Envisioning the energy future: from societal aspirations to technical challenges

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Mathematical models, which can arbitrate between several strategies, or even societal choices, allow the exploration of different scenarios and can help decision-making. A family of models allows a detailed comparison of three scenarios, which are based on a so-called "green" growth in energy consumption, involving either an increase or a phasing out of nuclear power, or a decrease in energy consumption.

When it comes to long-term energy issues, the question of the suitability of the various technologies arises. Models from the TIMES family *(The Integrated MARKAL-EFOM System)* [1] allow forecasting studies to be carried out from this perspective. The models are driven by a scenario of changes in demand up to 2050 and provide a detailed description of the technologies available, evaluating them in order to minimize the total actualized cost of the energy system over a given time-frame.

In order to feed such models, the following question must be addressed: *how will energy demand change over the next 50 years?* This is a complex question, as energy is used in a variety of ways: for heating, transportation, entertainment, manufacturing, etc. Moreover, energy use is influenced by infrastructures, behavior, consumer choices and, more broadly, by lifestyles and how societies are structured[(a)]. In order to explore the impact of different societal choices (including different nuclear options) and lifestyles on energy demand, we have developed a macroeconomic simulation model [2] for France[(b)].

We can therefore look at how the application of our models allows us to shed light on two options recommended as viable alternatives to current trends (see box, p. 51). The first is in line with the prospect of *green growth*. It is presented as a technological gamble: innovation and technical progress play a critical role, both as the drivers and fruits of economic growth, and also as expected sources of solutions to the depletion of natural resources. Translated into our macroeconomic model [2], this strategy leads to a 15% reduction in electricity consumption between 2012 and 2050.

The second option is intended to reflect the perspective of protagonists of the *degrowth* movement. It is more of an anthropological gamble: that of a cultural revolution resulting in a profound change in values, norms, behaviors, lifestyles and social organization, and a change from systems of needs towards greater sobriety. To understand this ambition, a series of interviews were conducted with people close to the degrowth movements, each interview being then translated into a scenario. We propose here to analyze the scenario reflecting the most ambitious of the visions gathered during the interviews. Our macroeconomic modelling [2] indicates that this scenario entails a 56% decrease in electricity demand between 2012 and 2050.

These two electricity demand scenarios, with their specific constraints, are used as a basis for developing the electricity sector's most cost-effective technology package for the period up to 2050.

The green growth scenario will be considered in terms of two options: a first option opens up the possibility of investing in new nuclear capacity, while a second option pursues a policy of nuclear phase-out and the aim of achieving a 100% renewable electricity mix by 2050. In the latter case, a 20-year extension of the life of existing reactors, at an additional cost, is envisioned.

The degrowth scenario advocates a nuclear phase-out hypothesis with no possibility of extension beyond the lifetime of the reactors (40 years). In keeping with the underlying spirit of technological austerity, it doesn't permit phase-out technologies, which enable a delay in electricity consumption (such as optimized networks, known as smartgrids), or new storage technologies[(c)] dedicated to electricity generation.

The first trade-off factor highlighted by the results of our model (fig. 1) is the level of electricity exports, which decreases drastically in the two "100% renewable" options. If the share of nuclear power changes according to the assumptions made, the levels of investment in electricity generating capacity are contrasted: the "100% renewable green growth" scenario comes first in terms of the total amount of new capacity built over the study period (fig. 2). The two nuclear phase-out scenarios use technologies based on the use of fossil resources. This result, recurrent in our studies [3], indicates that, beyond the question of decommissioning, a nuclear phase-out will have to be carefully environed to limit the use of high carbon-emitting technologies. The significant differences in investment levels between the scenarios have repercussions on the total projected cost of the electricity system:

