Applied Energy 136 (2014) 849–859

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Future prospects for nuclear power in France

Nadia Maïzi *, Edi Assoumou

MINES ParisTech, Center for Applied Mathematics, 1 rue Claude Daunesse, CS 10207, 06904 Sophia-Antipolis cedex, France

HIGHLIGHTS

- Applies a bottom-up energy system optimization model to define future energy choices.
- Derive scenarios to explore different combination of nuclear policy and emission target up to 2050.
- Underline the resulting challenges in term of power capacity renewal rate and flexibility.

ARTICLE INFO

Article history:
Received 15 October 2013
Received in revised form 5 March 2014
Accepted 25 March 2014
Available online 9 May 2014

Keywords:
Power generation
Environment
Climate change

ABSTRACT

Taking different nuclear policy options from a French perspective, we look at the issues that we were able to pinpoint thanks to the TIMES-FR model. The technico-economic analysis supported by the TIMES-FR model brings robust lessons, whichever technological options are selected:

- The cliff effect puts the French system “up against the wall”: sustained investments must be made to renew electricity production facilities coming to the end of their lives.
- This situation opens up opportunities to all industrial channels, with the main challenge being to sustain an ambitious pace of constructing new capacities and answering specific questions for each of them, such as acceptability and reliability.
- In parallel, the current paradigm of increasing electricity consumption is likely to be challenged over the coming decades if environmental issues are still part of public policy.
- These factors make it possible to consider that the question of political options in terms of long-term energy cannot be restricted to a technological choice and must go beyond pro- or anti-nuclear lobbying.

This contribution, which is mainly based on a technical thought process, should fit into the wider framework of a debate on society and behavior choices. The issue of the electricity user will be unavoidable.

1. Introduction

This paper explores the challenges raised by future alternative nuclear power policy in the unique context of today’s French power mix. The French electricity sector relies on the highest share of nuclear energy in the world: in France, 76% of electricity supply comes from nuclear power plants (see chart Fig. 1), which makes the French electricity generation structure unique. Hydropower is the second largest contributor to electricity generation, at 11%. Fossil power plants (half coal, half gas and oil) account for a mere 9% and are mainly used for peak and system operation.

Nuclear power replacement strategy will be a major issue in the future, as we can see by looking at the lifespan of the residual capacities from 2000 to 2050: Fig. 2 provides an aggregate view of the residual capacity evolution used for the model.

As the power sector is characterized by low emission levels, the future electricity generation mix and the share of nuclear energy constitute major issues. This future mix for electricity generation has to be assessed in a context involving numerous environmental constraints reinforced by the Fukushima triple disaster. Indeed, several countries already to envisaged to decrease their share of nuclear (see in Fig. 3 the share of nuclear power output for a set of countries). To understand the specific position of France, it is worthy to review some of these low nuclear transition scenarios.

The most striking case is the nuclear transition under emergency conditions in Japan. Before the Fukushima accident, 29% of

* Corresponding author. Tel.: +33 497157079; fax: +33 497157998.
E-mail address: nadia.maizi@mines-paristech.fr (N. Maïzi).

http://dx.doi.org/10.1016/j.apenergy.2014.03.056
0306-2619/

Nomenclature

ETSAP	Energy Technology Systems Analysis Programme
IEA	International Energy Agency
TIMES	The Integrated MARKAL-EFOM System
TIMES-FR	TIMES France
TSO	Transmission System Operator
RTE	The French TSO
NEEDS	New Energy Externalities Developments for Sustainability, FP6 European project.
RES2020	Monitoring and Evaluating the RES Directives implementation in EU-27 and policy recommendations, Intelligent Energy for Europe program.
WEO	World Energy Outlook

Japan's electricity generation was supplied by nuclear power making the country the third largest nuclear power producer worldwide behind the United States and France. By the end of 2013, all plants had been shut down. The components of this emergency response [2] included conservation measures, reactivating closed thermal plants and massive replacement by natural gas. Portugal-Pereira and Esteban [3] analyzes the implications of four-long term scenarios by 2030 covering different nuclear and renewable strategies and stresses the potentially adverse impacts of a zero nuclear scenario on imported fossil fuel dependency and GHG emissions. Fukushima's reactor meltdown also triggered a strong shift in Germany's nuclear policy, putting a stop to discussions on a possible lifetime extension and reactivating the anticipated phase-out plan decided in 2000. While nuclear accounted for 28% of electricity production in 2010, a complete phase-out is planned for 2022. Bruninx et al. [4] review this process and analyze the 2022 mix. This study focuses in particular on the preferential replacement by coal and lignite and stability issues both in terms of congestion on the German transmission grid and import/export conditions. Schmid et al. [5] analyzes 10 long-term scenarios that combine a nuclear phase-out by 2020 with 2050 mitigation objectives. They highlight a rapid growth in solar and offshore wind plants and discuss the potential shift from net exporter to massive electricity importer in most scenarios.

Belgium has one of the highest shares of nuclear power in the world and is also phasing out nuclear by 2025. The Belgian process has been similar to the German one, with the end of lifetime extension discussions and the reactivation of a 2003 phase-out plan. Kunsch and Friesewinkel [6] propose a 2050 view of alternative scenarios. They find CO_2 emissions increase by +30% to +312%, with only nuclear reactivation or a massive imports leading to a decrease. They consider imports from France with costs similar to domestic nuclear power production based on today's sufficient cross-border transport capacity.

In comparison, the UK is a European exception, with strong government support for nuclear power as a key element of its future energy transition. [7] provides a complete overview of today's actors and an ongoing discussion on creating 15.6 GW of new capacity in the UK. For the long term, [8,9] have evaluated transition pathways for the UK's electricity sector to move towards an almost decarbonized system in 2050. Using existing scenarios [10] and [11] provide an LCA and a water assessment of electricity transition in the UK by 2050. The authors converge in their findings or assumptions of significant nuclear growth, with the exception of one scenario that assumes a 7.5% decrease in electricity demand by 2050 compared to 2009 along with a massive development of CHP and wind.

Finally, we consider the US case, in which the expansion of nuclear power is currently threatened by market-based difficulties associated with the abundance of cheap unconventional gas. Byers [12] describes the decommissioning of existing plants new reactors and a regulatory environment. Sarica et al. [13,14] propose differentiated 2050 electric system scenarios for various mitigation strategies. Their results consistently point to the decisive role of natural gas in shaping the future US electricity mix and creating the stability to reduce contribution of nuclear power.

For France, the long-term environment target, specified in an energy orientation law dated March 2005, is to quarter total GHG emissions by 2050 with respect to 2000 levels. Beyond 2012, the main goal of the European Union's energy package for climate protection has been stated as a firm independent commitment to achieving a reduction of at least 20% in GHG emissions by 2020 compared to their level in 1990.

