the transition to be complementary to policy in transportation, agriculture and related sectors. Energy autonomy for Reunion Island, and more generally for many island territories, remains the ultimate goal. The island is seen as a territory full of resources and must be able to manage and exploit them but it is a delicate issue and a difficult process to put in place, especially on the economic level. Some islands succeed to meet the challenge, as for example El Hierro within the Canary Islands but not only historical, cultural differences have to be taken into account but also political, administrative and regulatory as suggested with the alternative development of biomass resources on Reunion Island, involving the abandonment of the sugar industry if the 100% energy cane option is considered.

6. Conclusion

Reunion Island is faced with crucial challenge regarding the future of its energy mix. This analysis aims at illustrate the changes in current electricity production patterns to move toward a system capable of achieving the electricity challenge of Reunion Island by 2030. Based on a comparison of alternative scenarios, the question is to determine how renewable resources could be deployed to substitute fossil fuels if a resource is specifically supported. The results from our optimization bottom-up model, TIMES-Reunion, highlight the significant role to play by renewable energies if the latter are politically or financially supported. Even if this issue of decarbonation of the electrical system cannot be isolated from a study of the energy system as a whole, at the risk of missing out on the reciprocal effects of changes in the different sectors, this analysis is crucial in the current context as it highlights the challenges to take up and the development potentials of the different options, some facing each other. Whatever the scenario, biomass appears the most promising substitute to fossil fuels. Wind and marine energy sources seem dependent from dedicated support to promote and develop them. These results can then be useful for questioning the political limits of resource development potentials. To what extent the economy of the island, its structure, and its historical organization can be transformed to benefit from these high potential of renewable resources and so, to reach the decarbonation of the electric system, and more largely the energy system.

Acknowledgements

This research was supported by the Chair Modeling for sustainable development, driven by MINES ParisTech, Ecole des Ponts ParisTech, and AgroParisTech, supported by ADEME, EDF, GRTgaz, SCHNEIDER ELECTRIC and the French Ministry of Ecology, Sustainable Development and Energy.

Appendix. Assumptions of the modelling activity

This model is a technico-economic bottom-up model with a high level of technological description, it is a data driven model with 121,195 assumed data in order to have the most faithful representation of the island in 2008 and the most coherent assumption possible over the time horizon, in the context of different possible scenarios. Among these assumptions:

Table A.1
Electricity demand projections.

Demand scenario	2008	2010	2015	2020	2025	2030
Median						
Electricity demand (GWh)	2318	2467	2831	3187	3464	3732
Energy demand control						
Electricity demand (GWh)	2318	2463	2750	2850	2913	2957
Electric cars						
Electricity demand (GWh)				0		1400

Table A.2
Grid's power peak in case of energy demand control.

EDM scenario	2008	2010	2015	2020	2025	2030
Median						
Power peak (MW)	408	445	520	595	670	750
Energy demand control						
Power peak (MW)	408	435	480	521	560	596

Table A.3
Renewable energy potential reference assumptions by 2030.

Energy sources	Level in 2008	Potential
Biomass	260 GWh	460 GWh
Hydroelectricity	121 MW	147 MW
	553 GWh	542 GWh
Wind	16.8 MW	50 MW
Solar PV	10 MW	750 MW
Ocean thermal energy conversion (OTEC)		100 MW
Ocean wave		20 MW
Geothermal		20 MW
Storage capacities		1 MW in 2009
		10 MW

Table A.4
Electricity production from the calibrated model in 2008 (based on data from EDF SEI, 2009) by comparison with observed data.

Energy sources	Model (%)	EDF (%)
Coal	14.97	55.55
Bagasse		10.31
Coal-Bagasse	45.34	
Oil	12.62	13.3
Hydro	21.87	24.86
Wind	1.16	0.53
Solar	0.43	0.42
Municipal wastes	0.62	0.03
Production	**2545.7 GWh**	**2546 GWh**

Table A.5
Fuel importation costs (Sources: WEO and CEREN).

