Flexibility and reliability in long-term planning exercices dedicated to the electricity sector

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Abstract

Long-term planning models are useful to build plausible options for future energy systems and must consequently address the technological feasibility and associated cost of these options. This paper focuses on the electricity sector and on problems of flexibility and reliability in power systems in order to improve results provided by long-term planning exercises: flexibility needs are integrated as an additional criterion for new investment decisions and, reliability requirements are assessed through the level of electrical losses they induced and a related cost. These approaches are implemented in a long-term planning model and demonstrated through a study of the Reunion Island.

Keywords: – Long-term energy planning. Flexibility. Reliability of supply –

Introduction

Electricity is a very convenient way to deliver huge amounts of power in areas where demand is concentrated. Due to the predicted population densification, electricity consumption is set to significantly increase over the next decades. Besides, the International Energy Agency estimates that during the next thirty years US$10 trillion will be spent on generation, transmission and distribution of electricity [1], in order to replace existing capacities in developed countries, to accompany the development of energy markets in developing countries or to substitute energy vectors that are less clean or growing scarce.

In this context, two critical features challenge forthcoming changes in power systems:

- the emergence of different paradigms for serving electricity than those for which the system was designed [2]. For instance, high shares of renewable energy

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sources may become a critical aspect of future energy systems, both for centralized scheme, with the Desertec concept [3], and for distributed architecture, with the smartgrid concepts [4].

- the will to improve the energy efficiency of electrical power transmission, given that the current system clearly lacks efficiency. For instance, since 1950 in the US, electrical losses have been twice as high as electricity consumption as pointed out in [5] and illustrated in figure 1 for the industrial sector (same trends for the commercial and residential sectors).

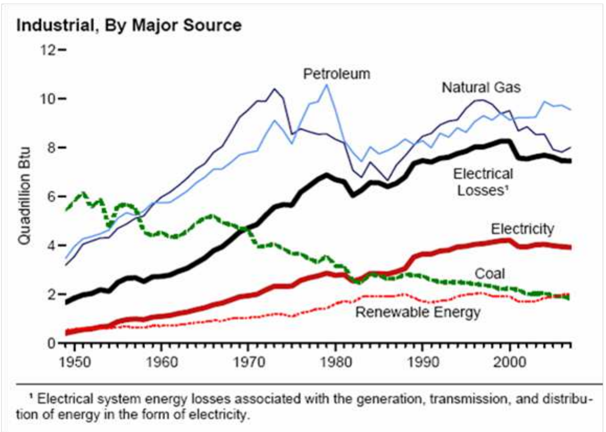


Figure 1: *Industrial Total Energy Consumption, Major Sources [5]: electricity use (and related losses) expanded dramatically.*

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 emitted by the electrical sector.

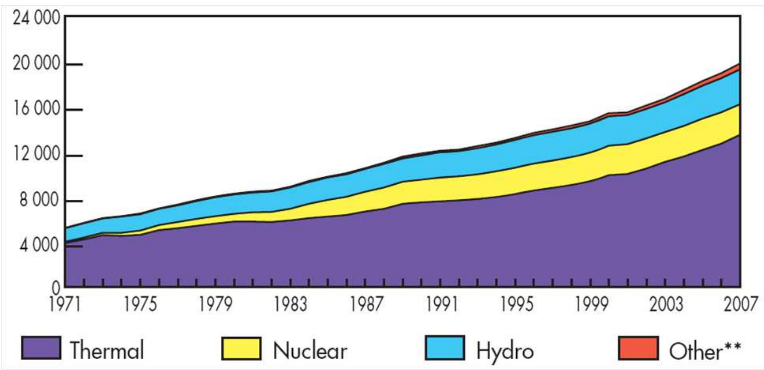


Figure 2: *Electricity generation in TWh by fuel since 1971 [6]. Other includes geothermal, solar, wind, combustible renewables and waste, and heat.*

These issues stress the need for assessing future electrical power systems and the MARKAL (MARKet ALlocation) type of technology-rich models provide a partial solution to this problem [7, 8, 9]. Actually, models for energy planning – like the MARKAL family of models – have proven useful to determine plausible evolutions of the energy sector in the mid- to long-term when facing strong environmental pressures, such as carbon mitigation or fossil energy depletion. Indeed, this kind of models offers substitution possibilities throughout the whole energy chain and subsequently enables to address different issues such as pointing out the main drivers of the energy system at a given regional scale, anticipating changes in and impacts of energy prices, or estimating pollutant emissions.