In this study we propose to assess, at French level, the issues regarding different nuclear policy options pinpointed using the TIMES-FR model which belongs to a category of technological models (bottom-up). Thus, we propose to explore the challenges involved by future alternative nuclear power policy in the unique context of today's French power mix. Section two defines the statements of the TIMES family of models as bottom-up partial equilibrium models and how they may guide energy strategy, namely in the electricity sector and with regard to nuclear power. In section three, we describe the hypothesis adopted for the assessment exercise in order to model the French electricity sector, using a

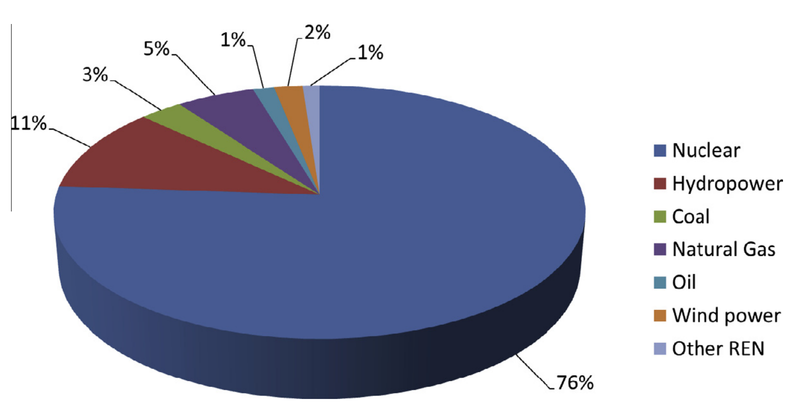

Fig. 1. Breakdown of electricity generation.

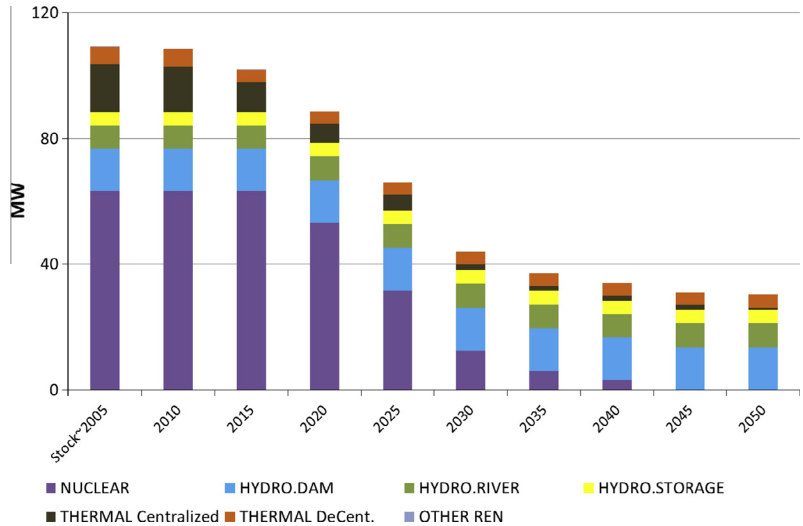

Fig. 2. Evolution of residual capacities from 2005.

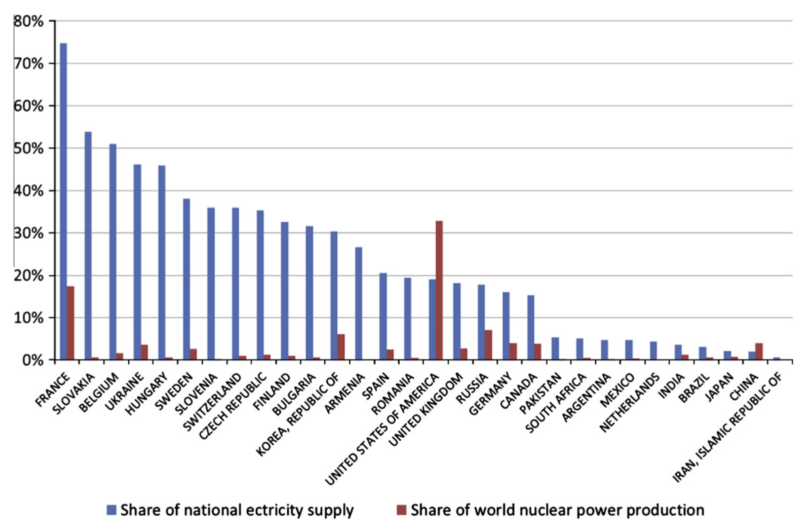

Fig. 3. Share of nuclear energy in different countries: data source [1].

long-term approach. Then in section four we discuss the modeling results based on specific demand scenarios and hypotheses for a nuclear future. Specific features related to the quality of power supply are also presented. In our fifth and final section, we conclude with the main lessons of this assessment approach, and introduce the point of view of the final consumer.

2. A prospective approach for the electricity sector

2.1. TIMES-FR model

TIMES models are prospective tools used to obtain normative information from analyses of scenarios reflecting different policies, measures or incentives. They belong to a family of optimization software programs developed by the IEA in the early 1980s to examine the mid- or long-term impact of production, transformation and demand technologies in the energy sector. This has since become the subject of the IEA's development program, ETSAP (Energy Technology Systems Analysis Program). The models are used by 80 institutes in 37 countries [15]. Since its creation, the model's basic methodology has been adapted to problems in the energy sector (e.g. trans-boundary exchanges, life-cycle analysis, assessment of demand, etc.) [16].

In its basic version, TIMES is a technical 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 discounted global cost, with decisions depending on the choice of technology activity level and capacity investments. Over a horizon of several decades, these models optimize the discounted cost (technical, economic or environmental) of a technico-economic representation of the French energy system under a demand satisfaction constraint. A full documentation of TIMES and MARKAL model generators is provided in [17–19] while various thematic and geographical scale applications can be found in [20–22]. For the country-scale studies reviewed in (Section 1), [8,13] used a similar methodology. TIMES-FR focuses on the French energy system.

