Long-term planning tools and reliability needs: focusing on the Reunion Island

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Abstract

In this paper, we tackle the issue of reliability of supply in future power systems. To build plausible options for future energy systems, long-term planning models – such as the Markal/TIMES family of models – must address the technological and economical feasibility of these options. This paper focuses on the electricity sector and how to take reliability into account when designing future power systems in long-term planning exercises. This approach is implemented and demonstrated through the development of a TIMES model for the Reunion Island.

Keywords: Long-term energy planning. Reunion Island. Reliability of supply.

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1 Introduction

The future of the energy industries have a number of challenges to overcome, in particular international constraints on carbon emission, the expected depletion of fossil fuels, the population densification or the tremendous growth in developing countries. At this point in time, the structure of the energy supplies is under questions. Furthermore, a number of studies suggest that high shares of renewable energy sources may become an essential feature of future electricity industry [1, 2].

The current power systems clearly lack of efficiency because the sector is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, which are one

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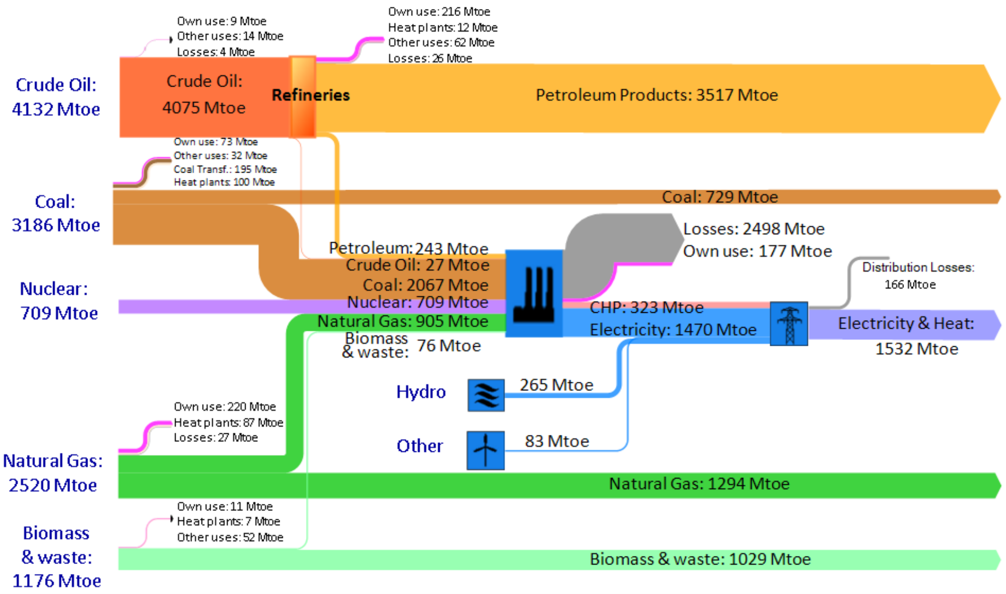

Figure 1: *Energy supply-chain in Mtoe in 2007 (e!Sankey diagram). The electricity sector is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, and by the electrical losses at the transmission, distribution and consumption levels [3].*

order of magnitude greater than electrical losses at the transmission, distribution and consumption levels (as shown in the figure 1).

Moreover, the world net generation of electricity increasingly relies on fossil fuels as shown in figure 2, which implies a higher impact on the environment due to the level of greenhouse gas emissions emitted by the electrical sector.

At first glance, the overall efficiency of the electricity sector is expected to increase with high shares of renewable energy sources. However, such a wide integration of renewable energy sources – in particular intermittent ones – raises several technical issues. An important issue to consider when evaluating the integration of renewable energy sources is that of a decrease in the ability of the electric system to withstand sudden disturbances, the reliability of the power system [4]. It is therefore strongly recommended to consider reliability of the power system when evaluating options with high shares of renewable energy sources.

For this task, we propose the use of Markal/TIMES models, which are technological rich, long-term, partial-equilibrium models. Markal/TIMES models can be used to evaluate and analyze investment alternatives and the future development of an energy sector [5].