However, the feasibility of the results provided by energy planning models – namely their sustainability and robustness – depends on the description of spatiality and time constraints of power systems:

- Spatiality constraints are related to the geographical distribution of power plants, the structure and availability of the transmission network, and the location of the consumers.
- Time constraints are related to the electric current and the management of the network in order to minimize the variations in tension and frequency at any time, while keeping the system within safety limits. After recovering a stationary behavior, the total electric power supplied by the stations must be equal to the network demand. In order to ensure this power balance in real time, electricity production modes will be chosen for their dynamic nature and for their location in the network.

These spatiality and time constraints come from the needs for flexibility and reliability when operating power systems. In this paper, we choose to improve the description of flexibility and reliability requirements in long-term energy planning models in order to provide more plausible results for the electricity sector. We quantitatively address these issues in section 1.2 and 2.2, respectively for the flexibility and reliability needs.

We start with a preliminary presentation of the current MARKAL modeling approach for the electricity sector. The paper is then divided into three contributions:

1. We present an augmented MARKAL model that introduces flexibility as an additional criterion for electricity generation investments: the choice of power stations relying on a cost minimization is then tempered by specific technical constraints (section 1).
2. We describe reliability requirements on power systems and we present a methodology that provides the cost of reliability of supply in future power systems. This analysis is based on a thermodynamic approach, which enables a synthetic description of power transmission (section 2).
3. Finally, we study the case of the Reunion Island for which we conduct a long-term analysis of the electricity sector, and for which we aim at implementing the approaches presented in sections 1 and 2. The Reunion Island is interesting because it relies on a small and isolated power system, which exarcerbates the needs for flexibility and reliability; and because they aimed to have in 2030 an energy consumption based to 100% on renewable energy sources [10] (section 3).

The last section gives some concluding remarks.

Preliminary presentation of the MARKAL models

To start with, we present the main features of the MARKAL long-term planning models and underline some strengths and weaknesses concerning the representation of the electricity sector.

Long-term global prospective models permit the assessment of multi-sectoral energy policies and are therefore persuasive. Among these models, the MARKAL family of models are technological models developed since the mid-eighties [7] under the auspices of the International Energy Agency [8]. MARKAL, in its basic version, is a technically optimum 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_{2eq} emissions, limitations on fuel shares in electricity generation, etc. The decision variables depend on 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, usually called the Reference Energy System.

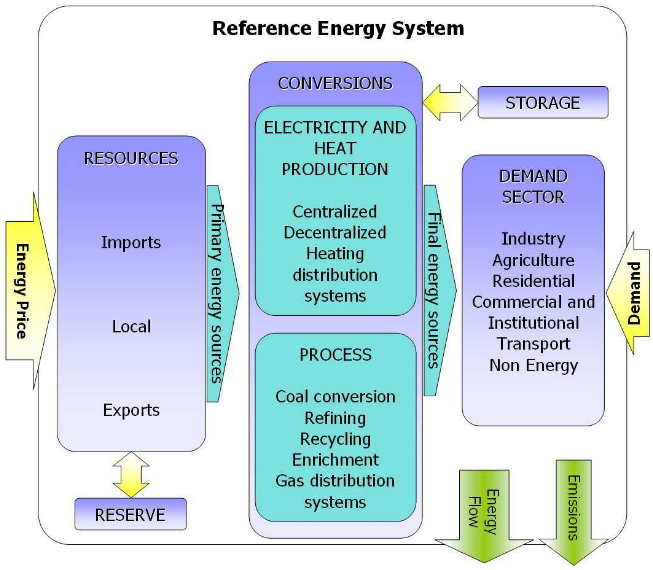


Figure 3: *Synthetic view of the Reference Energy System, issued from [11].*

MARKAL offers a more detailed description for the electricity sector. Specific technical constraints [12] are represented in the model:

- *Flow equilibrium constraints:*
  Electricity and heat are represented in more 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. A peak equation stipulates that the total production capacity must be oversized by a certain percentage[1] to satisfy the demand (for exports, 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.

1 Flexibility desciption in MARKAL

1.1 Description of the need for flexibility

The need for flexibility is related to the structure of the load curve: installations that run for a relatively long time throughout the year must be installed and actually used. Therefore, to satisfy the electricity demand, all functioning electricity systems require, a priori, the installation and effective use of power stations devoted to the baseload supply, as well as others devoted to peakload supply (few hours per year). There is a strong link between installation decisions motivated by power dimensioning, and the effective use of these installations for energy supply. Thus, the need for flexibility in time management of electricity systems corresponds to a challenging technical constraint, making it necessary to use more expensive technologies that can rapidly adapt their production level in order to meet the consumption level.

These flexibility constraints are on the whole largely ignored in MARKAL models, whereas in reality requirements for flexibility call for long-term investments. Indeed, least expensive ways of production are favored, as the MARKAL approach relies on the minimization of economic criteria [13] – which aims at choosing the electricity system that is cost-efficient. Ignoring flexibility presents several drawbacks for the MARKAL results in the electricity sector. They are listed below:

1. It leads to an over-estimation of the importance of power stations that have low production costs but may also have low reactivity on the load curve: this impacts the capacity needs, the type of technologies chosen, and their level of use.