The sectors that we want to analyze are considered as chains of transformations undergone by primary energy resources with the aim of satisfying different final demands for services. The energy chain is described both upstream (production and energy supply) and downstream (economic sectors using final energy), including all intermediary sectors that consume or produce

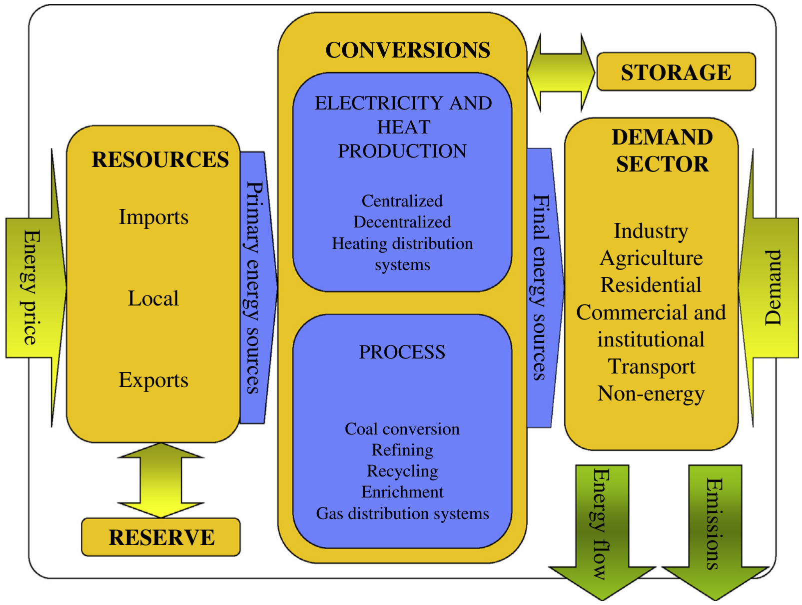

Fig. 4. The reference energy system.

energy, as shown in Fig. 4. In this diagram, a technology is defined as a convertor of "energy vectors" and associated with each stage of transformation.

This approach allows us to create a virtual economy in which the different technologies can compete. Concretely, the explicit formulation of input–output relationships for each technology means that, for a chosen horizon (30–50 years) and a given final demand, we can minimize the discounted overall cost and obtain the levels of activity and corresponding investments. Over the chosen horizon for TIMES modeling, a group of time periods of equal length (multiples of one year) is defined. The characteristics of the technologies can evolve from one period to another. As a result, any technological progress can be taken into account (improved yield, diminished costs, etc.).

Once the technologies have been informed and connected together, it is possible to attain a group of linear equations for each period, linking the activities to each of the technologies. These are the system's energy equilibrium equations. Among them, we can distinguish those equations that bring demand (demand is exogenous in the majority of TIMES versions). The latter equations, interpreted as "constraints through demand" render TIMES "a partial equilibrium model piloted by demand" [23–24].

2.2. The specific case of electricity

Electricity production has a particular position in TIMES. The TIMES electricity model (strictly speaking TIMES-FR_ELEC but referred to as TIMES-FR for the rest of this document) has thus been devised to best reflect the dynamics of the electricity system. Our aim is to capture load fluctuations, which turn out to be significant, even for some base load technologies like nuclear power. Thus, we ascertain that the maximum fluctuation over one year can be as high as 16 GW, as shown by this curve constructed from RTE (French TSO) data (see Fig. 5).

Thus, in order to take into account production peaks and more generally power variations, each period is split into 72 time slices, corresponding to:

- 6 seasons: every two months.
- 2 periods of the week: days of the week/weekend.
- 6 "intradays": 2 nighttime periods (N1 & N2), 2 daytime periods (D1 & D2), one peak (*P*) and one minimum point (*L*).

The basic functioning of TIMES is taken as uniform production, both night and day (pumping at night and releasing water during the day, etc.), with a peak participation coefficient (essential for renewable energy sources[1]). These coefficients, which are linked to obligatory capacity reserves for peak periods and to certain constraints defined by the user (e.g. the imposition of minimal reactive means), make it possible to create a realistic simulation of the generation system and to ensure that electric equilibrium is attained in each time slice.

2.3. A technico-economic optimizer

In addition, each technology is linked to its programmed capacity at the start of the horizon, to its lifespan and, for each period, to three costs: an annual investment cost, a fixed cost (annual maintenance, taxes, etc.), and a variable cost (fuel, maintenance, taxes, etc.). The cost of a technology over a given period therefore appears as the sum of these three costs, respectively counterbalanced by the decision variables: programmed capacity, investment and activity. If we observe that the programmed capacity at a given moment is the sum, over the equipment's lifespan, of capacity investments and residual capacity, we can derive the energy system's global cost as a linear combination of activities and investments over the whole horizon. This cost minimization provides capacity investments for each technology as decision variables.

The technico-economic optimum is solved as a classic problem of linear programming, i.e. the minimization of the system's discounted global cost over the model's horizon, while respecting: the constraints of the problem, the model's inherent constraints (equilibrium of energy vectors, satisfaction of demand, peak capacity reserve, activity/capacity constraints, etc.), and possible constraints defined by the user (environmental constraints, regional specificities, etc.). As well as providing levels of activity and investment, and the cost of each technology at a given time, TIMES

[1] For hydraulic and wind power, we use a maximum load per season.

supplies the marginal associated cost for each constraint (i.e. the increased cost when a unit's constraint is relaxed, all things being equal elsewhere), and the reduced costs for unused technologies (i.e. a reduction in cost that allows an unselected technology to participate).

The above-mentioned developments illustrate, on the one hand, the generality of the notion of "energy vector", which is TIMES's strength in so far as all scales can be envisaged, and on the other hand, the importance of an adequate technological database for handling the chosen technological and sectoral disaggregation.

3. Application to the French electricity production sector

This part focuses on an assessment of the evolution of the French electricity generation system over the 2000–2050 horizon using TIMES-FR. A reminder of the key aspects of the French electricity generation system is useful at this point. Firstly, the framework of our prospective exercises is restricted to electricity. This means that the demand satisfaction constraint is linked to exogenous, strictly electricity-based demand and that the technologies considered by the model are the only ones associated with the electric vector. However, a version of this exercise exists using our "all energy model" for France, which backs up the coherence of this exercise [25].

3.1. Evolution of electricity demand

The demand scenario chosen is taken from the RTE's July 2011 forecast and corresponds to a so-called "Reference" scenario. This is a domestic demand scenario, excluding losses, and extended to 2050, represented in Fig. 6 below.

From the reference demand scenario, we allow a fluctuation in demand impacted by two levers:

- The introduction of a price effect via an elasticity value matched to the reference scenario and fixed at −0.3, a generally accepted long-term value,[2] meaning that a price rise of around 10% will generate an average 3% drop in the quantity consumed,
- An authorized fluctuation in export levels, fixed at 70 TWh in 2010, and valued at €40 to €50/MWh over the horizon[3]: if the marginal production cost of electricity is above this value, then exports are no longer profitable, and the model does not allow them.

3.2. Evolution of current facilities: the nuclear option

Contrasted scenarios are commonly used to explore future technology choices. The key driver considered for France is the replacement rate of nuclear power stations since, as outlined in the literature review, this is directly associated with the issue of lifetime extension. In 2012, two government-commissioned reports were published related to nuclear power: one by the Court of Audit [26] focusing on cost issues, and one by an energy commission [27] on the strategic implications for 2050. The options considered by this commission included low nuclear futures assuming a strict 40-year lifetime or a partial extension to 60 years with revamping costs. In the current analysis, produced as a support to this commission, the core pilot group specified three replacement options. This led us to evaluate three scenarios associated with different future options for the nuclear industry:

- *{Fast exit = FAST}:* lifespan limited to 40 years, non-replacement of power stations, shown in blue in Fig. 7 below.
- *{Progressive exit = PROG}:* lifespan limited to 40 years for one reactor out of two, prolongation for the others to 60 years at an additional cost of 600 M euro/reactor, shown in green in Fig. 7 below.
- *{Maintenance = BAU}:* nuclear capacity maintained at 65 GW (lifespan extended to 60 years for existing stock then replacement when necessary), shown in red in Fig. 7 below.