The aim of this study is to discuss power systems provided by Markal/TIMES models in the light of reliability requirements (section 2) and also to assess the reliability of supply with different shares of renewable energy sources. A case study of the Reunion Island is performed, for which we model and analyze the long-term development of the supply and power sectors (section 3).

The Reunion Island aims to have in 2030 an energy consumption based to 100% on

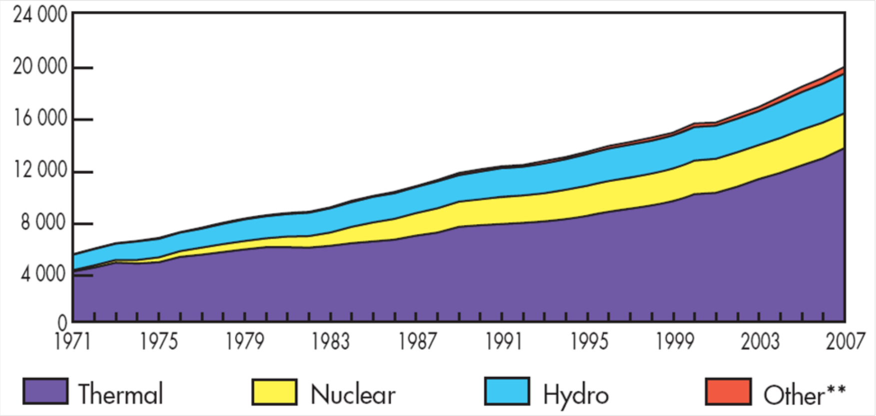

Figure 2: *Electricity generation in TWh by fuel since 1971 [3]. Other includes geothermal, solar, wind, combustible renewables and waste, and heat.*

renewable energy sources [6]. In 2008, the total primary energy consumption was 1295 ktoe, and as most of small islands, the Reunion Island was highly dependent on fossil fuel imports (86.5%). In the power sector, the current use of renewable energy sources is 36% [7]. The electricity mix has to change substantially to reach the announced target. Fortunately, this change is enabled by high potentials for renewable energy sources such as sugarcane bagasse, solar energy, wind energy, geothermal, and marine power.

2 Methods

This section is divided into two contributions. We rely on a deep understanding of reliability requirements in power systems and present the Markal/TIMES family of long-term planning models, stressing their strengths and weaknesses in the light of the reliability requirements.

2.1 Description of reliability of supply

As explained in [4], electric system reliability can be addressed by considering two basic and functional aspects of the electric system:

- Security – The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.
- Adequacy – The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

From a technical point of view, reliability of supply is ensured by the electromagnetic coupling energy on the system and by available levels of kinetic and spinning reserves. Indeed, power systems rely on frequency and voltage management [8]. Frequency and voltage are crucial quantities, whose deviations can lead to brownouts or power outages.

This typically occurs when the system experiences transient states (e.g. lightning), or is recovering from production or load fluctuations. Maintaining voltage and frequency between appropriate limits depends respectively on the electromagnetic coupling energy and on the kinetic and spinning reserves. This emphasizes the need for electromagnetic power and for appropriate levels of reserves on power systems. However, most renewable energy sources, and in particular intermittent ones, do not provide the required levels of reserves as efficiently as conventional power units (for example thermal units and hydroelectricity) [9]. Furthermore, intermittent energy sources commonly induce frequent and higher magnitude production fluctuations thereby further increasing the need for reliability of the electric system.

Maintaining sufficient amounts of the coupling, kinetic and spinning energies, induce extra-losses and may require additional investments. Therefore, in order to provide relevant comparisons between future electrical systems, and reliability of electricity supply, losses over the network must be assessed properly. Conveyance and reliability losses were defined as follows:

- Reliability-induced losses are related to the additional costs consented for maintaining the electromagnetic coupling and eventually investing in kinetic and spinning reserve capacities (e.g. wheighing generation machines, flywheels). When production capacities are distributed on smaller and less hierarchically organized grids (e.g. distributed ones), reactive power and kinetic reserve are critical to ensure a given reliability level. Each “small” grid relies on a few generation capacities and can not count on capacities from a large-scale system.