2. The system's running costs can be miscalculated since, even with identical technologies, the constraints of operating at partial load increase the costs of meeting

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

[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.

with demand (slower amortization, the need to use a greater number of power stations).

3. The consequences of the increased share of intermittent renewable sources in the power generation mix are not fully handled. In France, the theoretical potential is estimated at 66 TWh for 30 GW of onshore wind power and 97 TWh for 30 GW of offshore wind power [14]. As development of these power plants increases, there will be a greater need for more flexibility. The feasibility of scenarios figuring a low share of thermal production and a large share of wind or solar power is questionable. On top of that, intermittent sources call for thermal production capacities. As these plants are the only direct sources of greenhouse gas emissions in the electricity sector, they counterbalance the expected potential for reducing emissions attributed to renewable energy sources. This should be revised in order to better assess greenhouse gas emissions.

For these reasons, flexibility has to be integrated as a constraint within the model's framework.

1.2 An augmented *flexible* MARKAL model

This approach quantifies the average production needs for several specific operating modes, such as semi-base load or peak, and then introduces flexibility as one of the model's selection criteria. It was applied to the French electricity sector in [11], which is dominated by nuclear power. Technological choices are differentiated for each mode, and the flexibility criterion, defined globally, does not depend on short time divisions for the model's equations. Its quantitative assessment, relies on a time analysis that is both shorter and easier to put into place outside the model. The pre-existent mechanisms specific to the electricity sector are conserved.

Results for the standard and for the augmented MARKAL model – taking flexibility into account – are only given for fossil plants regarding that these power plants are sensitive to dynamical features (figures 4 and 5). The figures compare fossil capacities effectively used for electricity generation.

With the standard MARKAL model, gas, fuel or oil power plants are installed to satisfy the peak equation, but the figure 4 shows that they are not used for electricity production. Actually, power stations are used over long periods of time leading preferentially to baseload profiles of power plants running with cheaper fuels.

With the augmented approach, the figure 5 shows on the contrary that oil power plants appear in the electricity generation. Indeed, even if they are more expensive, they are essential plants to meet the peak demand. It confirms that the optimization process with the augmented MARKAL model provides results more plausible concerning the electricity sector. With this model, we also observe that a greater amount of energy is produced from fossil fuels (200 PJ in 2030 compared to 150 PJ), which corresponds to a best representation of the need for flexible technologies.

When flexibility is not properly handled, the results issued from MARKAL reflect a minimal (under-constrained) condition to satisfy global electricity demand. Thus it

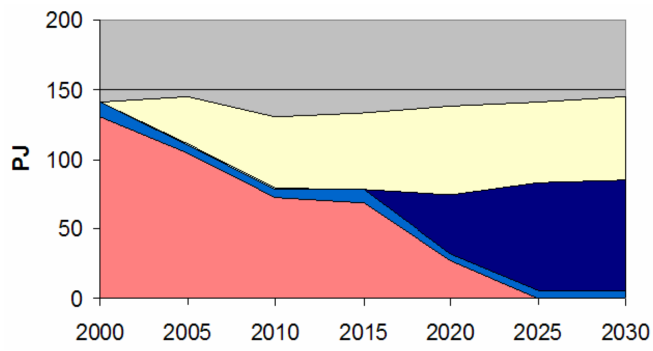


Figure 4: *Fossil plant production 2000-2030: a standard MARKAL approach.*

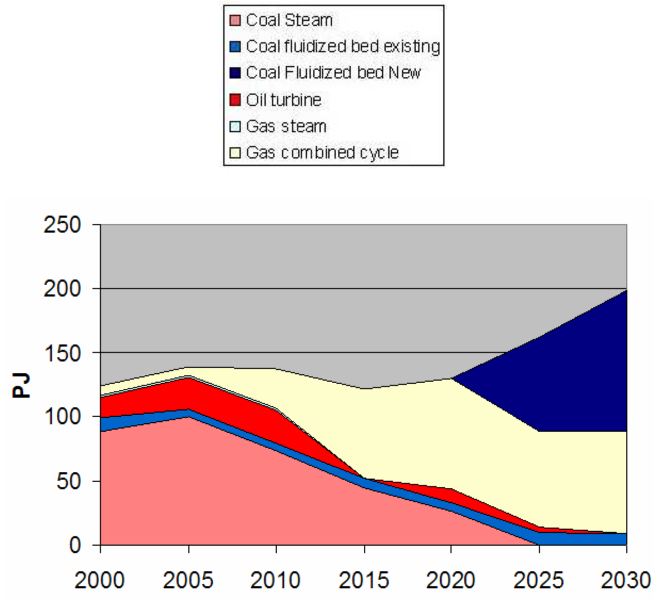


Figure 5: *Fossil plant production 2000-2030: an augmented MARKAL approach.*

fails to address properly the questions related to environmental issues, and namely the level of carbon emissions - except for regions where fossil fuels dominate the baseload mix. In France, the level of greenhouse gas emissions depends on the precision of the thermal production assessment [11].

