Long-term planning and the sustainable power system: a focus on flexibility needs and network reliability

Nadia Maïzi, Vincent Mazauric, Edi Assoumou and Mathilde Drouineau

***Abstract*—Long-term planning models are useful to describe future energy and technology options and to analyze environmental issues. They propose solutions for meeting future energy consumption. Focusing on the electricity sector, we argue that in order to provide a more relevant assessment of the power supply system ahead we need to tackle both flexibility needs and network reliability.**

On the one hand, flexibility is integrated in long-term planning models as an additional criterion for new investment decisions: it allows electricity generation capacity with short start-up periods to be part of the mix to satisfy peak demand, despite their higher marginal costs in comparison with the cost of base load technologies.

On the other hand, and in order to assess network reliability, a suitable representation of dynamic dissipative processes over the electrical network is necessary. We introduce the notions of conveyance and reliability losses and their qualitative impacts on power transmission. We propose a methodology to exhibit the level of losses associated with a given level of reliability, whether generation capacities are centralized or decentralized. Our methodology is based on a thermodynamic description of the electric system and lumps it into a "one-loop grid". It provides a figure for the amount of reactive power and kinetic reserve needed to ensure network reliability and face admissible load fluctuations.

***Keywords:* — Energy planning. Thermodynamics. Electrical power. Transmission grid. Optimization —**

I. 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. The International Energy Agency has estimated that US$ 10 trillion US will be spent during the next thirty years on the generation, transmission and distribution of electrical power, in order to replace existing capacities in developed countries, or to accompany the development of energy markets, or to substitute energy vectors that are less clean or growing scarce [16]. In this context, two essential features challenge forthcoming changes in the power system: (i) the emergence of different paradigms for serving electricity than those for which the system was designed [7]; (ii) the will to improve the energy efficiency of electrical power transmission, given that the current system clearly lacks efficiency (e.g. electrical losses are twice as high as electricity consumption was in 1950 as pointed out in [12], and illustrated in figure 1 for the residential and industrial sector in the US).

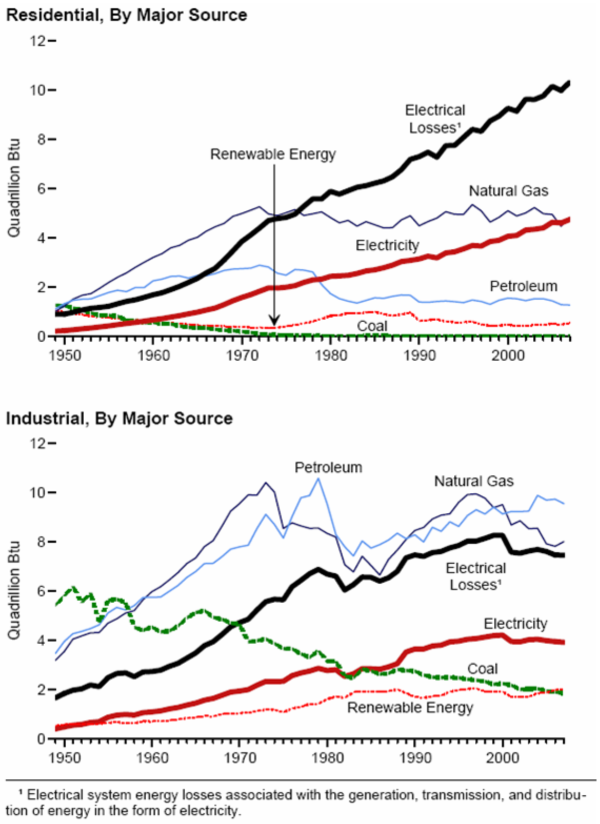

Fig. 1. Residential and Industrial Total Energy Consumption, Major Sources [12]: electricity use (and related losses) expanded dramatically.

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 emissions emitted by the electrical sector.