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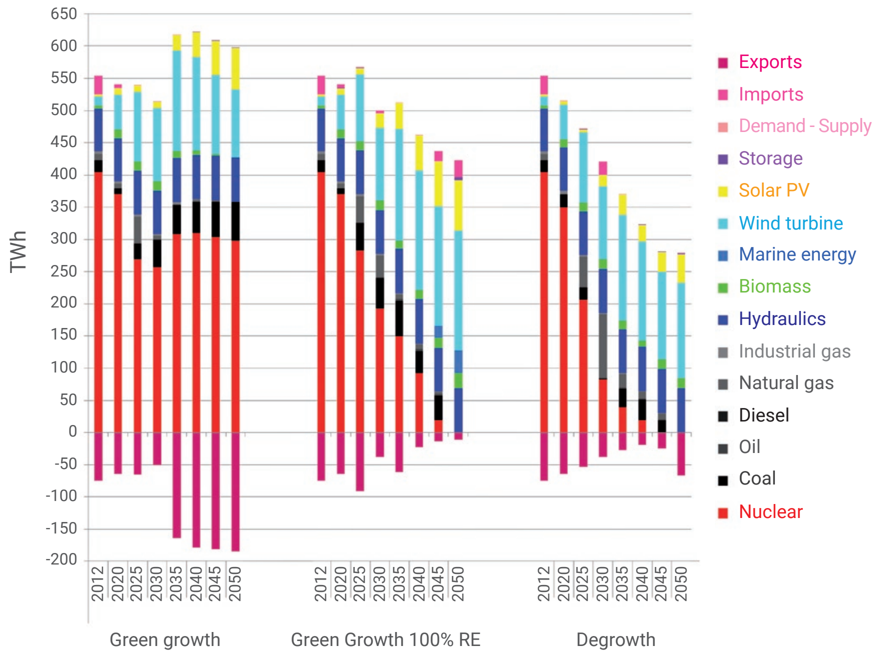
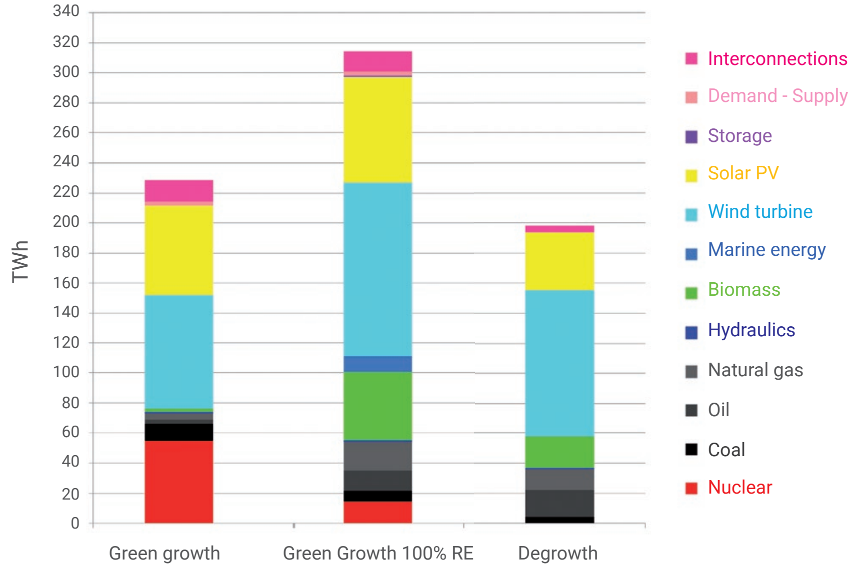


1. Different shares of electricity generation, over time, in the "green" growth scenarios with and without nuclear power, and in the degrowth scenario.