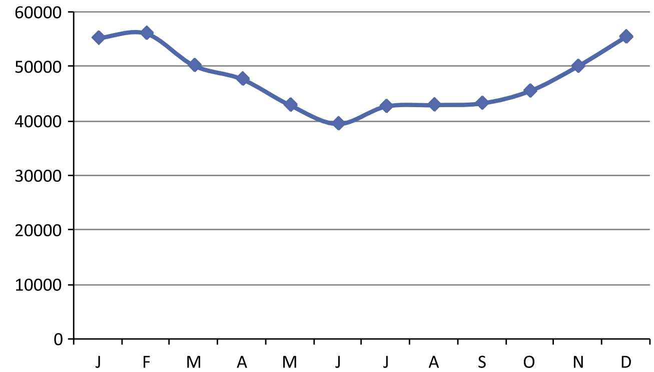

Fig. 5. Monthly average nuclear power contribution in MW.

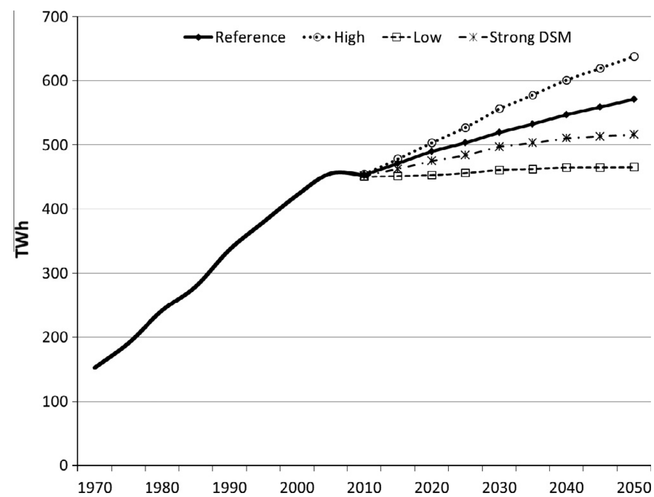

Fig. 6. Domestic electricity demand excluding losses according to RTE's 2011 forecast.

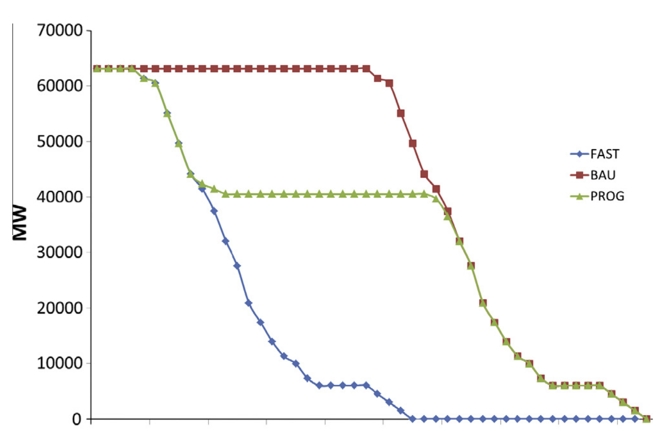

Fig. 7. Profile of evolution of installed nuclear capacity.

[2] The level widely used in econometric literature for electricity price/demand elasticity varies between −0.4% and −0.2%.

[3] In line with values given by the energy balance for France for 2009.

Table 1
Price of imported primary resources.

		2010	2020	2030	2040	2050
($/boe)	Oil	60.4	99	110	117.2	125.2
($/MBTU)	Gas	7.4	11.6	12.9	13.8	14.9
($/ton)	Coal	97.3	101.7	105.6	107.7	110

3.3. Constraints associated with CO_2 emissions

Two types of penalty are envisaged to limit CO_2 emissions:

- *Through pricing:* a penalty calibrated at levels compatible with the ETS market: from €20 to €50/tCO_2.
- *Through quantity:* the preceding penalty is used to calibrate emissions by volume in the "maintain nuclear" scenario. Thus, all scenarios have the same upper cap.

3.4. Primary resource prices

We use exogenous price and exogenous cost hypotheses drawn up by reference organizations to reflect a variation over time (see Table 1).

(WEO 2010 scenario,[4] "new policies" extended to 2050. In constant $ 2009.)

3.5. Costs of technology investments

The costs of the various means of electricity production constitute an important element in the prospective evaluation of the structure of electricity facilities. For the specific scope of France, the reference costs for centralized and decentralized production means were published from 2003 to 2004 by the DGEMP (general department for energy and primary resources) and are the most recent comprehensive public references available. These reference costs were updated in 2008 by the DGEC (general department for energy and climate) at a less-detailed level. However, in both cases, technologies such as carbon capture and sequestration are not envisaged and long-term evolution is not proposed.

At the same time, a large number of publications from different groups and institutions round the world have suggested values for these investment costs, based on calculation methods that are not always explicit. The variation is considerable, even when dealing with the same type of costs.

In addition, a significant rise in the cost of real projects has been observed over recent years, bringing into question the trend, based on the learning principle, which argues for a decrease in technology investment costs over time. We might also question the cyclical character of the driving factors behind this increase, e.g. rise in the price of raw materials, more restricting norms, or pressure on the engineering market. Thus, it is difficult to anticipate which trend the coming years will confirm: it could be, for example, that the cyclical effect of overstocks combined with the abandon of several projects due to the economic crisis, results in a new downward trend.

Despite these difficulties, the relative structure of costs in a normative vision remains a crucial hypothesis. The investment costs of electricity production means used in this study were taken from research projects on which we have participated in the past (in particular the European projects NEEDS and RES2020) and have been widely reexamined through an extensive review of other publications on the subject. More details on the methodological approach used are provided in [25].

The variable costs of the nuclear industry include dismantling costs.

[4] Global price for oil, European price for gas, OECD price for coal.

Table 2
Full set of scenarios chosen for the prospective electricity exercise.

Scenarios	CO_2	Demand	Nuclear policy	Common assumptions
BAU	Tax	Reference	65 GW maintained	Prices: WEO 2010
PROGt1	Tax	Elastic	Phase out (40-year lifespan)	Reference demand: RTE
PROGv1	Tax + cap			
FASTt1	Tax		Phase out (60-year lifespan)	Electricity exports: variable
FASTv1	Tax + cap			

4. Results of prospective electricity exercises

The following table (Table 2) sums up all five prospective exercises carried out and the hypotheses on which they are based.