Regarding these results, flexibility appears to be a key parameter for reaching a better representation of the electricity generation system and consequently achieving sustainable power systems. It has also appeared that providing power systems with enough installed capacities – both satisfying the electric demand and following the load curve – is difficult when ignoring the need for flexibility. Flexibility is a step towards planning long-term generation shares where installed capacities are well-anticipated.

2 The need for reliability of supply

At the side of the need for flexibility also stands the question of the reliability of electricity supply. Reliability of supply relies on the ability of the electric system to withstand sudden disturbances [15] and is ensured by technical properties of the production means.

Currently, power systems clearly lack of efficiency because this sector is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, which are about one order of magnitude greater than electrical losses at the transmission, distribution and consumption levels (figure 6).

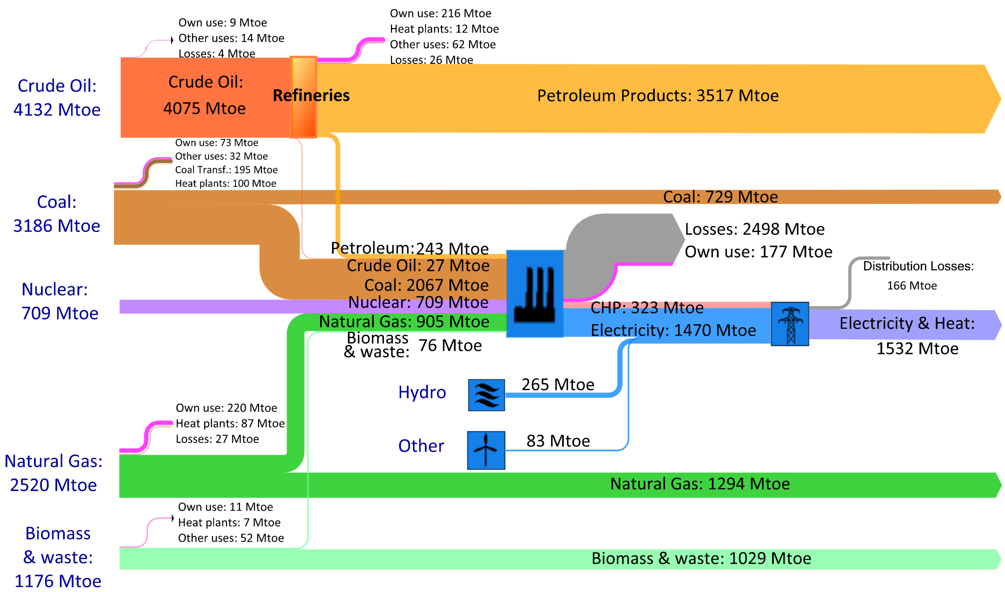


Figure 6: *Energy supply-chain in Mtoe in 2007 (e!Sankey diagram). The electricity sector is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, and by the electrical losses at the transmission, distribution and consumption levels [6].*

In this context, renewable and distributed energy sources seem to be attractive alternatives for cleaner and unlimited power generation. Furthermore, a wide integration of renewable energy sources is expected to improve the overall efficiency of power systems. Renewable energy sources decrease electrical losses at the production level, whereas distributed energy sources decrease electrical losses at the transmission and distribution levels. However, such a gain in efficiency may be counterbalanced by a decrease in the reliability of electricity supply. The reliability of electricity supply is defined as the capacity of a power system to handle safely sudden disturbances, such as production or load fluctuations. To maintain an appropriate reliability of supply, power systems must provide amounts of energy dedicated to the reliability of supply, which induces additional investments and extra-losses. Consequently, the need for reliability of supply may decrease the expected gain in efficiency with renewable and distributed energy sources. In this section, we introduce the reliability of electricity supply within an optimal discussion and aim at assessing the cost of reliability of supply.

2.1 Description of reliability requirements

Firstly, in order to provide relevant comparisons between future electrical systems, we must define accurately the three main kind of losses on power systems:

Losses induced by the Carnot cycles The electricity industry is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, which are about one order of magnitude greater than electrical losses at the transmission, distribution and consumption levels (figure 6).