2. Installed power generation capacities by 2050 according to the three scenarios.

The kinetic indicator

Provided that synchronism is ensured at network level [5,6], this indicator corresponds to the depletion time of the kinetic energy[d] stored in the power system in relation to the maximum possible fluctuation either in consumption (peak deviation) or in generating losses. It is expressed as

$$\frac{E_{kin}}{max(\Sigma_k S_k, P_{peak} - \Sigma_k S_k)}$$

where E_{kin} is the kinetic energy distributed on the network, $\Sigma_k S_k$ is the maximum apparent power supplied by the generator, before they fluctuate, and P_{peak} is the peak power demand.

the transition to the scenarios with lower greenhouse gas emissions leads, compared to the green growth scenario, to an additional cost of 16% in the case of 100% renewable green growth and a cost reduction of 4.5% in the degrowth scenario.

While a given electricity generation mix seems to meet environmental criteria, the question remains as to its ability to meet demands in order to avoid a disruption of electricity supply due to an imbalance between supply and demand (black-out). To address this problem, which involves transient events of the order of a second or even a millisecond, we have developed an indicator [4] which makes it possible to estimate the time needed for the system to recover a satisfactory operating state following a significant power disturbance (see box). In order to guarantee the stability of the power system, a minimum level[e] of this indicator must be maintained corresponding to the time needed to use the primary reserve, whose role is to restore a balance between production and consumption, independent of considerations of nominal regime or economic optimum. However, it can be seen (fig. 3) that the value of the indicator declines (compared to its 2012 baseline) for the two scenarios with a "100% renewable" objective. Indeed, with the introduction of variable renewables, the technologies in question have no (solar) or little (wind) mechanical inertia. The stability of the power system is therefore strongly impaired in both scenarios.

Far from invalidating the options tested and their aim of limiting the carbon emissions of the power system, these results encourage us to think about how the solutions proposed can be adapted to the operating requirements of the system. Through a case study of Reunion Island to 2030, we were able to show that a technical design that meets the requirement of maintaining the level of the kinetic indicator makes it possible to envisage a 100% renewable mix [6, 7] that allows both a share of more than 50% of intermittent energy sources and a reduction in newly-created capacity.

The forecasting tools we have developed, illustrated through these analyses, highlight the possible but sometimes overlooked consequences of certain choices, be they technical, linked to behavioral changes, lifestyles or social organization. By enabling an informed debate, they provide politicians "wishing to embark on a chosen path" [8] with the means to achieve it. ▮

3. Kinetic indicator as a function of time in the three scenarios. The higher this indicator, the more stable the system is with respect to fluctuations. The value indicated is the relative value compared to the minimum observed in 2012.

[a] Including demographic choices.

[b] For a study of scenarios on a global scale, see the article by S. Bouneau (p. 46).

[c] For example, high-capacity batteries and supercapacitors, thermal storage.

[d] Kinetic energy due to the rotation of mechanical parts.

[e] Of the order of a few tens of seconds, this time is 40 s on average for France in 2013, and 25 s for an island such as Reunion Island in 2008. The higher the indicator, the more the system can cope with significant fluctuations.

[f] The annual rate of improvement in energy efficiency is assumed to be twice the average rate observed in France for each sector over the period 1996-2012.

[g] Marginal gains in energy efficiency are assumed to be increasingly small and zero after 2050.

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Green Growth and Degrowth

Green Growth

The size of households continues to decrease, end-user consumption increases, long-distance mobility continues to grow, local mobility continues to develop, local mobility relies partially on public transport, electric vehicles are spreading rapidly, the economy is modestly continuing its tertiary sector development, the residential sector is benefiting from an increased rate of heating upgrades, and the assumptions of technical progress and energy efficiency of manufacturing processes and machinery are very strong(f).

Degrowth

Household consumption is changing and decreasing significantly as a result of the gradual adoption of “frugal” lifestyles and the development of pooling practices, long-distance travel is decreasing sharply, travel is largely shifting to less polluting modes (bicycle, public transport, train, etc.), the economy is being relocalized, agriculture is becoming essentially “organic”, heating upgrades in the residential sector are limited, and the assumptions for improving the energy efficiency of production processes and household equipment are very modest(g).