4.1. Mix of electricity production

The first three scenarios evaluated, BAU, PROGt1 and FASTt1, are subject to a single CO_2 penalty, and therefore illustrate the impact of nuclear policies differentiated as shown in Fig. 8 below, which illustrates electricity production levels over the forecast horizon.

The conjugated effects of a nuclear exit and a penalty on CO_2 emissions, even a low onePROGt1 & FASTt1, are compensated by the use of carbon technology (given the fuel price assumption) from 2025, and a marked drop in production.[5] Note that the new fuel based technologies selected by the model are of an IGCC type (integrated gasification combined cycle), i.e. they respect the GIC directive (major combustion installations) that is already respected by existing fluidized bed combustion technologies. The departure observed in 2025 translates the cliff effect that occurs at the end of the nuclear power plants' lifecycles, slightly attenuated in the hypothesis of a progressive exit. At the end of the horizon, CSS (carbon capture and sequestration) becomes an interesting option (because the level of emissions of the CCS + Coal combination moves closer to that of gas only[6] at a lower cost).

The volume of CO_2 emissions associated with electricity production in each of the three scenarios BAU, PROGt1 and FASTt1 on the forecast horizon is shown in the figure below. As mentioned above, it is calibrated on the level of emissions of the BAU, or "maintenance" scenario, in order to constrain the volume of the other scenarios. The values of the blue line can now be taken to be limit values of emissions from the electricity production sector in Mt.

We can observe a significant increase in CO_2 emissions for both nuclear exit scenarios, corresponding to three times the level of the BAU level for a progressive PROGt1 exit and five times the level for a rapid FASTt1 exit.

This would imply that a simple penalty on CO_2 emissions, without any additional measure, does not limit electricity production emissions for the exit scenarios (PROGt1 and FASTt1) to the level of the maintenance scenario (BAU). An additional limitation constraint by quantity is therefore introduced into the TIMES-FR model and leads to the two scenarios, PROGv1 and FASTv1. The emission ceiling is referenced by the level of emissions of the BAU scenario (Fig. 9, blue line).

The impact of an additional constraint on volume allows less effective compensation of the cliff effect. The competition between fossil resources is to the advantage of gas in the fast exit scenario FASTv1, with CCS gas at the end of the horizon. For the progressive exit option, PROGv1, the CCS coal combination comes out best in

[5] Permitted by the hypothesis of elasticity on demand.
[6] Which rises sharply (doubles) over the period as seen in Table 2.

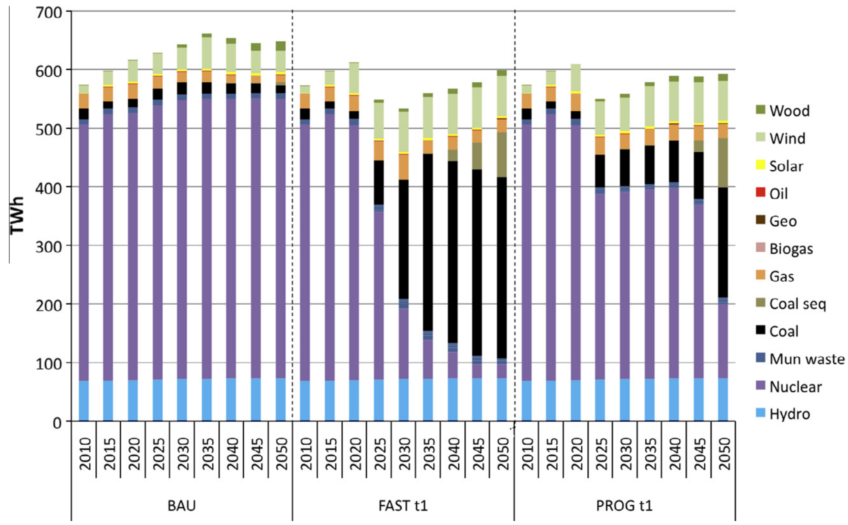

Fig. 8. Mix of electricity production obtained from TIMES-FR for the 3 nuclear policy options with a penalty on CO_2 emissions.

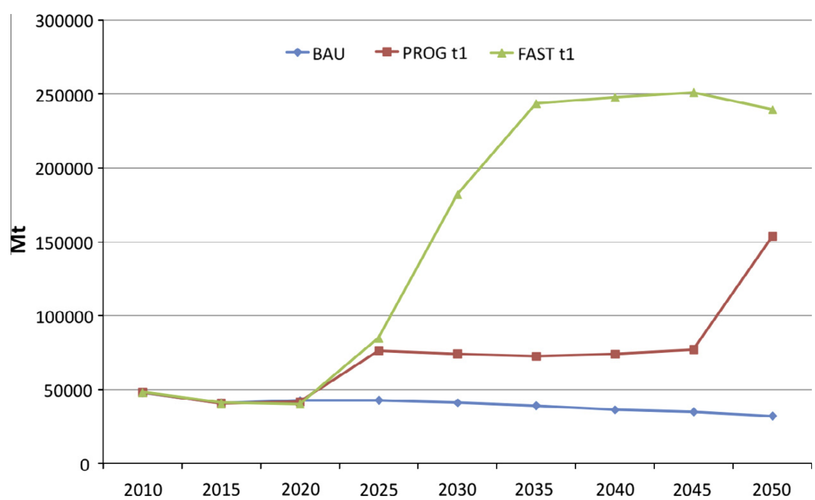

Fig. 9. CO_2 emissions associated with electricity production for the 3 scenarios.

2050. For both exit options, there is a high penetration of wind and solar energy during the time period; thus, the share of renewable energies evolves (see Fig. 10):

- In 2030, it is 18% for BAU, 43% for a fast exit FASTv1 and 28% for a progressive exit PROGv1.
- In 2050, it is 20% in the BAU, 55% for a fast exit FASTv1 and 50% for a progressive exit PROGv1.

4.2. Export fluctuations

In addition to decreased demand, we observe that the potential for reducing exports is exploited: in all scenarios, exports go down more or less rapidly and totally disappear at the end of the horizon, reflecting the rise in the marginal production cost of electricity over the horizon and reducing the domestic demand/installed nuclear capacity ratio. In both of the options that limit CO_2 emissions, the rate of the decrease in exports is identical when only the penalty is applied (Fig. 11) and when a volume constraint is added (Fig. 12). For the nuclear exit scenarios, exports practically disappear from 2025, which brings up the question of the European network's future dynamic equilibrium since France is the largest net exporter in Western Europe.

4.3. Capacity investments

The different scenarios induce sustained capacity investments over the horizon to compensate for the cliff effect corresponding to the decommissioning of the French electricity production system, as translated by the results of installed capacities in all scenarios of the prospective exercise. The total cumulated capacity investments over the horizon for each scenario are represented in Fig. 13 (excluding representation of a 60-year power station extension).

