Reliability in future electricity mixes: the question of distributed and renewables sources

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Abstract

Pushed by the need for carbon emissions abatement and the expected depletion of fossil fuels, electricity generation is entering a period of significant changes. Currently, integrating distributed and renewable energy sources questions the shape of the future electricity industry. In this paper, we are interested in the level of reliability in future electricity mixes and in whether or not these changes impact the level of reliability. Consequently, we propose a methodology to assess reliability of power systems relying on a few aggregated physical properties. Finally, we then exhibit “reliability indicators”, that help to provide valuable comments on reliability with distributed and renewable energy sources. To sum up, changes in the electricity industry must be done carefully with respect to reliability requirements.

1 Introduction

Pushed by the need for carbon emissions abatement and the expected depletion of fossil fuels, electricity generation is entering a period of significant changes. These new constraints will shape the future electricity industry, i.e. for a long term time horizon (typically a few decades). Currently two features of power systems are evolving:

• the generation share, with the integration of more renewable energy sources. For instance, we may consider the binding target of a 20% share of renewable energy by 2020 required by the spring 2007 European Energy Council.

• the architecture of power systems, with the development of distributed energy sources and the emergence of the concepts of smartgrids [1] and microgrids [2].

In the recent years, very optimistic scenarios have abounded forcing one or both of these trends, and in the meanwhile the question of their feasibility arises. In particular, long term planning tools have become essential tools to design the future energy system subject to new environmental constraints. And energy modelers are interested by finding to which extent these new trends in the context of electricity can be followed.

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Furthermore, there is an additional and growing requirement of modern economies for high power quality and reliability. In few words, reliability can be defined as the capability of a power system to handle load fluctuations. It relies on technical properties of the whole production system, which are essential to prevent from unexpected power outages. These properties stand now as essential constraints for power systems design and must be assessed to check the quality of future electricity mixes. So far, the over-sizing of installed capacities had ensured a subsequent high level of reliability and these properties were less crucial to assess.

But today, integrating of distributed and renewable energy sources in future mixes threatens their reliability. Eventually, additional amounts of electricity should be dedicated to maintain the level of reliability, due to additional losses and investments. The cost induced by reliability must be compared with the benefits of these new trends for the electricity industry.

So reliability needs must be fully addressed and implemented in long term energy planning tools, otherwise the forecasted energy systems may be unfeasible or at least sub-optimal.

In section 2 we present the weaknesses of long term planning tools regarding reliability of power supply. We then show the subsequent bias they can bring in future electricity mixes. In section 3 we present the central contribution of this paper: a methodology to assess reliability needs in future electricity mixes in a synthetic way. This method is based on current technical issues of power system stability, which are adapted to the design of future electricity mixes. Then we present in section 4 the main results of our investigations: a serie of indicators that measures the reliability of future electricity mixes. We also discuss qualitatively the case of distributed and renewable energy sources in the light of these indicators. Finally, in section 5 we provide some conclusive remarks.

2 Reliability requirements and long term planning tools

In this section, we first define which properties of power systems stand behind reliability requirements. To do we have both investigated the field of generation planning tools and the subjacent technical issues of reliable power supply. Then, we present the MARKAL/Times family of long term planning models and show their weaknesses concerning reliability requirements. Finally, we focus on the subsequent bias induced in future electricity mixes when reliability requirements are ignored in planning tools.

2.1 Reliability requirements

2.1.1 In the generation planning tools

Since years reliability of power supply have been a major concern of power generation planning exercises, which are a kind of long-term planning tools dedicated to the electricity industry. Before going further, we should focus on reliability description in these tools. The history of power generation planning can be divided into two major periods: generation planning in monopoly and generation planning in competitive markets.

In the first period, optimal long-term generation expansion planning was perceived as the determination of the minimum-cost capacity addition plan that meets the forecasted demand within a pre-specified reliability criterion over a planning horizon. At that time, production cost efficiency was driven with bigger plant sizes and consequently the electricity industry was very capitalistic and monopolistic. Then, capacity expansion models have a long tradition in both the power sector and the operations research literature.
In this literature [4, 5], the question of reliability of power systems is widely dealt with. Loss of load probability (LOLP) and Expected Unserved Energy (EUE) have been indices used to evaluate supply reliability of power systems, and are still used in transmission planning [6].