Conveyance losses occur during power transmission through the network. They mainly depend on whether or not the transmission grid is congested, on the voltage level, or on the network architecture. They can be assessed from the duration of peak, semi-base or base loads. When production capacities are centralized, transmission takes place through longer distances, and conveyance losses may increase, despite high voltage lines. In fact, 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 is more stable.

Reliability-induced losses are linked to the needed level of reliability. The level of losses corresponds to the stocks of electromagnetic coupling energy and of kinetic and spinning energy required to handle load fluctuations. A part of the electricity production must be dedicated to maintain the appropriate stocks of electromagnetic, kinetic and spinning energy. Consequently, the electricity industry must be (over-)sized to produce enough electricity for the consumers and also for providing the stocks. The part of the electricity dedicated to the stocks induces investments in dedicated capacities and additional electrical losses.

With a wide integration of renewable energy sources on power systems, the losses induced by the Carnot cycles are expected to decrease, as energy production will rely on fewer thermal units. With a wide development of distributed energy sources, the conveyance losses are expected to have similar benefits, as the average distance between production and consumption decrease. Conversely, reliability-induced losses are expected to increase, as renewable and distributed energy sources do not maintain sufficient stocks of electromagnetic coupling energy and of kinetic and spinning reserves.

Secondly, we describe more precisely reliability of electricity supply. According to the UCTE handbook [15], the reliability of an electric system is addressed by considering both the adequacy of the system, i.e. the ability to supply the aggregate electrical demand and energy requirements of the customers at all times, and the security of the system, i.e. the ability to withstand sudden disturbances such as unanticipated loss of system elements.

To ensure these two elements, power systems rely on the dynamic management of frequency and voltage [16]. Frequency and voltage are crucial quantities in power systems, whose great deviations can lead to brownouts or power outages when the system recovers from production or load fluctuations or when it experiences transient states (e.g. lightnings). Basically, maintaining appropriate variations of frequency depends on the levels of kinetic and spinning reserves on the system, and maintaining appropriate variations of voltage depends on the electromagnetic energy on the system.

Levels of kinetic and spinning reserves are ensured by the mechanical inertia of the rotating generators on the system and can be adjusted by investing in weighing generation machines or flywheel. The electromagnetic coupling energy is the energy involved in the electromechanical and electromagnetic power conversions. It is absolutely necessary to enable power transmission and it is stocked in electromagnetic materials, namely rotating power machines and transformers. The level of electromagnetic coupling energy can be adjusted by investing preferentially in rotating power machines and transformers.

Furthermore, with high shares of renewable energy sources on power system, levels of electromagnetic energy and of kinetic and spinning reserves decrease, whereas intermittent energy sources induce abundant production fluctuations, with higher magnitude. High shares of renewable energy sources in electricity mix may decrease the reliability of electricity supply.

2.2 Assessing the cost of reliability

In the following, we intend to compare the level of network losses for power systems with different production shares of renewable energy sources – in particular intermittent ones. To do so, we apply variational principles deduced from thermodynamics to achieve a global description of power systems and of their subsequent level of losses [17, 18].

The system on which we apply the variational principles is the electromagnetic field, conveying electricity from the generation units to the consumers:

1. In the thermodynamic framework, the deviation between the mechanical power flowing through the network and the variation with time of the Helmoltz free-energy F gives an evaluation of the Joule losses P_{Joule}, at the transmission, distribution and consumption levels. P_{Joule} gives an evaluation of the irreversibility experienced by the system. According to the thermodynamics, Joule losses are always positive and the lower they are, the more reversible is the evolution of the system. The latter statement can be expressed with an optimal condition, which means that the system always tends to minimize the Joule losses during its evolution. *Ideally*, a centralized power system can be described from the Helmoltz free-energy, and this reversibility condition provides the very minimum amount of Joule losses during the power transaction and matches the conveyance losses.

   Added to the losses induced by the Carnot cycles, it gives the total amount of primary energy lowered in a centralized system.

2. *Conversely*, in order to explicitly take reliability into account, the description should also include the inertial behavior of the electromagnetic coupling. Hence, the actual level of Joule losses should be assessed from another reversibility condition obtained with the Gibbs free-energy $G = F - \Phi \mathrm{I}_{\mathrm{exc}}$, where $\Phi \mathrm{I}_{\mathrm{exc}}$ is the electromagnetic coupling and $\mathrm{I}_{\mathrm{exc}}$ the excitation provided to the generator. As a

physical result, the latter description provides the level of both conveyance and reliability losses. Compared to the case (1), the argument of the optimum is drastically changed. This leads to new stability requirements for dynamic management.

Added to the losses induced by the residual Carnot cycles, it gives the total amount of primary energy lowered in a distributed system.

This analysis provides the level of Joule losses P_{Joule} for operating electric power systems in a reliable way. It will enable to compare the overall amounts of losses for a centralized power system and for a distributed one, when the electrical demand and the level of reliability of supply are the same. The cost of electricity production in centralized systems is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, whereas in distributed system it is more penalized by the cost of reliability of electricity supply.