The market for building power stations expands significantly. The additional GW that need to be installed compared with BAU increase in line with Fig. 13:

- By 16% in the case of a progressive exit with a penalty on emissions.
- By 33% in the case of a rapid exit with a penalty on emissions.

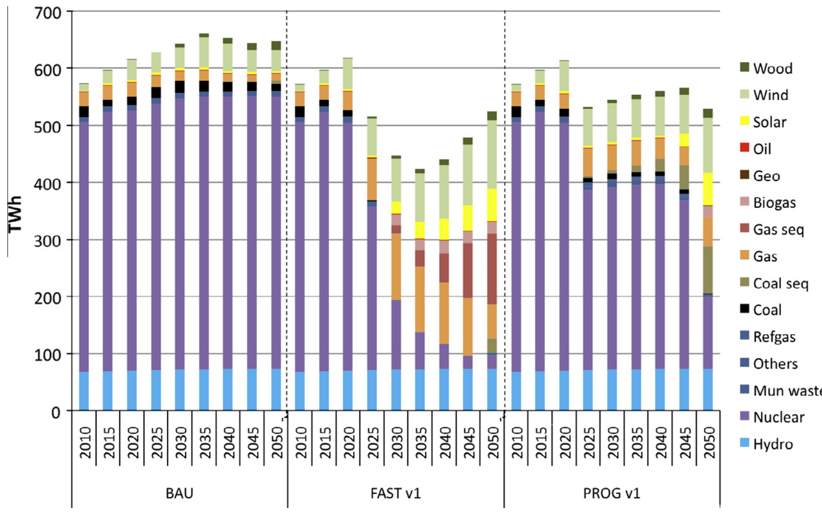

Fig. 10. Mix of electricity production obtained from TIMES-FR for the 3 nuclear policy options with a penalty on CO_2 emissions and quantity limitation captured by the BAU.

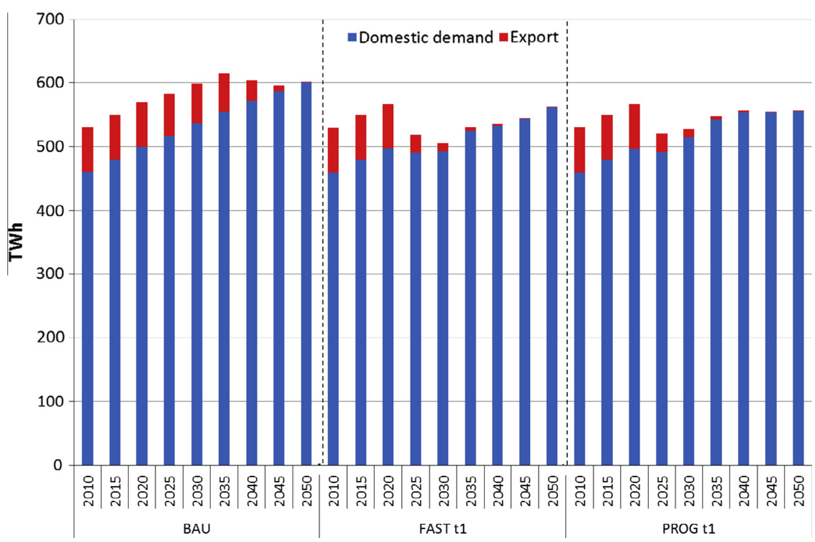

Fig. 11. Share of exports in the electricity production mix obtained from TIMES-FR for the 3 nuclear policy options with a penalty on CO_2 emissions.

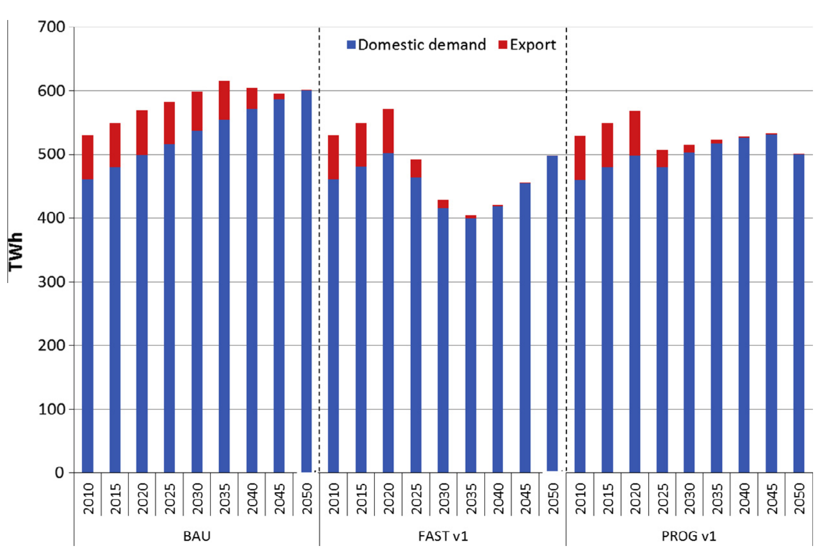

Fig. 12. Share of exports in the electricity production mix obtained from TIMES-FR for the 3 nuclear policy options with a penalty on CO_2 emissions and a quantity restriction.

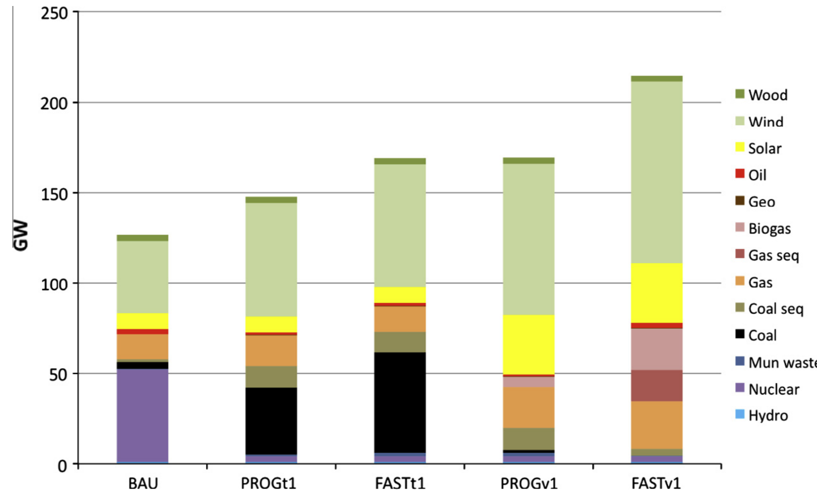

Fig. 13. New installed capacities cumulated over the horizon (excluding 60-year extensions of nuclear capacities for BAU and PROGxx scenarios).

- And when the volume constraint is added, by respectively 33% and 70%.