These issues stress the need for assessing future electrical power systems. Models for energy planning have proven useful to determine a plausible evolution of the energy sector in the mid -to long term in the face of strong environmental pressures, such as carbon mitigation or fossil energy depletion. 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, and estimating pollutant emissions, require models of substitution possibilities throughout the

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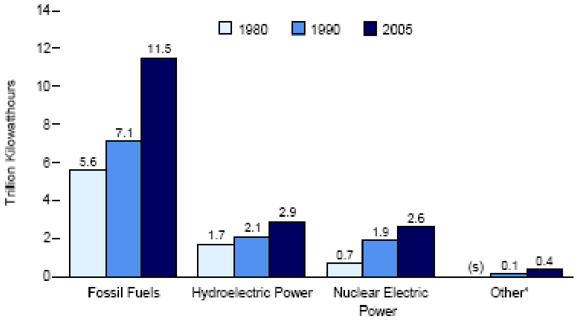

Fig. 2. Net Generation by Type, 1980, 1990, and 2005 [12]

whole energy chain. The MARKAL (MARKet ALlocation) type of technology-rich models provide a partial solution to this problem [4], [13], [1]. However, in order to assess the sustainability and robustness of these energy planning model results, it is necessary to give a suitable description of the time and space constraints of electricity generation systems.

Spatial constraints relate to the geographical distribution of the power plants, the structure and availability of the transmitting network, and the location of demand.

Time constraints relate 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 stationary behavior, the total electric power supplied by the stations must be equal to network demand. In order to ensure this power balance, electricity production modes will be chosen for their dynamic nature and for their location in the network.

In section II, we explore the limit of the actual MARKAL modeling approach for the electricity sector. Then, section III presents 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 technical constraints.

In section IV, the need for reliability assessment on the power network is described. In section V, we present how a methodology based on a thermodynamic approach enables the description of the power transmission grid in a comprehensive and synthetic way. Section VI then provides a conclusive discussion, in which we present how this method can be adapted to network reliability assessment and implemented in energy planning models such as MARKAL.

II. Limitations of the long-term prospective modeling

Long-term global prospective models permit the assessment of multi-sectoral energy policies and are therefore persuasive. Among these models, MARKAL is a technological model developed since the mid-eighties [4] under the auspices of the International Energy Agency [13]. 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 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. MARKAL offers a more detailed description for the electricity sector, whereby flows are represented as energy units. Specific technical constraints [15] 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:*
  The peak reserve constraint therefore guarantees the setting-up of a supplementary capacity reserve to show what level of over-capacity is actually necessary to cope with high demand periods. In such cases, the user stipulates a global electricity or heat reserve factor. Each electricity or heat production technology is then represented by a supplementary coefficient of participation (of the technology's capacity) in the realization of the reserve. This coefficient (from 0 to 1) makes it possible to differentiate between the contributions of each power station: typically 1 for nuclear stations, and 0.2 to 0.3 for wind power stations. The peak equation stipulates that total production capacity, counterbalanced by the peak participation coefficients, must be oversized if it is to satisfy demand (for exports, processes and demand technologies), and increased by the chosen level of reserve.

The need for flexibility is linked 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 electricity demand, all functioning electricity systems require, a priori, the installation and effective use of power stations that can run practically all year, as well as of power stations that do not run for more than 200 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 production levels to meet consumption.

These flexibility constraints are on the whole largely ignored in MARKAL models, despite the fact that the requirement for short-term flexibility calls for long-term investments. Indeed, and as the MARKAL approach relies on the minimization of economic criteria [2], which aims to chose an electricity-system that is economically efficient, the least expensive method of production is favored. Ignoring flexibility presents several drawbacks for the MARKAL results in the electricity sector:

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

- 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 with demand (slower amortization, the need to use a greater number of power stations).
- 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. As development of these reserves 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 renewables. Thus, this should be revised in order to better assess the level of carbon dioxide emissions.

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

III. AN AUGMENTED FLEXIBLE MARKAL MODEL

This approach, applied to the French case in [9], where the electricity sector is dominated by nuclear power, 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. 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 that are specific to electricity are conserved. MARKAL's philosophy of linear programming through constraints leads to a natural tendency to be guided by constraints.

The results of this augmented MARKAL model applied to the French electricity system are given for fossil plants (figures 3 and 4), which are power plants that are very sensitive to dynamical features. The two figures compare the actual installed capacities used in the power production process.