Imported fossil energy prices (2008)	Unit	2008	2015	2020	2025	2030
Coal	^{2008}USD/t	120.59	91.05	104.16	107.12	109.40
Crude oil	^{2008}USD/barrel	97.19	86.67	100.00	107.50	115.00
Heavy fuel oil	^{2008}€/t	195.50	174.34	201.15	216.24	231.33
Domestic fuel	^{2008}€/hectoliter	46.54	41.50	47.89	51.48	55.07

Table A.6
Technologies costs reported with a base index of 100 for wind energy.

Technologies	Investment costs				Fix costs			
	2010	2015	2025	2035	2010	2015	2025	2035
Turbine Peak. OIL-FOD	25	23	23	24	45			
Turbine Peak. OIL-HFO	25	23	23	24	45			
Steam Turb. OIL-HFO	44	43	44	45	50			
Wind	**100**	**100**	**100**	**100**	**100**			
Steam Bagasse Cane Fibre.	143	131	123	109	112			
IGCC Bagasse Cane Fibre	152	142	135	129	136			
PV Plant	266	187	129	77	74	74	74	49
PV Roof panel	360	255	155	105	100			
Solar Thermal	336	309	279	263	126	114	102	94
Wave energy	430	407	347	288	200			
Ocean thermal energy	430	407	347	288	200			

(continued on next page)

Table A.6 (*continued*)

Technologies	Investment costs				Fix costs			
	2010	2015	2025	2035	2010	2015	2025	2035
Geo Steam Plaine des Sables	450	408	351	358				
Geo HDR Salazie	500	439	351	358	688	484	438	340
Hydro Run	585	0	0	0	148			
Hydro Dam	350	0	0	0	113			

References

Aboumahboub, T., 2012. Modeling and Optimization of the Global Electricity Generation System with High Shares of Fluctuating Renewable Energy Sources. [Ph.D. Thesis]. Technische Universität München.

ARER, 2009. *PETREL – Île de la Réunion: Plan Economique de Transition et de Relance via des Energies 100% Locales à l'Île de la Réunion. Prospective et Mix énergétique de la Réunion aux horizons 2020-2030*. Contribution de l'ARER au programme STARTER de la région Réunion via la demande d'intervention de la région datée du 12 mars 2009 (référence 200904913 DEC/JD/CV) et aux travaux de Mix Energétique 2009 inscrits dans le programme Général de l'ARER. 9 juillet 2009.

Arshad, Muhmmad, Ahmed, Sibtain, 2016. Cogeneration through bagasse: a renewable strategy to meet the future energy needs. Renew. Sustain. Energy Rev. 54, 732–737.

Bénard-Sora, Fiona, Praene, Jean-Philippe, Calixte, Yatina, 2018. Assess the local electricity consumption: the case of Reunion island through a GIS based method. AIMS Energy 6 (3), 436–452.

Bénard-Sora, Fiona, Praene, Jean-Philippe, 2016. Territorial analysis of energy consumption of a small remote island: proposal for classification and highlighting consumption profiles. Renew. Sustain. Energy Rev. 59, 636–648.

Bouckaert, S., 2013. Contribution des Smart Grids à la transition énergétique: évaluation dans des scénarios long terme, Ecole Nationale Supérieure des Mines de Paris, 2011, Français. < NNT: 2013ENMP0056 > .

Bouckaert, S., Wang, P., Mazauric, V., Maïzi, N., 2014. Expanding renewable energy by implementing dynamic support through storage technologies. Energy Procedia 61, 2000–2003.

Bouly de Lesdain, Sophie, 2015. Installing rooftop solar panels in private homes: the case of small electricity producers on Reunion island (Indian Ocean), climate change, culture, and economics: anthropological investigations. Res. Econ. Anthropol. 35, 25–46.

Bundhoo Zumar, M.A., 2018. Renewable energy exploitation in the small island developing state of Mauritius: current practice and future potential. Renew. Sustain. Energy Rev. 82 (Part 3), 2029–2038.