Now that also smaller installations are economically justified, competition has become possible among power producers leading to deregulated liberalized market. This change has drastically altered the nature of utility planning and it seems that less attention has been paid to the long-run efficiency of restructuring, especially in the area of investments in generation [3]. As an illustration, we may consider the case of the California power crises in 2000-2001, where the most important factor was presumably the shortage of supply relative to demand.

Nevertheless, the description of reliability needs in this literature is not well-suited to the current changes in electricity production. Basically, reliability assessment is based on, historical or expected, values of power outages or unserved energy within a year, and the LOLP estimates the probabilities of outages for a power system with hundreds of consumption scenarios.

In the following, we present the specificity of the electricity supply in order to define what are the reliability requirements in power systems.

2.1.2 The subjacent technical issues

Electricity is a non-storable commodity. Therefore electricity flows must comply with real-time adequacy between supply and demand, which can be derived on three subconstraints:

- **Energy flows**: It is the adequacy in terms of energy exchanges.
- **Power capacities**: This subconstraint refers to dimensioning the park of electricity production. It ensures that there are enough capacities to provide power during the highest period demand, e.g. peak hours in winter.
- **Ancillary services**: The Federal Energy Regulatory Commission (FERC 1995) defined ancillary services as “those services necessary to support the transmission of electric power from seller to purchaser given the obligations to maintain reliable operations of the interconnected transmission system.” FERC identified six ancillary services: reactive power and voltage control, loss compensation, scheduling and dispatch, load following, system protection, and energy imbalance. Ancillary services prevent from power outages and relies on the properties of the production units. Thus, reliability can be defined as the capability of a power system to handle load fluctuations.

Electrotechnicians have already assessed reliability of power systems by power system stability studies [7]. It is a well-known topic of interest, which checks the real-time capability of a wide power system to maintain synchronism. It is fully used by the transport system operators (TSOs) in power systems regulation.

Without going in further details, one must bear in mind that these stability studies involve time scales from few milliseconds to few hours, while long-term planning models deal with few years. This gap is the main reason why reliability requirements are often ignored, or in the best case not accurately implemented in long-term planning models.

2.2 The MARKAL/Times family of models

Long-term planning models are essential tools to assess the consequences of new constraints applied on the energy mix. Hence, they enable decisions making for politicians and major
actors of the energy field. As reliability of power supply depends on the physical properties of power systems, this work relies on the explicit representation of technologies proposed by technological models. In the technical models, or bottom-up models, the representation of technologies is explicit and produced by disaggregating the energy sector. In such models, the demand is generally exogenous. Such an approach enables substitution among different technologies, choosing the best-suited ones to reach the demand under a set of constraints.

The models of the MARKAL/Times family optimise energy systems in the long term with an explicit bottom-up approach through a description of individual technologies by explicit input-output relationships. The main decision variables are investments levels, activity levels and total installed capacities.

The energy sector is seen as a chain of transformations that goes from raw materials to final energy demand. A technology is described as an energy vector converter. Over the studied horizon, a group of time periods is defined and the characteristics of the technologies can evolve from one period to another. In this way, we can describe any technological progress. When the technologies are fully informed and interconnected, the model builds a group of linear equations for each period, known as the system’s energy equilibrium equations. The equations that bring the exogeneous demand are interpreted as the constraints through demand, rending the models of the MARKAL/Times family “partial equilibrium models driven by demand”.

MARKAL/Times models offer a detailed description for electricity production [8, 9]:

- In order to take into account production peaks and more generally the variations in power demand, each period is split up into six time slices that correspond to the possible combinations between day and night, and between winter, summer and the intermediate seasons. Then, electricity demand is proportionally or in a more subtle way distributed over these time slices. The flow equilibrium equations are published separately, enforcing the equilibria of electricity flows for each time slice.

- Therefore, the peak reserve constraints guarantee the setting-up of a supplementary capacity reserve in order to model the need of over-capacity for high demand periods. These constraints enable the model to size correctly the level of capacities to install (in MW). Each production technology is then affected with a coefficient of participation to this reserve, in order to differentiate between the kinds of production units.

