THREE INVESTMENT SCENARIOS FOR FUTURE NUCLEAR REACTORS IN EUROPE

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ABSTRACT

While nuclear power may experience a technological breakthrough in Europe with Generation IV nuclear reactors within a few decades (2040), several events and drivers could question this possibility, e.g. the Fukushima accident, climate issues and liberalization of the electricity market.

This article analyzes how the conditions necessary for their industrial development from now up to 2040 can be either favorable or detrimental to future nuclear reactors compared with other technologies and according to four main investment drivers: 1) technical change, 2) policy, 3) market, and 4) power company drivers.

Twenty-four scenarios have been identified through structural analysis, with only three proving to be favorable to the development of future nuclear reactors.

KEYWORDS

Power System Economics, Electricity Investments, Nuclear Energies

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I. INTRODUCTION

In a context of post-Fukushima nuclear development and climate protection, this article addresses the issue of investment in future nuclear technologies in Europe, focusing in particular on Generation IV nuclear reactors or fast reactors (FR). The MIT publication called *The future of nuclear power after Fukushima* (Joskow and Parsons 2012) reports the expected growth of nuclear power in the world fleet (1% per year through 2035 in OECD countries and 6% per year in non-OECD countries through 2035). This report states that nuclear growth will not be significantly reduced, except in Germany, Japan and Switzerland, thus an increase in the consumption of natural uranium can still be expected. This nuclear growth and carbon reduction measures such as those detailed in the *European Climate Action and Renewable Energy Package* (Da Costa *et al.* 2009) could make FRs a viable choice for further electricity generation capacities.

This technology based on fast neutrons instead of thermal neutrons uses natural uranium more effectively. It could ensure several thousand years of nuclear generation, whereas identified resources in uranium only allow for about one century of generation with thermal neutrons reactors (OECD and IAEA 2012). Yet, the thermal neutron technology represents the most common technology in use. It is the predominant technology used for Generation II reactors which represent the majority of reactors currently in operation in the world. This technology has also been chosen for Generation III reactors that are currently under construction in France (Flamanville), Finland (Olkiluoto) and China (Taishan). Generation IV is still in its research & development stage in several countries such as France, Russia, India and China. Other than the improved use of natural uranium, FRs are capable of recycling both the plutonium it uses and that produced by fuels from thermal neutrons reactors. FRs contribute to long-term waste management thanks to the transmutation of minor actinides.

The industrial deployment of this technology is expected to be possible from 2040, at least for the French FR given its maturity and the objectives of the French research program (Ministère du Développement durable 2013). The question is to assess the potential penetration of this technology on the European market within this timescale: despite its attractiveness, the context may be unfavorable because of the uncertainties that liberalization brings to the electricity market regarding prices and pricing, sector organization, corporate structures, etc. (Rogner and Langlois 2001). The changes in the generation mix and the potential integration of FRs into this mix from 2040 also depends on many other factors such as climate and energy policies. In the end, however, is it determined by the power generation companies who decide to invest in new capacities in order to replace their ageing capacities and to satisfy the growing demand. This is why we have chosen to focus on investors, i.e. power generation companies, and to analyze their behavior regarding investments in generation capacities in general and not specifically in the nuclear sector.

This article therefore examines two research issues: 1) The drivers pushing power generation companies' decisions to invest in new capacities on the European electricity market, and 2) The impact of these decisions on the development of the European generation mix and the integration of FRs.

We focus on France, Germany, the United Kingdom, Spain and Italy since they represent 65% of European Union (EU27) power generation (Grand and Veyrenc 2011). The timescale is fixed to approximately 2040 considering that most reference scenarios are situated between 2030 and 2050. Since we aim to cast light on the future according to today's most certain data, the panel of technologies considers those most commonly used on an industrial scale and disregards technologies that are not yet fully developed such as biomass, geothermal energy, carbon capture and storage (CCS), as well as small modular reactors (SMR) in the nuclear field.

Our analysis identifies three key drivers: 1) policy (divided into climate policy and nuclear policy), 2) technical change and 3) market drivers; that are behind the choices of investors and construction scenarios for the European generation mix based on the development of these drivers in the future. Our structural analysis shows that the market driver proves negligible compared with the two others and that business-as-usual scenarios are not favorable to FRs. Climate policy appears to be the *sine qua non* condition for further nuclear development; this is why both strong and moderate pro-nuclear policies are compatible with FR investment in the "climate constraint" scenarios where nuclear is the only economically viable alternative. The "totally green" scenarios combined with a strong pro-nuclear policy assumption are also favorable to FRs in a context of flourishing renewables. Three scenarios favorable to FR investment have thus been identified regardless of the market driver; that is to say, they combine the necessary conditions for FR investments.

The article is divided in three parts. Firstly, Section II provides a literature review describing the common academic approaches to electricity investments and explaining the choice of a strategic foresight methodology to answer our research issues. Secondly, the methodology itself – structural analysis – is presented and applied in Section III. In this section, the three key drivers are identified on the basis of a literature review and interviews with experts; each driver is described by several variables, and the interactions between variables are analyzed and quantified. Thirdly, Section IV describes scenarios for the future generation mix which are built on a couple of low/high assumptions for each driver. The interactions between variables have been processed with the structural analysis software called MICMAC (Godet 2008, 2001, 2000) in order to assess the relative importance of the different variables and to rank the scenarios. To conclude, the most favorable scenarios for the penetration of Generation IV nuclear reactors are identified and discussed in Section IV.