- Conveyance losses occur during power transmission through the network. They mainly depend on the voltage level, the network architecture, and whether or not the transmission grid is congested. The losses can be assessed from the duration of peak, semi-base or base loads. When production capacities are centralized, transmission takes place through long distances, and conveyance losses may increase, despite high voltage lines. For a given geographical distribution of loads and generators, the more the meshing of the grid increases, the more the Joule losses decrease, the voltage profile improves and the system becomes more stable. Besides, if the installed generation capacities increase, the power system also has similar benefits.

The balance between the conveyance and reliability losses is highly dependent on energy generation shares and the associated network architecture. However, it is difficult to allocate these two kinds of losses as they take place in the same system.

2.2 The Markal/TIMES family of models

Long-term global prospective models are persuasive as they permit the assessment of multi-sectoral energy policies. Among these models, Markal is a technological model developed since the mid-eighties [10] under the auspices of the International Energy Agency [5]. Markal, in its basic version, is a linear optimization model. It relies on an explicit formulation of the input/output relationships for each technology and minimizes - over the chosen time horizon and for a given final outcome - the actualized global cost. The optimization is subject to constraints such as energy management features, caps for CO_2 emissions, limitations on fuel shares in electricity generation, etc. The decision variables represent the choice of the activity level of technologies, and of capacity investments. The equilibria of energy flows are generally expressed over the year and evaluated on total energy rather than on hourly power demand. A synthetic description of the input/output relationships is given in the scheme covering the whole energy chain depicted in the figure 3. It is usually called the Reference Energy System.

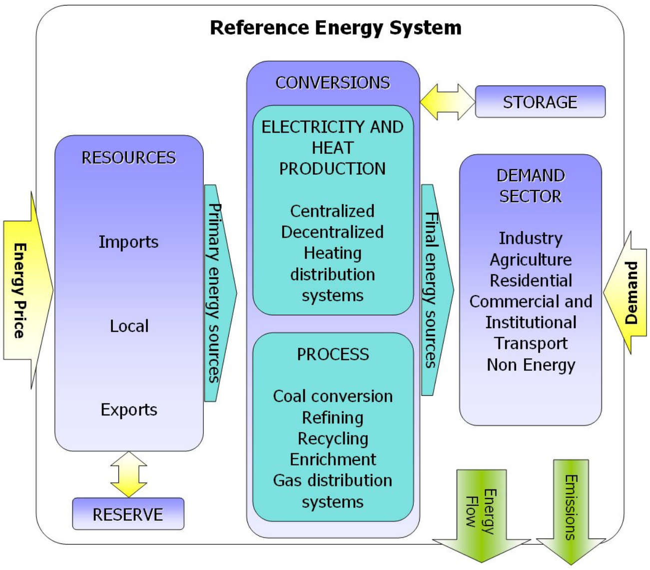

Figure 3: *Synthetic view of the Reference Energy System, issued from [11].*

Markal offers a detailed description for the electricity sector, in which flows are represented as energy units. Specific technical constraints [12] are represented in the model:

- *Flow equilibrium constraints:*
  Electricity and heat can be represented in detail in the model. The time divisions applied to these two energy vectors are shorter and each period is broken down into six sub-periods showing the combinations between, on the one hand, three seasons (summer, winter, intermediate), and on the other hand, day and night. The flux equilibrium equations are then published separately for each of these sub-periods.

- *Peak reserve capacity constraints:*
  A peak reserve constraint guarantees the setting-up of a supplementary capacity reserve to cope with high demand periods. The peak equation itself stipulates that the total production capacity, counterbalanced by these peak coefficients, must be oversized by a certain percentage[1] to satisfy the demand (for exports,

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[1] For instance, in Metropolitan France, the value of this peaking factor can be set to 1.6.

processes and demand technologies) and to insure against several contingencies. It forces to increase the production capacity by the chosen level of reserve. The user specifies two parameters: a global electricity or heat reserve factor, and the contribution[2] of each electricity or heat production technology to the reserve factor.