The standard MARKAL model installs power stations such as gas or fuel turbines (for the capacity reserve), but hardly ever uses them for electricity production, as shown by the results given in figure 4. Power stations are preferably used over long periods of time and therefore have a base load type profile.

Conversely, the flexible approach illustrated in figure 3 selects, for instance, oil power plants, which are very expensive but essential for responding to peak demand. The augmented MARKAL model makes more plausible the electrical system resulting from the optimization.

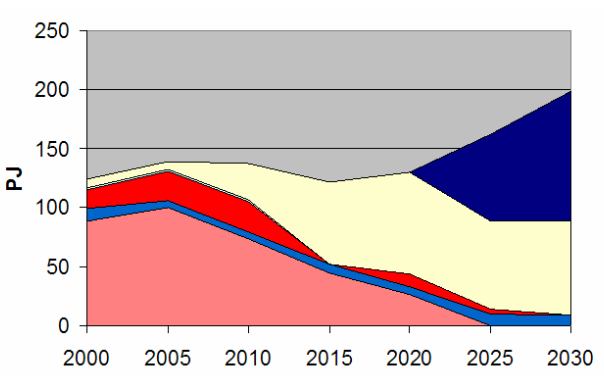

Fig. 3. Fossil plant production 2000-2030: a flexible MARKAL approach

This comparison demonstrates that when flexibility is not properly handled, the results issued from MARKAL reflect a minimal (under-constrained) condition to satisfy global electricity demand. Thus it fails to address properly the questions related to environmental issues, and namely the level of carbon emissions - except for regions where the base load mix is dominated by fossil fuels. This carbon level depends in France on the precision of the thermal production assessment [9].

Regarding these results, flexibility appears to be a key parameter for reaching a better representation of the electricity generation system and consequently achieving sustainable systems. In fact, this issue of flexibility has led to difficulties in forecasting an elelectric system that translates the need for enough installed capacities in order to both (i) satisfy electric demand and (ii) roughly follow the load curve. Flexibility is a step towards forecast generation shares for which installed capacities are well-anticipated.

Next to this crucial need for flexibility also stands the question of reliability of supply structures. In the following section, we focus on the description of dissipative processes through the network, because losses over the network need to be balanced by greater investments in generation capacities. This second issue on reliability also tackles the dimensioning of the electrical power system, and proposes a complementary path to reach sustainability.

IV. THE CRUCIAL NEED FOR ASSESSING RELIABILITY-INDUCED LOSSES IN THE ELECTRICAL NETWORK

When comparing different technological options that satisfy the same electric demand, one should also assess the quality of the delivered electricity. This is defined by both:

- the continuity of electric power supply, related to the occurrence of power outages, defined as a large-scale disruption in electric power supply;

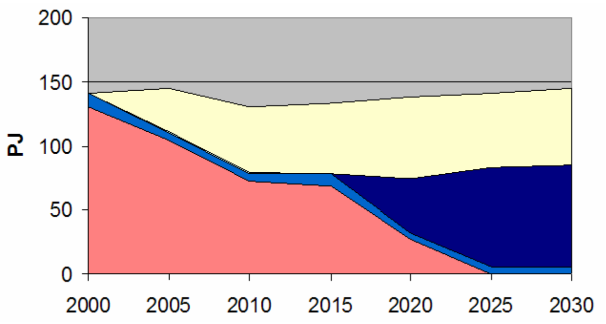

Fig. 4. Fossil plant production 2000-2030: a standard MARKAL approach

- the quality of the delivered electric power, which means that the signal's voltage and frequency must remain between contractual bounding values. When electric power is delivered outside these bounding values, both producing and consuming equipments on the network may fail to perform correctly or disconnect.

Thus, to provide relevant comparisons between future electrical systems, these losses should then be assessed properly, and plausible alternatives must rely on an accurate description of these losses. We define two kinds of dissipative processes on the electrical network: conveyance and reliability losses.

Conveyance losses are losses that 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 becomes more stable. Besides, if the installed generation capacities increase, the power system also has similar benefits.