These two features express the constraints on energy flows and power capacities, characterising power transmission. But, reliability requirements are ignored in this family of models.

Of course, long-term planning models are not supposed to rely on an accurate description of power systems management. However, the integration of distributed and renewable energy sources may modify the merit order of the generation units, subsequently impacting investments’ decisions of the model.

In the next subsection, we present qualitatively how forecasted electricity mixes are impacted when reliability issues are not addressed in long term energy planning tools.

2.3 Subsequent bias in forecasted electricity mixes

Here, we define a new nomenclature of electricity losses, introducing the reliability-induced losses. It shows a link between the desired level of reliability and additional losses of the system. These losses have a cost, which increase the total cost of the energy system. Furthermore, these losses also call for additional investments in capacities, which also increase the cost of the energy system. These two effects change the features of the optimal energy system, and for this reason reliability requirements should be implemented in the MARKAL/Times family of models. In
particular, in the paragraph 2.3.3 we qualitatively discuss the variation of losses and subsequent additional investments regarding changes in power supply.

2.3.1 Electricity losses

The conveyance losses The conveyance losses refer to the losses happening 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, relying on steady state analysis. When production capacities are centralised, transmission happens through longer distance 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 stability of the system increases.

The reliability-induced losses Conversely, reliability-induced losses are linked to the desired level of reliability. This level depends both on the load of the grid and on the admissible load fluctuation. For facing these fluctuations, the system relies on reactive power and kinetic reserve (i.e. voltage and frequency automatic adjustments) to recover a stable state, before any control action on active power can happen, requesting the spinning reserve. Reliability-induced losses are associated to the additional costs consented for both maintaining reactive power and investing in kinetic reserve capacities (e.g. weighing generation machines, flywheels). When production capacities are distributed on smaller and less hierarchically organised grids (e.g. decentralised), reactive power and kinetic reserve management is critical to ensure a given reliability level: each grid relies on fewer generation capacities, without counting on capacities from a large-scale system. Reliability-induced losses are related to the dynamic management of the system.

The balance between conveying and reliability losses presumably depends on the electricity mix and on the network architecture following the curve of the figure 1. Conveyance losses are lowered when capacities are close to the loads and the reliability-induced losses, required to handle dynamic management, are lowered with centralised conventional plants.

2.3.2 The burden of electricity losses

We now present some figures to picture the burden of electricity losses. In the European networks, the average losses in transmission networks are between 1% and 2.6% and the losses in distribution networks are between 2.3% and 11.8% [10]. The cost of these losses is even more impressive. For instance, in France in 2006, the amount of charges for losses in the transmission network was estimated at 487 M € and at 837 M € in the distribution networks.

Considering the size of the French electricity industry in 2006 (111.6 GW), the cost of losses comes down to 11.85 €/kW.

This figure is clearly an average value for losses, but it shows that electricity losses are of the same order than the forecasted operating costs of power plants (see table 1) and that they cannot be neglected.

2.3.3 Investments in additional capacities

Of course electricity losses are not ignored in long-term planning models. But they are forecasted as a fix percentage of electricity consumption based on historical data. We have seen that mutations in the generation share and the network architecture are expected to change the global
Figure 1: Qualitative level of losses versus network architecture. Electricity losses can be divided into the conveyance losses, occurring during transmission, lowered when capacities are close to the loads; and the reliability-induced losses, required to handle dynamic management, lowered with centralised conventional plants. The latter affect the mix itself whereas the first are usually assessed for a given mix.

Table 1: Forecasted operating costs for different power plants in Europe in 2015 (Source: OECD/IEA, 2008), compared to the cost of losses for the French electricity industry in 2006.
cost of the electricity system and to move the technically optimum energy system, regarding the cost of losses.

The plausible bias for future electricity mixes are to propose electricity systems which are not economically optimal, regarding the cost of losses or with a poor quality of distributed power.

- In centralised architecture, generators interconnections increase and provide a high level of reliability. These networks induce “electricity highways”, increasing dissipative processes over the lines. By the way, in the history of centralised networks, the centralised decision of investments have encouraged over-sizing of production means, preventing these systems from reliability issues.