3 Model development

In this section, we describe the main hypothesis of a TIMES-Reunion model dedicated to the supply and power sectors of the Reunion Island. The study covers the period 2008-2030. The data developed for the TIMES-Reunion model consist of the following components:

- Resource supplies: imported fossil fuel and domestic sugarcane bagasse.
- Electricity demand projections.
- Characterization of existing power plants.
- Characterisation of new power plants and renewable potentials.

3.1 Resource supplies

The considered resource in the TIMES-Reunion model are: imported coal, imported heavy fuel oil, imported distillate fuel oil, and domestic sugarcane bagasse production.

3.1.1 Imported fuel supplies

Small markets, such as the Reunion Island, which are price takers on the international market, can be accurately modeled utilizing a single supply step with unlimited availability at a projected international market price. The fossil energy import prices are based on the projections of the World Energy Outlook [13]. In the Reunion Island, there are no refineries and heavy fuel oil and distillate fuel oil are imported. We assume that their prices follow the projections for crude oil prices. The fossil-fuel price assumptions are listed in table 1.

3.1.2 Domestic sugarcane bagasse production

The Reunion Island produces around 10% of its annual electricity consumption with the combustion of the sugarcane bagasse. The highest value of electricity production with sugarcane bagasse was recorded in 2004 (292 GWh). The cost of the bagasse sugarcane is set to zero as the bagasse is a co-product of the sugar factories and that these factories are on the same production areas than the thermal power plants using

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[2] The coefficient (from 0 to 1) specifies the fraction of the technology's capacity that is allowed to contribute to the peak load and makes it possible to differentiate between the contributions of different power plants. Nuclear power plant has a peak coefficient of 1, whereas wind farm has a peak coefficient of 0.2 or 0.3.

	Unit	2000	2008	2015	2020	2025	2030
Real terms (2008 prices)							
OECD steam coal imports	\$2008/ton	41.22	120.59	91.05	104.16	107.12	109.4
IEA crude oil imports	\$2008/barrel	34.3	97.19	86.67	100.00	107.50	115.00
Heavy fuel oil	€2008/hl	-	196	174	201	216	231
Distillate fuel oil	€2008/ton	-	47	42	48	51	55

Table 1: *Fossil-fuel price assumptions [13].*

	Unit	2008	2010	2015	2020	2025	2030
Electricity consumption	GWh	2 546	2 710	3 110	3 500	3 805	4100
Growth rate	%	3.4	3.2	2.6	2.4	1.5	1.5
Power	MW	408	445	520	595	670	720

Table 2: *Electricity consumption growth in the Reunion Island from the medium scenario of EDF [7]. This scenario is extended from 2025 to 2030 with a growth rate of 1.5.*

the bagasse. Electricity production from bagasse takes place in the power plants of Le Gol (111.5 MW) and Bois-Rouge (100 MW). These boilers also work with coal, thus producing electricity apart from the season of sugar production. However, during the sugar production, the efficiency of the power plants is decreased from 28% to 24% due to steam use in the sugar factory [6].

3.2 Electricity demand

In 2008, the general features of the electricity sector in 2008 were as follow [7, 14]:

- Electricity consumption rose up to 2546 GWh, divided into 50% coal, 14% other fossil fuels, 25% hydroelectricity, 10% sugarcane bagasse and 1% others.
- The electricity peak demand was 408 MW.
- The total installed capacities were slightly less than 650 MW.

Since 1995, the growth rate of electricity demand has decreased from 6.7% to 2.8%, and it is expected to continue decreasing and reach a value between 1 and 2% in 2025 [7]. Two forces for electricity consumption growth may explain the decrease: a decrease in the population[3] and economic growth. The economic growth decreases because the penetration rates of new end-uses, such as space cooling and consumer and business electronics, are already high.

A projection for electricity consumption growth until 2025 was provided by EDF [7] (see table 2).

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[3] The current population is 795 000 and is expected to reach 1 000 030 in 2030.