Conversely, reliability 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, defined as the maximum loss of generation capacities the electric system must overcome. To face these fluctuations, the system relies on reactive power and kinetic reserve (i.e. automatic adjustments in voltage and frequency) to recover a stable state in the system, before any control action on active power can occur, which would request the spinning reserve. When production capacities are distributed on smaller and less hierarchically organized grids (e.g. decentralized), 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 losses are related to the dynamic management of the system, but can hardly be compressed if the desired level of reliability remains constant.

To summarize, the balance between these conveyance and reliability losses is highly dependent on energy generation shares and the associated network architecture. In fact these two kinds of losses take place in the same system and therefore it is difficult to allocate them.

V. TOWARDS A THERMODYNAMIC APPROACH TO THE ELECTRICAL SYSTEM

Basically, thermodynamics assumes that the steady-state of any system is obtained from the maximum-entropy principle, keeping the macroscopic information on the system including the positions of the moving bodies $\mathbf{X}$, the internal energy U; and, in the specific context of electromagnetism, the magnetic flux Φ and the electric charge Q squeezed from the earth [8] as shown figure 5.

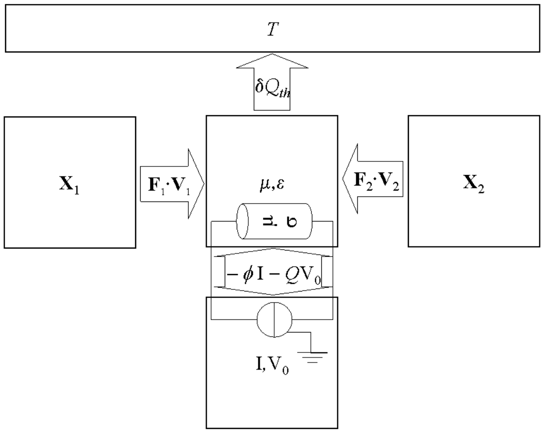

Fig. 5. Chart of the energy exchanges between the various subsystems involved in the thermodynamic framework. While current generators and moving parts can only exchange work with the electromagnetic field (respectively through a current variation and a modification of the boundary conditions on the magnetic moving parts), the thermostat can only receive heat from the other sub-systems.

Besides, thermodynamic assignment should also include an explanation of non-equilibrium conditions and actual processes enforced by some coupling variations, since equilibrium is merely an ideal limiting case of the behavior of matter. Through enforcing an isothermal evolution thanks to the contact of the system with the thermostat at temperature T, two cases - summarized in the *second principle* - may be considered in order to remain coherent with the maximum-entropy principle checked by any isolated system. First, the evolution does not modify the entropy of the isolated system [11]. Such an evolution is said to be *reversible* and involves only *work* exchanges, through sufficiently smooth variations of the energy couplings, namely:

- the mechanical power exchanged between the actuators $\mathrm{P}_{\mathrm{mech}} = \sum \mathbf{F} \cdot \mathbf{V}$ where $\mathbf{V} = \frac{\mathrm{d}\mathbf{X}}{\mathrm{d}t}$ is the velocity of the moving body $\mathbf{X}$ (e.g. the rotor) experiencing the external force $\mathbf{F}$; and, in the specific context of electromagnetism,
- the electromagnetic coupling variation $\frac{\mathrm{d}(\Phi \mathrm{I} + Q\mathrm{V}_0)}{\mathrm{d}t}$ where I is the net current exciting the electromagnetic field (e.g. the excitation in a synchronous machine), and V_0 the earth voltage.

On the other hand, the evolution increases the entropy of the isolated system, so that some amount of work exchanged between actuators is lowered in heat during the process: such an evolution is said to be *irreversible*.

Despite some improvements summarized in [3] for the steady state regime, thermodynamic approaches to electromagnetism do not consider any extensions toward time-varying regimes. In the following, a thermodynamic interpretation of Faraday's Law within the quasi-static approximation is given, giving physical sense to the former variational presentation [6].