3 The case of the Reunion Island

Figure 7: *Electricity generation on the Reunion Island [19].*

We now focus on a TIMES model dedicated to the supply and power sector of the Reunion Island (figure 7), where TIMES is the latest evolution of the MARKAL family of models. The Reunion Island is blessed with high potentials of renewable energy sources, which may decrease the reliability of electricity supply, its power system is small, weakly-meshed and isolated, and its regional government has set the binding target of an energy consumption based to 100% on renewable energy sources in 2030 [10]. The current use of renewable energy sources in the electricity sector is 36% [20], so the energy system has to change substantially for reaching the target. In this section we present the model development and the results obtained with the TIMES-Reunion model. The case study of the Reunion Island finally poses the question of the technological feasibility of the results proposed by the model. The technological

Real terms (2008 prices)	Unit	2000	2008	2015	2020	2025	2030
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/ton	-	196	174	201	216	231
Distillate fuel oil	€2008/hl	-	47	42	48	51	55

Table 1: *Fossil-fuel price assumptions [21].*

feasibility may be studied in the light of the flexibility and reliability requirements presented previously.

3.1 Model development

3.1.1 Resources supplies

The resources in the Reunion Island are domestic sugarcane bagasse and importations of coal, and fuel oils (heavy and distillate). The fossil energy import prices are based on the projections of the World Energy Outlook [21]. We assume that fuel oil prices follow the projections of crude oil prices. Fossil-fuel price assumptions are listed in table 1. The Reunion Island also produces around 10% of its annual electricity consumption with the combustion of the sugarcane bagasse. 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 sugarcane bagasse. Electricity production from bagasse takes place in the power plants of Le Gol (111.5 MW) and Bois-Rouge (100 MW), which also work with coal, thus producing electricity apart from the season of sugar production.

3.1.2 Electricity demand

In 2008, the general features of the electricity sector were the followings [20, 22]:

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; and 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 [20]. A projection for electricity consumption growth until 2025 was provided by Électricité de France (EDF) [20] (see table 2).

3.1.3 Existing and coming 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) [20, 22]. 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.

	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 [20]. This scenario is extended from 2025 to 2030 with a growth rate of 1.5%.*

Energy sources	Current levels	Potentials
Biomass	260 GWh	400 GWh
Hydropower	121 MW (553 GWh)	177 MW until 2012, then 268 MW
Wind	16,8 MW	50 MW
Solar PV	10 MW	160 MW
Ocean Thermal Energy Conversion	–	10 MW in 2020, 100 MW in 2030
Wave Energy	–	30 MW (by 2014)
Geothermy	–	30 MW
Storage Capacities	–	1 MW in 2009, then 10 MW

Table 3: *Renewable energy potentials in the Reunion Island.*

Costs and performance characteristics of new power plants are derived from the database of the European RES2020[3] project.

3.1.4 Renewable potentials

According to experts and to the literature, the available renewable sources for the Reunion Island and their technical and economic resource potential are those presented in the table 3.

3.1.5 Scenarios specification

Various scenarios are investigated wherein the electricity system is required to simultaneously meet a given level of electricity demand (table 2) and reach the 2030 target with an electricity consumption based to 100% on renewable energy sources. Height scenarios are built around three main assuptions concerning levels of fossil fuels imports, electricity demand, and sugarcane bagasse potential. They are summarized in the table 4:

- An upper limit for the fossil fuels imports is set in 2008 and linearly decreased to 0 in 2030. The objective is to study the evolution of the electricity production

[3] 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.

without fossil fuels. We propose an alternative scenario with a softened constraint, where the limit is only set on coal imports. These scenarios are compared with a business-as-usual with no limits on importations.

- We consider scenarios with lower electricity consumption to study how lowering the demand helps reaching the 100% target.

- For all these scenarios, we set the potential for the renewable energy sources at the maximum rates described previously, except for sugarcane bagasse. We finally consider the option with a higher available potential, where the sugarcane industry is only dedicated to energy production.

	Limit on imports			**Sugarcane Bagasse**
Demand	No limit	Limit on coal	Limit on all fuels	Higher potential
Standard	MedDEM	MedDEM_NoCOA	MedDEM_NoFOS	MedDEM_NoFOS_UpBAG
Low	LowDEM	LowDEM_NoCOA	LowDEM_NoFOS	LowDEM_NoFOS_UpBAG

Table 4: *Scenarios specification. The scenarios are built around three main assuptions concerning electricity demand, fossil fuel imports and sugarcane bagasse potential.*

The scenario MedDEM corresponds to the business-as-usual scenario.