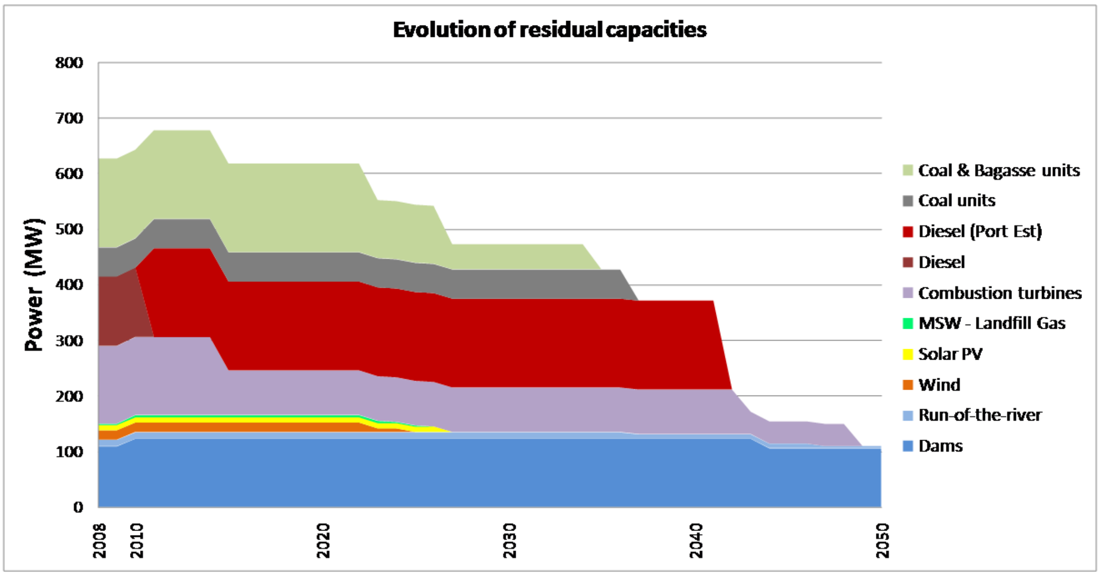

Figure 4: *Evolution of residual capacities.*

3.3 Existing power plants

Data for existing capacity, capacity factors, and efficiency are derived from reports on existing power plants by EDF and the Regional Agency for Energy in the Reunion Island (ARER) [7, 15]. Following discussion with experts, some of the technico-economical data have been revised to correspond more accurately to the electricity mix, in particular with the current spread of renewable energy sources.

Figure 4 provides an aggregate view of the residual capacity evolution used for the model. The figure only represents the lifespan of existing power plants and projects under construction.

3.4 New power plant options and renewable potentials

Costs and performance characteristics of new power plants are derived from the database of the European RES2020[4] project. The 14 MW expansion of the dam of Rivière de l'Est is represented by a fix investment in 2009, as well as the 160 MW new heavy fuel oil plants at Le Port that is projected to be built.

According to experts and to the quantitative and qualitative literature, the available renewable sources for the Reunion Island, and their technical and economic resource potential are as follows.

3.4.1 Biomass

For the past 40 years, the sugarcane industry has been reorganized and centralized: the number of sugar factories has decreased from 40 to 2 units, where the two remaining

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[4] RES2020 is a European project which aims at monitoring and assessing the implementation of the directives on Renewable Energy Sources and the policy recommendations for 2020 in the EU-27. With this project, a number of future options for policies and measures are defined and studied with the use of TIMES.

	Unit	2000	2002	2004	2006	2008
Electricity production	GWh	261	241	292	273	263
Sugarcane	ktons	1 821	1 811	1 969	1 864	1 772
Surgarcane bagasse	ktons	565	539	561	524	510
Electricity production by ton of bagasse	MWh/ton	0.46	0.45	0.52	0.52	0.51
Ton of bagasse by ton of sugarcane		0.31	0.30	0.28	0.28	0.29

Table 3: *Electricity production from sugarcane bagasse [15].*

units have been built close to bagasse and coal power plants. The thermal power plants are those of Le Gol (111.5 MW) and Bois-Rouge (100 MW).

For the past ten years, the production of sugarcane bagasse has fluctuated between 470 000 and 570 000 tons/year for a production of sugarcane slightly below 2 millions of tons. The total amount of cultivable land dedicated to sugarcane cultivation is 25 000 ha, accounting for 60% of the Reunion Island's cultivable land. However, the amount of land used for sugarcane has declined since 2004, due to a severe competition in land use with the rapid increase in urban spread. At present, the average sugarcane yield varies between 70 to 75 tons/ha. The yiels are very heterogeneous due to different harvesting techniques and to disparities of the agronomical and climatic conditions (see table 3).