II. LITERATURE REVIEW

A. Investment decisions in energy: short-term opportunities rather than long-term strategies

The dominant economic theory used for electricity investment choices in the second half of the 20th century was the cost–benefit analysis (Chick 2007). It takes its roots in the welfare economics theories founded in the 1930s and 1940s (Hicks 1939; Pigou 1924; Samuelson 1943; Allais 1943), and became known in the early fifties (Massé 1953; Boiteux 1956). It remained the dominant academic current until the start of the liberalization process in 1986, though academics had already started to question it. With the Suez crisis in 1956, empirical research tended to show the shortcomings in the cost-benefit analysis: it became apparent that it did not include risks properly, in particular exogenous risks, like that on fuel supply (Chick 2007). Theoretically, new economics in the 1940s and 1950s addressed the issues of risk on decision makers' rationality (Friedman and Savage 1948; Neumann and Morgenstern 1944). These theories were expanded in the 1960s and 1970s by addressing the issue of public decisions in uncertain environments (Arrow 1965; Henry 1974; Weisbrod 1964). In the context of a liberalized market cost-benefit analysis, it was still a classic tool for electricity investment choices: shorter payback periods and higher rates of return were considered (Bibas 2011).

History shows that the cost-benefit analysis led state choices about electricity investments mostly in France and partly in other European countries, but it tended to be forgotten in times of crisis (Suez Crisis, oil crises) in favor of national security of supply or national employment protection (Chick 2007). Cost-benefit analysis was thus an efficient approach to introduce economic rationality into choices, but not the appropriate tool to describe investment choices in a realistic manner. Indeed, long-term economic rationality is neither the only driver, nor the main one for investment choices. Choices can been seen and considered on two levels: individual or collective, and they are made according to both strategy and opportunity. This classic opposition between strategy and opportunity led to a new trend (Chabaud and Messeghem 2010) based on Venkataraman's work (Venkataraman 1997). Given that a decision-making process is faced with a context of complexity and the need for quick action, Chabaud and Messeghem argue that a decision often seizes an opportunity instead of being based on a long-term rational strategy. It is thus not the result of a precise analysis of all the parameters at stake, but of a more intuitive decision or an exploratory decision (Alvarez and Barney 2007). Chabaud and Messeghem explain this side of decision-making as a way of optimizing resources by seizing opportunities.

This latter interpretation is very consistent with the reactions observed after the oil crises in Europe. Many countries returned to using domestic coal, started new exploration for local resources or accelerated their nuclear programs, seizing every immediate opportunity to reduce energy dependence in the long term.

Since long-term economic rationality is neither the only driver nor the main one for investment choices, we thus sought to identify the actual drivers for investment behavior.

B. Prospective approaches of energy: strategic foresight methods

Our research aims at studying investment choices beyond economic rationality and taking into account such behavior in the description of the investment process. As mentioned above, there are two steps to our research problem:

- Identifying the drivers for investor decisions;
- Analyzing their effects on future changes: elaboration of scenarios illustrating future trends in a descriptive and exploratory approach (contrary to normative: there are no fixed objectives).

Such an approach clearly belongs to the field of strategic foresight, contrary to other scenario-building techniques, e.g. forecasting or fictional futures (Bland and Westlake 2013). For the first step, foresight methods usually recommend conducting interviews or creating a set of collective workshops. For the second, it is necessary to isolate the key variables influencing the system's development and to build the scenarios based on these variables. Among strategic foresight manuals and literature, the works of Godet describe a full set of tools to practice strategic foresight from problem definition to scenario probabilities (Godet 2000; Godet and Roubelat 2000; Godet 2001, 2002, 2008). Structural analysis using the MICMAC tool is one way of identifying all the drivers for a system, especially those determining its development. This method focuses on clarifying the data of the problem, which is consistent with the purpose of our study.

There are many applications of these methods to the electricity and energy fields addressing the issue of market liberalization, e.g. the work by Bergman *et al.* (2006) who built development scenarios for the business environment in the electricity industry, according to different assumptions of success for European market reform in Finland. Another example is energy saving as described by Wang, Wang and Zhao (2008) who apply these methods to the major barriers which prevent the implementation of energy saving practices in China and the interactions among them. These methods can be used to assess low carbon scenarios in the UK and worldwide as shown in Hughes and Strachan (2010). Schenk and Moll (2007) also use them for energy scenarios, showing that physical variables (e.g. amount of energy generation) rather than monetary indicators provide additional insights in scenario analysis.