- Now, with the development of distributed energy sources, power systems tend to be divided and smaller, decreasing losses during power transmission but questioning the reliability of the system. To counterbalance the latter effect, investments in additional capacities or back-up reserve must be considered.

The balance between conveyance losses and reliability-induced losses should be well-known so that strategic energy choices could clearly arbitrate between losses over the network, the related additional investments and the other constraints binding the electricity mix.

3 Assessing reliability in future electricity mixes

This last remark emphasises the need to take into account reliability requirements in long term energy planning tools. We now present a methodology to assess them. It relies on a technical point of view, and we first propose a brief overview of power system stability to introduce the main technical features of reliability needs.

3.1 Current regulation for power system stability

3.1.1 Load variations and frequency control

In any electric system, power generated must be maintained in constant equilibrium with power consumed / demanded, otherwise a power deviation occurs. Disturbances in this balance causes a deviation of the system frequency, which is initially offset by the kinetic energy of the rotating generating units and motors connected.

As electricity can hardly be stored, the production system must have sufficient flexibility in changing its generation level. It must be able instantly to handle both changes in demand and outages in generation and or transmission.

Any imbalance results in a frequency change in the complete interconnected and synchronised network. At system frequencies below 50 Hz (in European networks), the total demand has been larger than the total generation, at frequencies above 50 Hz, the total demand has been less than the total generation.

In response to a sudden imbalance, the primary control re-establishes the balance between demand and generation at a system frequency other than the frequency set-point value (50 Hz). It causes a deviation in power exchanges between control areas from the scheduled values.

Then the function of the secondary control is to restore the system frequency to its set-point and restore the power exchanges between the control areas.

3.1.2 Voltage control and reactive power management

Voltage is a measured physical quantity, which fluctuates as a function of the network state, i.e. grid topology, generation, load, transmission lines and transformers. For network security
reasons, i.e. the compatibility with the rating of equipment, the supply of customers within the contractual ranges of voltage and voltage stability of the power system towards disturbances, a control of voltage is needed to maintain the voltage deviations within predetermined ranges.

The voltage levels are maintained by reactive power, assured by different facilities: depending on their operational state, all generators, loads, lines and transformers are either reactive power consumers or producers. Reactive power cannot be transmitted over long distances efficiently and voltage control is thus a regional problem.

The primary voltage control is implemented by the voltage regulators of generating units. These regulators initiate a variation in the excitation of generators, and reactive power is adjusted by automatic devices in a time response less than a few second.

Secondary or tertiary voltage control are implemented within a delay that can vary till some minutes by either control automatic devices within a given zone of voltage control, or by manual actions of the TSO to active reactive compensation equipments.

3.2 The methodology for reliability evaluation

This methodology is based on a thermodynamic approach, which leads to a reversible assignment for power transactions [11] and demonstrates that electricity is the most efficient power conveyor. It comes down to a one-loop circuit (see figure 2), which lumps the technical properties of a wide power system (namely its inertia constant and its inductive properties).

3.2.1 Using a thermodynamic framework

This framework has already been applied to describe electromagnetism laws and provides in this field accurate results, especially finding the Faraday’s law. In this work, we apply this framework to power systems, where the number of connections is high, in order to avoid the exhaustive and time-consuming methods relying on the Kirchhoff laws.

The thermodynamic approach is also a global approach, which gives the possibility to reach an aggregated representation of the electricity industry and exhibits the main drivers of losses. In addition, it shows that electricity can achieve the best power transactions. A demonstration based on the thermodynamical principles states that the evolution of the system during energy transactions tends to be the more reversible. This is expressed in the reversibility condition, which exhibits the Joule losses and a term related to dynamic management.

With the thermodynamic approach, we focus on the properties of power conveyor of the electromagnetic field. Electromechanical generators and motors exchange work through this field. The coupling energy between the field and the machines is also described. Finally, the coupling energy with the thermostat is introduced.