The amount of bagasse that remains at the mills after grinding and crushing of the sugarcane represents 110 tons/h out of 340 tons/h of sugarcane. The heat content of this amount of sugarcane bagasse provides 260 tons/h of medium pressure steam and generates 56 MWh of electricity. 42 MWh are transmitted to the power system of the Reunion Island, whereas only 9 MWh are used for the sugar refinery and 5 MWh for the power plant itself. The crushing season lasts from july to december and the amount of electricity produced with the sugarcane bagasse finally rises up to 260 GWh in average.

Two sugarcane potential scenarios have been developed: one representing the current sugar industry with no major changes, and one representing a sugarcane industry exclusively dedicated to energy production. Furthermore, in the latter scenario, it is possible to choose sugarcane species that enables harvest twice a year, increasing the share of bagasse in electricity production. In both cases, research and development are made to develop new sugarcane species improving the average sugarcane yield and increasing the amount of bagasse issued from the sugarcane.

According to the first scenario, sugarcane improvements can lead to an additional available potential of 130 GWh. For the second scenario, optimistic assumptions proposes an additional potential above 700 GWh [16].

3.4.2 Hydropower

Until the 1980s, hydropower has been the main energy source in the Reunion Island. There was an historical electricity mix in 1982 exclusively relying on hydropower installations. The current hydropower capacity is 121 MW, 109.4 MW is produced from dams and 11.6 MW fom run-of-the-river capacities.

The remaining and currently undeveloped hydropower resource in the Reunion Island has been estimated at 147 MW, 26 MW from pump storage capacities and 121 MW from new hydropower plants [17]. These potential installations would correspond to the actual level of hydropower capacities and also double the amount of hydroelectricity.

Considering the environmental constraints due to the boundaries of the National Park, only a project of 56 MW in Takamaka was declared feasible despite the high available potential. It appears that keeping the boundaries of the National Park and increasing hydroelectricity production in order to reach the target of 100% of renewable electricity sources might be incompatible objectives. Though, in the future, the limit set at 56 MW may be subject to discussions and evolve. This can be developed with different levels of hydropower development from 56 MW to a higher upper bound.

3.4.3 Geothermy

Despite the presence of the volcano, the potential for geothermal power is not yet accurately estimated. The inhabitants do not accept the development of such projects. However, if things change, it is plausible to reach 30 MW of geothermal power in 2030.

3.4.4 Solar PV

The Reunion Island has excellent solar resources which are exploited with the use of solar photovoltaics and of thermal solar panels. At the end of 2008, electricity capacities reached 6.4 MW for solar farms and 3.6 MW for distributed solar PV. In remote areas close to the volcano, some other distributed solar PV are used off-grid.

Photovoltaics benefit from appealing policy mechanisms to encourage their development. Consequently, PV capacities may have a high growth rate. However, for grid stability reasons, the French government put a legal limit of 30% on the level of intermittent capacities of its overseas territories (decree of April, 23th 2008), including the Reunion Island. According to the system operator EDF, this will limit the spread of photovoltaics to roughly 160 MW.

3.4.5 Marine renewable energy

Two main projects using marine renewable energy are currently studied:

- A prototype of 1 MW Ocean Thermal Energy Conversion (OTEC) project. The technology uses the temperature difference that exists between deep and shallow waters to run a heat engine.

- A series of Pelamis wave energy converters. The Pelamis is a unique system to generate renewable electicity from ocean waves, and aims at reaching 30 MW offshore production by 2014.

3.4.6 Wind

Wind power on the Reunion Island has reached 16.8 MW with two wind farms. Estimations of wind potential ranges between 50 MW to 100 MW [6].

3.4.7 Storage capacities

Finally, the island promotes the integration of storage capacities on its power system in order to manage more efficiently intermittent sources. Two examples are the installation of a 5 MW NaS battery on the power system, and the call-for-tenders issued for 10 MW renewable energy farms with storage units.