The *first principle* conveys energy conservation and reads

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \mathrm{P}_{\mathrm{mech}} - \mathrm{T}\frac{\mathrm{d}S_{\mathrm{th}}}{\mathrm{d}t}$$

Hence the irreversibility experienced by the system coupled with its thermostat may be discussed from the Helmoltz free-energy $F = U - \mathrm{T}S$ by expressing

$$\mathrm{P}_{\mathrm{mech}} - \frac{\mathrm{d}F}{\mathrm{d}t} = \mathrm{T}\left(\frac{\mathrm{d}S}{\mathrm{d}t} + \frac{\mathrm{d}S_{\mathrm{th}}}{\mathrm{d}t}\right) \tag{1}$$

where the RHS matches the power lowered in heat by the whole system, commonly known as the Joule losses P_{Joule}. According to the *second principle*, this term is always positive and the lower the Joule losses, the more reversible the evolution. In order to take explicitly into account the inertial behavior of the electromagnetic coupling (Lenz law), it is convenient to introduce the so-called Gibbs free-energy $G = F - \varPhi\mathrm{I} - Q\mathrm{V}_0$ on which another reversible assignment may be expressed

$$\mathrm{P}_{\mathrm{mech}} - \frac{\mathrm{dG}}{\mathrm{d}t} = \min\left(P_{\mathrm{Joule}} + \frac{\mathrm{d}(\varPhi\mathrm{I})}{\mathrm{d}t} + \frac{\mathrm{d}(Q\mathrm{V}_0)}{\mathrm{d}t}\right) \tag{2}$$

As a matter of fact, Faraday's Law is achieved by enforcing the condition of reversibility expressed from the Gibbs free-energy (2), whereas the condition obtained from the Helmoltz free-energy (1) restores only the direct current flow behavior and underestimates actual losses [10]. This reversible interpretation of Faraday's Law gives new insights and raises issues on improving the energy efficiency of the electrical system as a whole, and is very promising for further investigations:

- Globally, expressing the reversibility condition (2) over the electromagnetic energy coupling variations prevents tremendous Joule losses and therefore mitigates any load fluctuation. This striking property offers a way of recovering the stability of the network by delaying and softening the impact of the fluctuation.
- Locally, the reversibility condition (2) addresses a multiscale description from the very deep structure of material to the network. While the former allows to agregate properly the losses over the system, the latter provides the electrical power density as the local variation between the LHS and the RHS in (2). Hence, a decentralized network favors smooth electrical power density whereas a centralized network exhibits a rough profile.

To summarize, the equilibrium condition in (2) provides a true optimization of the power transaction between producers and consumers on the electric system, for a set of state variables. The best transaction results from a compromise between the minimization of (i) the Joule losses and (ii) the variation of electromagnetic coupling energy. (The variation of the electrostatic term $Q\mathrm{V}_0$ in (2) is negligible when studying the whole electricity network.) Acting as a stock in this description, the electromagnetic coupling energy is related to reactive power and subsequent reliability. This coupling energy enables electromechanical conversion and transmission throughout the network and ensures network reliability, but requires maintaining the excitation current in compensation.

VI. CONCLUSION

In order to assess a sustainable power generation system, space and time constraints have to be considered.

On the one hand, flexible features of electricity are handled using an improved version of the MARKAL model.

On the other hand, the thermodynamic approach applied to the transmission power system leads to a suitable description of losses related to reactive power and kinetic reserve management to ensure network reliability. Thanks to (2), the network can be studied as a one-loop system, as far as one has access to the state variables that characterize this system and its evolution. This one-loop description comes down to a schematic network gathering the properties of the whole electric system. Two relaxation time constants are exhibited when applying both (2) and the mechanical energy conservation equation. They are, by order of magnitude, related to the variation with time of the reactive power and of the kinetic reserve. To ensure the stability of the system, they should both occur before the automatic adjustments and the spinning reserve. With knowledge of the load of the system, these relaxation time constants are respectively bound by the admissible variations of voltage and frequency, under normative load fluctuations (i.e. the level of reliability). Basically, these constants are related to the amount of electrical steel, rotating mass, inductive components on the network and the excitation of generators.

These results, added to the level of conveyance losses, explicitly depend on the shares of electricity generation. The implementation of these results in a long-term planning model such as MARKAL is in progress.

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