CGDD, 2009. Le projet Réunion 2030 – GERRI, Commissariat général au développement durable, Le point sur, no 28, Octobre 2009.

Combeau Yvan and Fontaine Guy, Ile de la Réunion: Les mutations de la départementalisation, Encyclopaedia Universalis. https://www.universalis.fr/encyclopedie/ile-de-la-reunion/3-les-mutations-de-la-departementalisation/.

Delucchi, M.A., Jacobson, M.Z., 2011. Providing all global energy with wind, water, and solar power, part ii: reliability, system and transmission costs, and policies. Energy Pol. 39 (3), 1170–1190.

DESA, 2010. Trends in Sustainable Development: Small Island Developing States (SIDS). Department of economic and social affairs [Last visited: February 28th, 2018]. http://sustainabledevelopment.un.org/content/documents/313Trends_in_Sustainable_Development_SIDS.pdf.

Dornan, Matthew, 2015. Renewable energy development in small island developing states of the Pacific. Resources 4, 490–506.

Dornan, Matthew, Shah, Kalim U., 2016. Energy policy, aid, and the development of renewable energy resources in Small Island Developing States. Energy Pol. 98, 759–761.

Drouineau, M., 2011. *Modélisation prospective et analyse spatio-temporelle: intégration de la dynamique du réseau électrique*, Energie électrique, Ecole Nationale Supérieure des Mines de Paris, 2011, Français. < NNT: 2011ENMP0104 > .

Drouineau, M., Assoumou, E., Mazauric, V., Maïzi, N., 2015. Increasing shares of intermittent sources in Reunion Island: impacts on the future reliability of power supply. Renew. Sustain. Energy Rev. 46, 120–128.

EDF, 2017. Systèmes énergétiques insulaires – La Réunion Bilan prévisionnel de l'équilibre Offre/Demande d'électricité. EDF SEI, pp. 14 BP217, Juillet.

EDF, 2016. Transition énergétique à la Réunion: l'engagement d'EDF pour les énergies renouvelables, Dossier de presse, 02/02/2016. 6 pages.

EDF SEI, 2009. Bilan Prévisionnel Pluriannuel: investissements en production (La Réunion). Rapport technique. Electricité de France.

Eirgrid, 2017. All-island Generation Capacity Statement 2017-2026, Report. pp. 76.

Elliston, B., MacGill, I., Diesendorf, M., 2013. Least cost 100% renewable electricity scenarios in the Australian national electricity market. Energy Pol. 59, 270–282.

ESCAP (Economic and Social Commission for Asia and the Pacific), 2008. Energy Security and Sustainable Development in Asia and the Pacific. United Nations report 240 pages.

Gorrie, Seth, 2012. *The Scientific and Cultural Aspects of Renewable Energy Development Success in Samoa*. Thesis of Master of Science. University of Otago, Dunedin, New Zealand 194 pages.

Ince, David, Vredenburg, Harrie, Liu, Xiaoyu, 2016. Drivers and inhibitors of renewable energy: a qualitative and quantitative study of the Caribbean. Energy Pol. 98, 700–712.

IRENA (International Renewable Energy Agency), 2013. Pacific Lighthouses. Renewable energy roadmapping for islands. Report. 55 pages. www.irena.org/Publications.

Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, part i: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Pol. 39 (3), 1154–1169.

Jacobson, M.Z., Delucchi, M.A., Ingraffea, A.R., Howarth, R.W., Bazouin, G., Bridgeland, B., 2014. A roadmap for repowering California for all purposes with wind, water, and sunlight. Energy 73, 875–889.

Khoodaruth, A., Oree, V., Elahee, M.K., Clark II, Woodrow W., 2017. Exploring options for a 100% renewable energy system in Mauritius by 2050. Util. Pol. 44, 38–49.

Levanti, T., 2008. Oil price vulnerability in the Pacific. Econ. Bull. 23, 214–225.