Thus, in all cases, the level of investment that needs to be agreed to satisfy the reference demand of the 2011 forecast is considerable and should be made at a steady pace to reflect the need to replace almost all of the current electricity production facilities. This induces intensive equipment construction phases. For wind power, for example, a total exit leads to an average 3 GW installed per year[7] during the decades 2030–2040 and 2040–2050 (to be able to increase and replace existing wind capacities that will be decomissioned). Over the same period, the rate would be 1 GW/year for solar power, 890 MW/year for biogas, and 900 MW/year for CCS (gas and coal).

We can observe that the levels of investments in new installed capacity are not as high for the BAU scenario in Fig. 13 as for the 4 nuclear exit scenarios, PROGxx and FASTxx, where the latter need to satisfy a demand diminished by the price effect (elasticity). This shows that in the exit options, we need to take into account that alternative production means to nuclear power have shorter lifetimes, and that the load factors of technologies based on renewable resources are not so high. In the case of nuclear exit, it will therefore be necessary to not only undertake a continuous policy of equipment renewal but to restrict electricity usage to go beyond the reference forecast scenario.

4.4. Reliability of electricity supply

Since they are developed from prospective modeling tools used for evaluating future electricity systems, results achieved using a TIMES-FR optimal prospective approach risk coming up with unrealistic solutions regarding the dynamic stability of the systems envisaged. Thus, to analyze the results further we decided to use a method [28] that allows us to assess the reliability of supplying future electricity systems. To do so, we developed two stability indicators, Hmag and Hcin, which are able to measure an electricity system's capacity to deal with an incident (fluctuation, loss of generator, etc.). These indicators measure the levels of magnetic and kinetic reserves required to procure the inertia the system needs to reestablish its stability [28]. Thus Hcin is a time expressed in seconds that measures the kinetic energy stocked in the system in relation to the system's apparent power. Hcin represents the time it takes for the stock of kinetic energy to completely run out if the entire production system is suddenly disconnected. The variation in frequency following a load fluctuation goes down as Hcin goes up, to the extent that Hcin is an indicator of the system's reliability for the frequency variation. Beyond this, Hcin is therefore an indicator for production. The second indicator, Hmag, is also expressed in seconds and measures the magnetic energy stored by Megavolt ampere of apparent power. In the same way as Hcin for kinetic energy, Hmag corresponds to the time it takes to use up the magnetic energy stores when the system's entire production suddenly stops. As a result, the measurement of magnetic energy stored in the system, Hmag, is an indicator of reliability for voltage variation. Beyond that, Hmag is therefore an indicator of transmission.

The values of these indicators are directly evaluated at the end of prospective exercises using the TIMES model, which makes it possible to easily determine whether the electric systems proposed are realistic regarding supply stability.

Indicators are calculated for each time slice corresponding to the time division of the load curve as used in the model (72 time slices). They are given in time units – seconds (s) for the kinetic reserve, milliseconds (ms) for the magnetic reserve – to indicate the time required to reconstitute each of the reserves in the case of a total production loss.

For the nuclear maintenance scenario, BAU, we can thus evaluate the evolution of the level of reliability over the horizon, as indicated by the magnetic and kinetic reserves respectively:

It is interesting to note that the indicator reveals a split resulting from the cliff effect and a pick-up towards the end of the horizon for both types of reserve.

The indicators for nuclear exit scenarios can be positioned in relation to the BAU, for example, for the summer peaks in Figs. 14 and 15 below.

We observe that the values taken by these indicators differ depending on the scenario studied, with a clear downturn over time for the nuclear exit scenarios. This indicates that the electricity systems on which the scenarios are based do not guarantee sufficient reserve levels to maintain the reliability reference level given by the BAU (see Figs. 14 and 15).

These results do not exclude the massive integration of renewable energy sources into future electricity systems but they call for a careful transition in the electricity sector. If the production mixes envisaged do not permit sufficient supply stability, then it will be necessary to either anticipate additional costs to install elements participating in magnetic and kinetic reserves (e.g. flywheels,

[7] Currently, new installed capacities reach an average 1 GW/year.

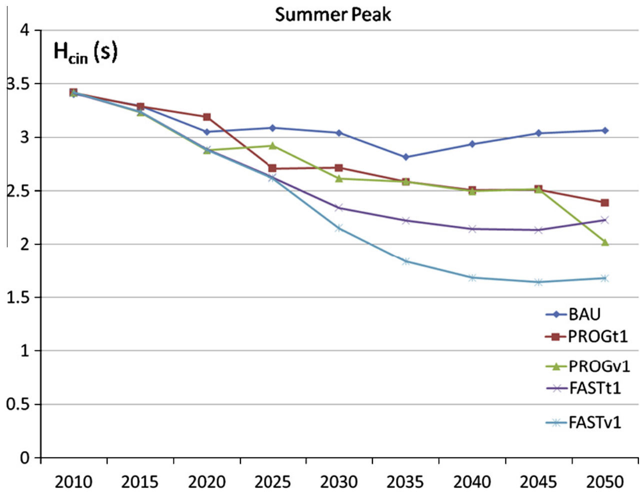

Fig. 14. Evolution of Hcin for the summer peak for all scenarios.

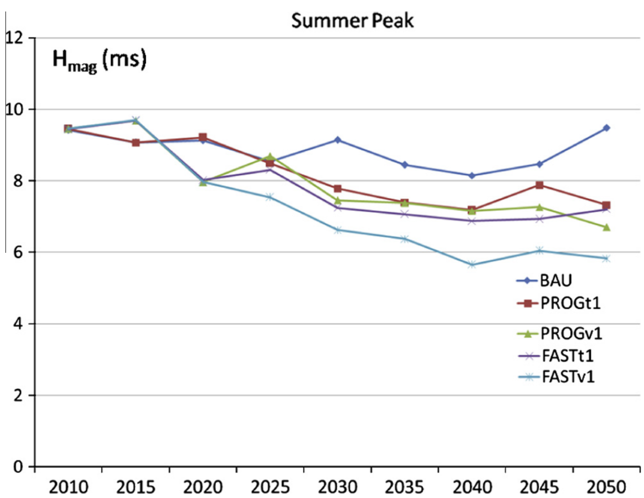

Fig. 15. Evolution of Hmag for the summer peak for all scenarios.

safety measures), or to accept a drop in stability (i.e. more regular breakdowns), in other words a decline in the service offered to users of the electricity vector.