3.2.2 Working with a one-loop equivalent circuit

Thanks to the thermodynamic background, the description of power systems is reduced to their upper scale and comes down to a one-loop equivalent circuit presented in the figure 2. This system is described by a mechanical equation (1) and an electrical equation (2).

\[
\frac{d}{dt} \left( \frac{J\Omega(t)^2}{2} \right) = P_{\text{mech}} - \sum_{\varphi} \varepsilon_{\varphi}(t)I_{\varphi}(t) \tag{1}
\]

\[
\varepsilon_{\varphi}(t) = L \frac{dI_{\varphi}(t)}{dt} + (R_d + R_1)I_{\varphi}(t) \tag{2}
\]

The mechanical equation (1) describes the energy conservation in the generator. It rules the angular velocity \( \Omega \), where \( J \) is the moment of inertia of the generator; \( P_{\text{mech}} \) is the power
Figure 2: The One-loop Grid, a circuit equivalent for a wide power system. One-phase \( \varphi \) representation. The mechanical part represents the generators. In the electrical part, the impedances gather the inductive and resistive properties of the loads, the generation capacities and the transmission capacities of the system. \( R_1 \) models the load and connecting \( R_2 \) models a load fluctuation. \( T \) is the thermostat.

The variation of \( \Omega \) obeys to the frequency variations described in the paragraph 3.1.1.

The electrical equation (2) rules the voltage drops in the grid (at Very High Voltage), i.e. the current \( I_\varphi(t) \) in the grid, where \( \varphi(t) \) is the voltage provided by the generator; \( L \) represents the inductive properties of the grid and \( L \frac{dI_\varphi(t)}{dt} \) the subsequent voltage drop; \( R_1I_\varphi(t) \) is the load (or consumer) voltage; \( R_d \) represents the resistance of the lines. The inductive properties \( L \) participate in maintaining the reactive power described in the paragraph 3.1.2.

From these equations, achieving the best transaction between the generator and the load states an optimisation problem (3) expressing simultaneously the minimisation of the Joule losses and the dynamic management term. These two are related respectively to the conveyance losses and the reliability-induced losses.

\[
\min \left( \begin{array}{c}
R_dI_\varphi^2(t) \\
\text{Power Transmission}
\end{array} \right) + \frac{d}{dt} \left( \begin{array}{c}
\frac{LI_\varphi^2(t)}{2} + \frac{J\Omega(t)^2}{2} \\
\text{Dynamic Management}
\end{array} \right)
\]  

(3)

In fact, frequency and voltage variations are bound by the contractual and stability limits presented in the paragraphs 3.1.1 and 3.1.2. These constraints shape the feasible space for reliable electricity mixes with (3).

With this methodology, dynamic behaviour of wide power systems can be deduced from their aggregated properties, using the one-loop equivalent circuit. To check whether or not the power system can be operated in reliable conditions, we compare the dynamic behaviour of the one-loop circuit with the stability limits. In the next section, we present the relevant indicators of power systems exhibited with this methodology.

4 Consequences for future electricity mixes

The relevant properties of power systems which contribute to their dynamic stability are related to the frequency deviations, the voltage deviations and the synchronism. They are respectively related to the following physical properties, the “reliability indicators”: the kinetic energy storage, the reactive power and the power angle of the generators. In this section, we present the constraints on these indicators, related to the dynamic management.
4.1 Indicators for reliability in future power systems

4.1.1 Frequency variations and mechanical inertia of the system

The results concerning frequency variations can be separated into three main contributions:

- First, solving equation (1) gives a relaxation time constant $\tau_{\text{mech}}$ characterising frequency, i.e. $\Omega$, variations. $\tau_{\text{mech}}$ depends on the inertia $J$ of the machines, the set-point value of frequency (i.e. $\Omega_0$) and the mechanical power $P_{\text{mech}}$ the machine provides to the system. $\tau_{\text{mech}}$ is related to the kinetic energy stored in the generators.

$$\tau_{\text{mech}} = \frac{J\Omega_0^2}{P_{\text{mech}}}$$

(4)

For a simple model with one generator, simulations gave $\tau_{\text{mech}}$ equals to 16 s.