Maïzi, Nadia, Mazauric, Vincent, Assoumou, Edi, Bouckaert, Stéphanie, Krakowski, Vincent, Li, Xiang, Wang, Pengbo, 2017. Maximizing intermittency in 100% renewable and reliable power systems: a holistic approach applied to Reunion Island in 2030. Appl. Energy. https://doi.org/10.1016/j.apenergy.2017.08.058.

Mishra, V., Smyth, R., et al., 2009. The energy-GDP nexus: evidence from a panel of Pacific Island countries. Resour. Energy Econ. 31 (3), 210–220.

OER, 2017. Bilan énergétique de l'île de La Réunion 2016. Observatoire Energie Réunion, Agence régionale énergie Réunion, ARER 78 pp. [Last visited: February 28th, 2018]. http://energies-reunion.com/wp-content/uploads/2015/01/BER-Technique-2016-BD.pdf.

OER, 2016. Bilan énergétique de l'île de La Réunion 2015. Observatoire Energie Réunion, Agence régionale énergie Réunion, ARER 78 pp. [Last visited: February 28th, 2018]. http://energies-reunion.com/wp-content/uploads/2016/07/BER-Technique-2015-TOTAL-BD.pdf.

Plessmann, G., Erdmann, M., Hlusiak, M., Breyer, C., 2014. Global energy storage demand for a 100% renewable electricity supply. Energy Procedia 46, 22–31.

PPI, 2009. Programmation pluriannuelle des investissements de production d'électricité. Période 2009-2020, Rapport au Parlement, 2009. 132pp.

Praene, Jean-Philippe, David, Mathieu, Frantz, Sinama, Dominique, Morau, Olivier, Marc, 2012. Renewable energy: progressing towards a net zero energy island, the case of Reunion Island. Renew. Sustain. Energy Rev. 16, 426–442.

Robert, D., 2013. Action plan, territorial growth Pact La Reunion, Pact 2014-2020. 29p. [Last visited: February 28th, 2018]. http://ec.europa.eu/regional_policy/sources/activity/outermost/doc/plan_action_strategique_eu2020_lareunion_en.pdf.

Savidan, Lise, Schaffar, Alexandra, Michel, Dimou, François, Garde, 2008. La consommation énergétique des ménages à La Réunion: vers un retour à l'autonomie par le biais des énergies renouvelables. http://journals.openedition.org/etudescaribeennes/3519.

Sawatzky, Matthew, Albrecht, Moritz, 2017. Translating EU renewable energy policy for insular energy systems: Reunion Island's quest for energy autonomy. Fennia 195, 2.

Selosse, S., Ricci, O., Garabedian, S., Maïzi, N., 2014. Reunion Island Energy Autonomy Objective by 2030. EcoMod2014, International Conference on Economic Modeling, Jul 2014, Bali, Indonesia.

Shirley, Rebekah, Kammen, Daniel, 2013. Renewable energy sector development in the Caribbean: current trends and lessons from history. Energy Pol. 57, 244–252.

Surroop, Dinesh, Raghoo, Pravesh, 2017. Energy landscape in Mauritius. Renew. Sustain. Energy Rev. 73 (June), 688–694.

Taliotis, Constantinos, Taibi, Emanuele, Howells, Mark, Rogner, Holger, Bazilian, Morgan, Welsch, Manuel, 2017a. Renewable energy technology integration for the island of Cyprus: a cost-optimization approach. Energy 137, 31–41.

Taliotis, Constantinos, Taibi, Emanuele, Howells, Mark, Rogner, Holger, Bazilian, Morgan, Welsch, Manuel, 2017b. Technoeconomic assumptions adopted for the development of a long-term electricity supply model for Cyprus. Data in Brief 14, 730–737.

Weisser, D., 2004. On the economics of electricity consumption in small island developing states: a role for renewable energy technologies. Energy Pol. 32 (1), 127–140.

Wolf, Franziska, Surroop, Dinesh, Singh, Anirudh, Leal, Walter, 2015. Energy access and security strategies in small island developing states. Energy Pol. 98, 663–673.