4 Discussion

This work is ongoing and we expect to find plausible shares for renewable energy sources for different scenarios. These scenarios will mainly rely on alternative hypotheses on renewable energy potentials, electricity consumption growth or efficiency improvements. We propose to compare the different scenarios through several environmental and economic indicators, such as the total discounted cost of the system, technology choices, investment levels, actual shares of renewable electricity production in the future and levels of CO_2 emissions over the years.

These results should be discussed in the light of the technological and economical feasibility, as these two features are very sensitive to the spread of renewable energy sources.

4.1 Technological feasibility

Distributed renewable plants such as solar PV, wind or marine renewable energy, may provide substantial benefits where transmission capacity is inadequate. However, they also degrade the reliability of electricity supply. A detailed transmission system analysis would be necessary to assign a quantitative value of these effects.

In the Reunion Island, the power system is small, weakly meshed and with no interconnection (see figure 5). With high shares of renewable – and in particular intermittent – energy sources in power systems induces a decrease of reliability of electricity supply. Thus, restoring an appropriate level of reliability on power systems may require additional investments and extra-losses, which will add to the assumed total cost of future power systems. Besides, experts have estimated at 4 hours/year/consumer the average duration of electricity not supplied, to be compared to 1h15 in Metropolitan France.

To determine the technological feasibility of the different scenarios, we rely on a methodolgy described in [18] and assess the reliability of electricity supply.

4.2 Economical feasibility

Furthermore, integrating high shares of renewable energy sources – or even reaching the target of 100% of renewable energy sources on a power system – poses another

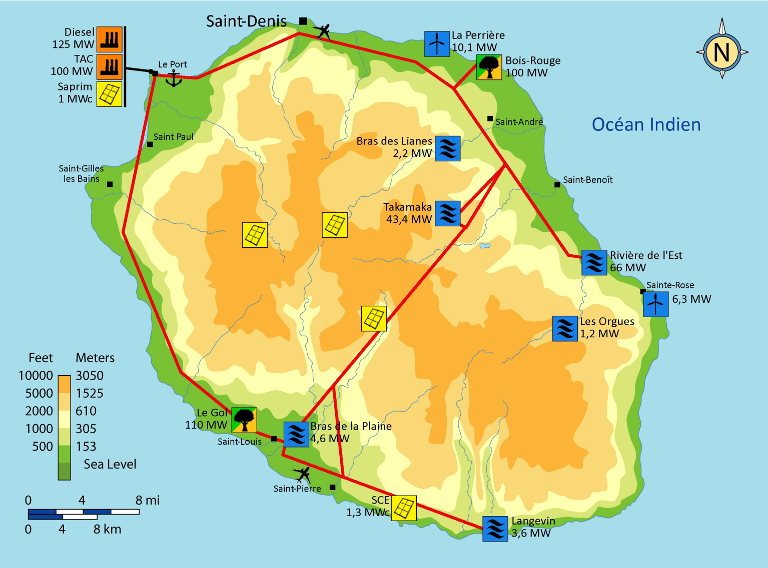

Figure 5: *The power system of the Reunion Island [19].*

challenging problems to energy planners: energy policies should be designed to promote efficiently their development. But electricity market designs and appropriate levels of incentives and subsidies are already difficult issues to deal with for small and isolated electricity systems [20, 21]. The electricity sector of the Reunion Island strongly relies on subsidies to balance out its geographical situation compared to Metropilitan France and these subsidies are preferentially devoted to renewable energy sources. For instance, photovoltaics, and in a lesser extent sugarcane bagasse, benefits from appealing policy mechanisms that encourage their development.

The investigated scenarios will enable to compare the economical feasibility of the future electricity sector of the Reunion Island.

5 Conclusion

In this paper, we have introduced the need to take reliability requirements into account for the design of future power systems. We have presented the development of the TIMES-Reunion model, for which results concerning the spread of renewable energy sources will be discussed in the light of reliability requirements. This study emphasizes the need to implement reliability requirements in long-term planning models.

Furthermore, this work is a part of a larger project, which aims at integrating reliability in prospective studies. Another aspect of the project focuses on the evaluation of the cost of reliability in future power systems.

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