Also important in power stability, is the kinetic energy stored in the system. If a system has a large amount of kinetic energy then only a minor adjustment in speed is necessary to account for the power difference, whereas for a system with lower kinetic energy a greater speed variation is required to account for the same difference in power. The kinetic energy stored, $\frac{1}{2}J\Omega_0^2$, explicitly depends on $J$.

- Besides, the resolution of equations (1) and (2) shows frequency or angular velocity variations in adequation with the dynamic properties of power systems. The curves of the figure 3 are obtained when we model a load fluctuation in the one-loop equivalent circuit.

Interestingly, this constant $\tau_{\text{mech}}$ exhibited from the one-loop circuit, is similar to the inertia constant $H$ defined by electrotechnicians, also expressed in seconds. $H$ represents the magnitude of the stored kinetic energy and is an important factor in the determination of machine dynamic performance and stability.
Figure 4: For a given set of $P_{\text{mech}}$ and $\Omega_0$, an inertia constant $J^*$ defines a limit between reliable and unreliable power supply. This curve is purely conceptual.

(figure 2). Load fluctuations are modeled when virtually connecting $R_2$ to the grid or modifying the value of $R_1$.

- Finally, frequency deviations are bounded for both stability and contractual reasons. The variation margins are $\pm 0.5$ Hz and the delay between fluctuation and adjustment is around 30s [12]. Knowing the set-point value of frequency and the nominal power of the system, the latter values define a lower limit for the inertia $J$ above which the system is vulnerable to load imbalances. It is possible to determine a certain value of inertia $J^*$, which draws a limit between reliable and unreliable electricity mixes (figure 4).

4.1.2 Voltage variations and inductive properties of the system

Voltage variation margins are $\pm 5\%$ and the reaction time is around a second [12].

The inductive properties expressed in the inductance $L$ of the generators, motors, transformers and lines, refers to the magnetic energy storage. It influences their behavior as reactive power consumers or providers and their contribution in maintaining voltage levels.

Solving equation (2) also provides a relaxation time constant $\tau_{\text{elec}}$:

$$\tau_{\text{elec}} = \frac{L}{R_1}$$

(5)

Under the same hypotheses used for $\tau_{\text{mech}}$, $\tau_{\text{elec}}$ is evaluated at 14 ms.

Similarly to the kinetic energy storage, the magnetic energy storage, $\frac{1}{2}LI^2$, or the related level of reactive power available is crucial to for the dynamic management.

Unfortunately, the magnetic energy storage is hard to model and we have encountered difficulties with the dynamic behaviour of voltage variations. These difficulties are mainly due to the complexity of magnetic interactions between the fields within the machines. The value of $L$ changes during transient and even subtransient regimes and is consequently hard to catch. However, we expect to find the qualitative variations of $\tau_{\text{elec}}$ with $L$ presented in the figure 5.

4.1.3 Synchronism and power angle of the machines

Another important issue with power system stability is the synchronism of the interconnected machines. This property is related to the power angle $\delta$. The power angle is a physical measure of the difference between the two magnetic fields of the machines. The power provided by the machine depends on the value of this angle.

-or in the reactance $X$
Stability of power systems is achieved for values of $\delta$ between $\pm 90°$. This constraint gives an additional criteria for checking the feasibility of future electricity mixes. Such a criteria can be found with transient stability studies.

These indicators underline especially the need for proper values for $J$ and $L$ in reliable future electricity mixes, respectively related to kinetic reserve and reactive power management. In the next subsection, we discuss the evolution of these quantities with regards to the emerging energy sources: distributed power units and renewable sources.

### 4.2 The case of distributed power units

Trends emerging in the power system suggest that the centralised paradigm may be replaced by an alternative one in which control is more dispersed. The development of distributed power units has become possible with their cost efficiency and provides an alternative to investments in expensive conventional power plants.

The existence of dispersed energy sources and controlled sinks that exercise some autonomy, possibly grouped in microgrids may change the nature of the grid itself. Currently, development of microgrid technologies is an active area of research in several countries:

The interest is also strongly increasing in the concept of intelligent power systems, known as smartgrids, along with the concept of aggregators controlling the flexibility of the consumption for a set of end-users. These two effects contribute to flatten the load curve and also to lower the capacity constraint in the future electricity industry, encouraging the development of microgrids and smartgrids.