3.2 Results

3.2.1 Electricity shares of 2008

In table 5, we compare the 2008 electricity production given by the model with actual data [20] and the similarity of the results is encouraging. In particular, the proportion between production based on fossil fuels and production based on renewable sources are the same.

The main difference concerns the production based on fossil fuels. With the model, coal participates to a higher share of electricity production. This is explained by the fact that in this TIMES-Reunion model, load curves and peak demands are not fully described. Thus, the modeled electricity system requires in a lesser extent power plants dedicated to peak loads such as fuel oil turbines.

3.2.2 Towards an electricity consumption based to 100% on renewable energy sources

We then present the evolution of the electricity mix when the limitation of coal or all fossil fuel imports is set on the standard level of electricity demand. In the business as usual scenario (figure 8(a)), the actual shares of production roughly follow the increase in the demand. However, there is no development of renewable energy sources despite their potentials. This is explained by the cost of power plants relying on these sources, compared to those relying on coal. The model may be improved with a precise description of the incentives' system favoring renewable energy sources or with another

Energy sources	**Model (%)**	**EDF (%)**
Coal	56.90	50.55
Fuel Oils *(Distillate and Heavy)*	9.06	13.30
Sugarcane bagasse	10.21	10.31
Hydroelectricity	21.71	24.86
Wind energy	1.19	0.53
Solar energy	0.41	0.42
Municipal waste	0.52	0.03
Production	2 547 GWh	2 546 GWh

Table 5: *The 2008 electricity shares given by the TIMES-Reunion model compared to the actual values of EDF [20].*

constraint on the greenhouse gas emissions in the Reunion Island. Furthermore, in this scenario, power plants based on fuel oils are still hardly used, which corroborates the need to describe the time characteristics of the electricity demand.

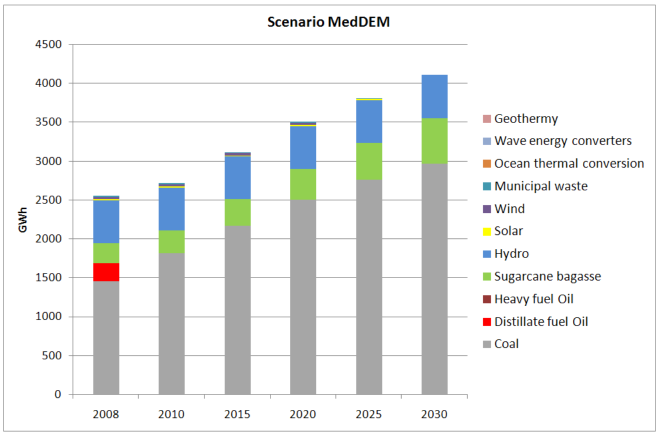
The two other scenarios (figures 8(b) and 8(c)) show that there is a large room for the development of renewable energy sources when a constraint is set on coal and all fossil fuels import. In both scenarios, new renewable energy sources appear such as geothermy, ocean thermal energy, or wave energy. Hydroelectricity increases sharply. Nevertheless, with the constraint on both coal and petroleum products, the figure 8(c) shows that around 500 GWh of electricity demand can not be met in 2030.

3.2.3 Lower growth of electricity demand

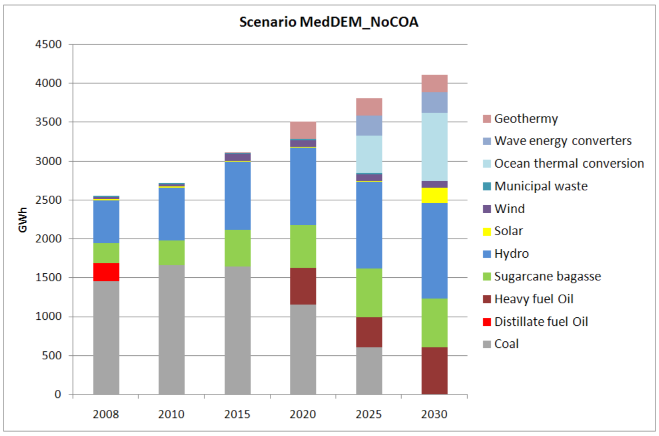
The decrease in the electricity demand may be due to two main features: a slower growth rate of the demand, and a deep improvements of energy efficiency of end-use devices. If electricity consumption goes in this direction, it will consequently ease the Reunion Island to reach its ambitious target of 100% of renewable energy sources by 2030. The new electricity consumption growth is taken from a lower scenario also provided by EDF [20]. The results with a lower electricity demand are depicted in the figure 9, which presents the changes induced on the electricity mix.