5. Conclusion: lessons learned from the study

This study allowed us to envisage several scenarios put forward by the French Treasury. It is important to stress that numerous other scenarios could have been anticipated using this same approach, by restricting or favoring certain technologies, and integrating more or less coercive measures for managing CO_2 emissions or demand. However, the technico-economic analysis supported by the TIMES-FR model brings enduring, robust lessons, whichever technological options are selected:

- The cliff effect puts the French system "up against the wall": sustained investments must be made to renew electricity production facilities coming to the end of their lives.
- This situation opens up opportunities to all industrial channels, with the main challenge being to sustain an ambitious pace of constructing new capacities and answering specific questions for each of them, such as acceptability and reliability.
- In parallel, the current paradigm of increasing electricity consumption is likely to be challenged over the coming decades, if environmental issues are still part of public policy.
- These factors make it possible to consider that the question of political options in terms of long-term energy cannot be restricted to a technological choice and must go beyond pro- or anti-nuclear lobbying.

This contribution, which is mainly based on a technical thought process, should fit into the wider framework of a debate on society and behavior choices, with a focus on the demand side [29]. The issue of the electricity user is unavoidable.

While in France the unique starting point amplifies the challenges of transition scenarios, some of the lessons drawn are consistent with other studies:

- The first of these is preferential replacement by fossil-fueled power plants subject to no explicit mitigation targets.
- Considering CO_2 emissions objectives, a modification of import/export strategies appears to be a cost-efficient alternative. In [4,5] Germany moves from a net exporter situation to a net importer in most scenarios. The analysis of a nuclear phase-out in Belgium in [6] also highlights the need for increased imports to control GHG emissions. In this study, the preferred option is imports from France.
- Reliability issues are also questioned, although mostly from a transmission capacity point of view. Bruninx et al. [4] identify several congestion issues in Germany as early as 2017 related to both cross-border capacities and within the German transmission grid. In [14] the clean energy standard scenarios rely on a low nuclear and high renewable electricity mix. However, the required multiplication by 3–6 times of the transmission grid in the next 40 years is identified as the main barrier.

Acknowledgement

This research was supported by the Modeling for sustainable development Chair, led by MINES ParisTech, Ecole des Ponts ParisTech, AgroParisTech, and ParisTech, supported by ADEME, EDF, RENAULT, SCHNEIDER ELECTRIC and TOTAL.

References

[1] http://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx. February 15th 2014.
[2] Hayashi M, Hughes L. The policy responses to the Fukushima nuclear accident and their effect on Japanese energy security. Energy Policy 2013;59:86–101.
[3] Portugal-Pereira J, Esteban M. Implications of paradigm shift in Japan's electricity security of supply: a multi-dimensional indicator assessment. Appl Energy 2014;123:424–34.
[4] Bruninx K, Madzharov D, Delarue E, D'haeseleer W. Impact of the German nuclear phase-out on Europe's electricity generation. Energy Policy 2013;60:251–61.
[5] Schmid E, Pahle M, Knopf B. Renewable electricity generation in Germany: a meta-analysis of mitigation scenarios. Energy Policy 2013;61:1151–63.
[6] Kunsch PL, Friesewinkel J. Nuclear energy policy in Belgium after Fukushima. Energy Policy 2014;66:462–74.
[7] Nuclear Power in the United Kingdom. http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/United-Kingdom/ [February 15th 2014].
[8] Anandarajah G, Strachan N. Interactions and implications of renewable and climate change policy on UK energy scenarios. Energy Policy 2010;38:6724–35.
[9] Foxon TJ. Transition pathways for a UK low carbon electricity future. Energy Policy 2013;52:10–24.
[10] Hammond GP, Howard HR, Jones C. The energy and environmental implications of UK more electric transition pathways: a whole systems perspective. Energy Policy 2013;52:103–16.
[11] Byers EA et al. Electricity generation and cooling water use: UK pathways to 2050. Global Environ Change 2014. http://dx.doi.org/10.1016/j.gloenvcha.2014.01.005.
[12] Nuclear Power in the USA. http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/USA–Nuclear-Power/ [February 15th 2014].
[13] Sarica Kemal, Tyner Wallace E. Alternative policy impacts on US GHG emissions and energy security: A hybrid modeling approach. Energy Economics 2013;40:40–50.

[14] Logan Jeffrey, Lopez Anthony, Mai Trieu, Davidson Carolyn, Bazilian Morgan, Arent Douglas. Natural gas scenarios in the U.S. power sector. Energy Economics 2013;40:183–95.
[15] ETSAP (Energy Technology Systems Analysis Programme). http://www.etsap.org.
[16] Goldstein GA, Greening LA. Energy planning and the development of carbon mitigation strategies: using the MARKAL family of models. IAE Partners, International Resources Group, 1211 Connecticut Avenue, NW Suite 700, Washington DC 20036; 1999.
[17] Loulou R, Goldstein G, Noble K. Documentation of the MARKAL family of models. Energy Technol Syst Anal Prog 2004.
[18] Loulou R, Remme U, Kanudia A, Lehtila A, Goldstein G. Documentation for the TIMES model (Parts I to III). Energy Technol Syst Anal Prog 2005.
[19] Loulou R, Labriet M. ETSAP–TIAM: the TIMES integrated assessment model Part I: model structure. CMS 2008;5(1):7–40.
[20] Gracceva Francesco, Zeniewski Peter. A systemic approach to assessing energy security in a low-carbon EU energy system. Original Research Article Applied Energy. in press, corrected proof, 10 January 2014.
[21] Seck Gondia Sokhna, Guerassimoff Gilles, Maïzi Nadia. Heat recovery with heat pumps in non-energy intensive industry: A detailed bottom-up model analysis in the French food & drink industry. Applied Energy 2013;111(November):489–504.
[22] Comodi G, Cioccolanti L, Gargiulo M. Municipal scale scenario: analysis of an Italian seaside town with MarkAL-TIMES. Energy Policy February 2012;41:303–315.
[23] Berger C, Dubois R, Haurie A, Lessard E, Loulou R, Waaub J-P. Canadian MARKAL: an advanced linear programming system for energy and environmental modelling. INFOR 1992;30(3).
[24] Fishbone LG, Abilock H. MARKAL, a linear programming model for energy systems analysis: technical description of the BNL version. Int J Energy Res 1981;5:353–75.
[25] Maïzi N, Assoumou E. Scénarios prospectifs France à l'horizon 2050. Working paper no. 2012-02-05. <www.modelisation-prospective.org>.
[26] Cour des comptes. The costs of the nuclear power sector, Thematic public report (PDF, 3,36 MB) – Janvier 2012 http://www.ccomptes.fr/Publications/. February 15th 2014.
[27] Jacques PERCEBOIS, Claude MANDIL. Rapport Energie 2050, Février 2012. http://www.strategie.gouv.fr/system/files/rapport-energies_0.pdf/ [February 15th 2014].
[28] Maïzi N, Drouineau M, Mazauric V. Impacts of intermittent sources on the quality of power supply: the key role of reliability indicators. Appl Energy 2014;116(1):333–43.
[29] Mackay RM, Probert SD. Crude oil and natural gas supplies and demands up to the year 2010 for France. Appl Energy 1995;50(3):185–208.