With the development of distributed power units, presumably close to the sensitive consumers, the idea of an homogeneous quality of service is replaced by the idea of an heterogeneous quality of service tailored to the requirements of classes of end-uses. For instance, a pyramid of heterogeneous quality of supply end-uses is built accordingly to their power quality and reliability requirements [2].

With distributed power units and on-site production, the number of interconnexions between power units decreases and leads to three main reasons of dissatisfaction, the reliability requirements:

- When power systems tend to be divided and smaller, it is not possible to benefit from the dispersion of energy sources, which can lower the development of intermittent energy sources. For instance, the development of wind farms in France is partly due to the un-correlation between wind production around the Channel and around the Mediterranean
Table 2: Inertia constant ($H$) values for conventional and renewable power plants issued from [14]. $H = \frac{\tau_{\text{mech}}}{2}$. There is no inertia constant for photovoltaics.

<table>
<thead>
<tr>
<th>Generating unit</th>
<th>$H$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal unit</td>
<td></td>
</tr>
<tr>
<td>(a) 3600 r/min (2-pole)</td>
<td>2.5 to 6</td>
</tr>
<tr>
<td>(b) 1800 r/min (4-pole)</td>
<td>4 to 10</td>
</tr>
<tr>
<td>Hydraulic unit</td>
<td>2.0 to 4.0</td>
</tr>
<tr>
<td>Wind unit</td>
<td>3</td>
</tr>
<tr>
<td>Tidal energy unit</td>
<td>0.9</td>
</tr>
</tbody>
</table>

see [13], and is even more due to their integration in a wide system with other predictable energy sources.

- In relation with the previous section, imbalances and disturbances in smaller grids have to be compensated both locally and immediately. In this case, the system only relies on a few other power units, which must store enough kinetic energy and reactive power to balance the power imbalance. So, in smaller and weakly interconnected systems, the average value of energy stored by installed kW and investments in back-up generation capacities must increase.

- Finally, the time constants $\tau_{\text{mech}}$ and $\tau_{\text{elec}}$ must stay high enough to ensure a reliable dynamic management in future electricity mixes, since the margins for deviations have not changed.

4.3 The case of renewable energy sources

With the integration of renewable energy sources, it is crucial to assess their contributions to dynamic management compared to those of conventional sources. In fact, with conventional synchronous generators, the kinetic energy exchange is immediately reflected by a change in the system frequency. But most renewable energy sources do not use synchronous generators and can not participate with the same efficiency to dynamic management.

In the table 2 we present the values of the inertia constant $H$ – proportional to $\tau_{\text{mech}}$ – for different power plants [14]. It shows that power plants do not participate equally to the kinetic energy storage$^{2}$, and so to the dynamic management.

Wind or tidal power units can store less kinetic energy than thermal units, suggesting that renewable energy sources lower the reliability of power supply. Integrating renewable energy sources in electricity mixes should be done carefully.

5 Conclusion

In the section 2 we have stressed the need to take reliability requirements into account when designing future electricity mixes and energy systems. The constraints on the level of reliability induce additional losses and investments in the forecasted energy systems. They consequently increase the global cost of the energy system, which may be sub-optimal regarding these new constraints.

$^{2}$The greater $H$ is, the more kinetic energy is stored by kW of installed power plants.
Eventually, we have qualitatively shown that reliability requirements are more crucial with the emerging trends for electricity production, than they were at the time of over-sizing the production capacities.

Then we have proposed in the section 3 a methodology to assess the level of reliability of future electricity mixes. This methodology is based on the technical properties involved in dynamic management of power systems. It has finally exhibited “reliability indicators” introduced in the section 4. These indicators are related to the dynamic management of power systems. They reveal that integrating of distributed and renewable energy sources tends to lower the reliability of power systems, telling that changes in the electricity industry should be done with caution.

This last remark underlines the need to implement these indicators in long term planning tools, in order to design plausible – i.e. reliable – options for future electricity mixes. We consider to link this methodology with the MARKAL/Times family of models. Interestingly, small island grids with little interconnections exacerbate the reliability constraints and could be the first case of study.
References