3.2.4 Higher potential for sugarcane bagasse production

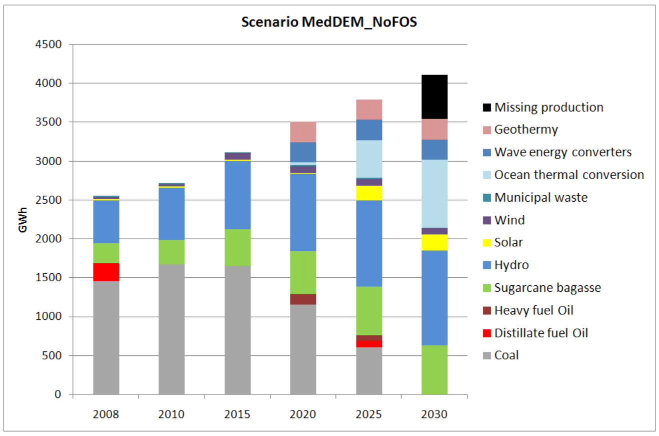
Finally, we consider a radical change of the sugarcane industry, where sugarcane production is only dedicated to electricity production, as suggested in [10]. In this case, the available potential of sugarcane bagasse is increased as the whole sugarcane is used for energy purposes. Interestingly, it seems that the whole available potentials for renewable energy sources can meet the lower electricity demand (figure 10).



(a) Business as Usual.



(b) Without importation of coal in 2030.



(c) Without importation of fossil fuels in 2030.

Figure 8: *Shares of the electricity production for the electricity demand proposed in the table 2. The importations of coal and petroleum products are constrained over the time horizon: from their levels in 2008 to 0 in 2030.*

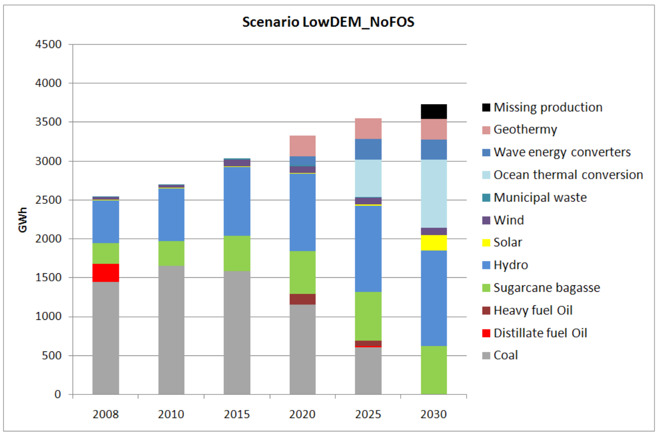


Figure 9: *Shares of the electricity production with a lower electricity demand.*

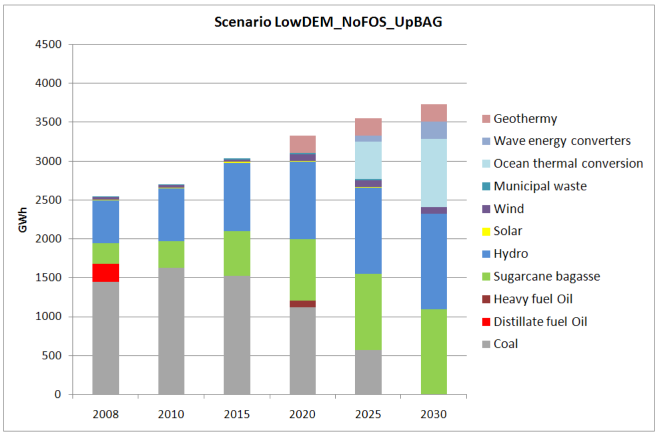


Figure 10: *Shares of the electricity production with a higher sugarcane bagasse potenatial and a lower electricity demand.*

Concluding remarks

In this paper, we have studied spatiality and time constraints for power generation system with the flexibility and reliability requirements. This work allows the following understandings:

- On the one hand, flexible features of electricity are handled using an augmented version of the MARKAL model. Regarding its results, flexibility appears to be a key parameter for reaching a better representation of the electricity generation system and consequently achieving sustainable systems. Taking flexibility into account has made it possible to provide electric systems with enough installed capacities, both satisfying the electric demand and following the load curve. It is a step towards long-term planning models where electrical installed capacities are well-anticipated.

- On the other hand, for reliability requirements, we have proposed a method that provides the cost of reliability of supply. This method is based on a thermodynamic approach applied to power systems. It emphasizes the need to take reliability requirements into account for the design of future power systems. As a result, the total cost of future energy systems may increase.

- Finally, we propose to implement the approaches dealing with the flexibility and reliability needs of power systems in a TIMES model dedicated to the Reunion Island. This case study is a good illustration of the previous results: its small island grid without interconnection and the proposed shares for renewable energy sources raise the two challenging issues – flexibility and reliability requirements – for future power systems.

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