The limits of Godet's methods are, however, described by Gonod. He identifies its subjectivity, its static character and the lack of uncertainty assessment as its main weaknesses, the last two being a consequence of the former (Gonod and Gurtler 2002). He proposes a different approach of foresight which is more dynamic and open to deep structural changes in the system under study (Gonod 2006). Approaches similar to Godet's have thus been developed with a stronger focus on the collaborative aspects of foresight methods in order to lessen their subjectivity. Hines and Bishop (2006) insist on the bias of the participants interviewed and establish a typology of participant profiles (Laggards, True Believers, etc.) to identify common biases in such foresight approaches and separate them from relevant collected data. Markard, Stadelmann and Truffer (2009) also point out that scenarios neglect the co-development of technological and societal processes, and that they lack the theoretical foundation explaining the interactions between the strategies of different players; they build a methodology that emphasizes the links between technological variables, player networks and institutional structures in order to identify plausible future innovation, in the case of biogas. Hughes, Strachan and Gross (2013) show that the level of uncertainty affects the relevance of low-carbon scenarios. They propose to reduce uncertainty by a player-based system with a more in-depth analysis of the interactions between them, thereby leading to better scenarios.

However, in a recent review of foresight methods (Coates, Durance and Godet 2010) and reflections on the numerous uses of strategic foresight (Godet 2010; Durance and Godet 2010), the authors recall that the validity of the analysis conducted with their tools is not only dependent on the tool's performance, but also on the user's rigorous approach and common sense. Bearing in mind the limits cited above and the existing bias, we chose Godet's structural analysis method to pursue this prospective study.

III. Framework of the Study: Structural Analysis

This section describes the structural analysis performed in an attempt to provide answers to our research issues within a rigorous methodological framework. Since we are interested in the investment decision of the power generating company, the system under study thus comprises the power generation company and the related set of investing conditions.

A. Retrospective analysis: generation mix and market liberalization in Europe

The first step of our analysis must involves reviewing historical aspects in order to determine the constants in human behavior and to achieve some kind of perspective on the bias of our time: it is commonplace to say that '*History does not repeat itself, but human behavior* *certainly does*'. In the history of the European market, there are two main processes to be studied: 1) the constitution of the European generation mix from the fifties up to now in order to understand past investment choices, and 2) the European market liberalization that started in the nineties in order to understand the kind of context with which current investors are confronted.

This historical analysis shows that European countries have massively privileged local resources (such as coal in Germany) or the development of a locally well-mastered technology when local resources were poor (such as nuclear in France). This tendency was reinforced after the two oil crises in the seventies, leading European power companies to ensure the security of supply at high costs. The driver to these decisions was the state policy with the purpose to ensure energy independency.

After the oil-price slumps in the eighties, a market reform was implemented in Europe in the nineties to create a single European competitive market out of all the national markets in place, which were often integrated monopolistic markets (Grand and Veyrenc 2011; Hansen *et al.* 2010). The reform was unequally applied in the different countries: to a great extent in the UK which was a pioneer of liberalization, and very little in France where the natural monopoly model was considered a success within the rule of the Ramsey-Boiteux pricing (Baumol 1977). This led to various market structures and concentrations, creating very different environments for investors. The unification of the European market remains unachieved, mostly due to a lack of interconnections between countries (Grand and Veyrenc 2011). Market structure is thus another driver for investors' decisions.

B. Drivers: from investment conditions and power companies

1) Investment conditions in electricity generation technologies

As for listing the variables, we interviewed a number of experts taking into account all the bias of such interviews, before exploiting this information and expanding on it with a close review of related literature. Sixteen experts known for their visions in their area were interviewed: 3 technology development experts in the nuclear field, 9 policy experts from a research institution (the CEA) and embassies (12 countries in Europe, North America and Asia), 4 economic experts from energy companies (EDF, Areva), and 1 independent consultant (see Annex).

Our historical approach showed that drivers were state policy (energy independency and local employment), the local technology and the market structure.

As a result of these semi-directive interviews and our literature study, we were able to distinguish three mains drivers that shape the investing conditions for power generation companies: 1) State policy driver; 2) Market driver; 3) Technical driver.

From a general point of view, the state's priorities are usually security of supply and energy independency. However, there is no real electricity supply problem in the particular context of Europe: it is more the case in emerging countries such as China and India with high growth. The technological advancement of the country is a driver that goes hand in hand with satisfying demand in emerging countries. In Europe, the energy policy is more about climate change, renewable energies and nuclear acceptance (reducing the use of fossil fuels for improved energy independency). Today and within our European scope, the policy driver thus contains four dimensions:

- Climate policy, which is divided into two parts: carbon policy and renewable policy:
    - Carbon policy, which will determine the incentives regarding carbon emissions and promote low-carbon energies (the focus of our study);
    - Renewable policy, which is closely related to carbon policy and can be described in Europe by four kinds of tools: feed-in tariffs, green certificates, tenders and fiscal incentives (Bordier 2008).
- Nuclear policy: the use of this energy can be controversial depending on the national

context. The positions of the five countries investigated proved to be very different. France has historically adopted a strongly pro-nuclear stance; the importance of the nuclear facilities and expertise inherited from the past should allow France to maintain a strong pro-nuclear stance. The UK has adopted a moderate pro-nuclear stance, although recent nuclear developments in the UK shows strong support, e.g. the Hinkley Point agreement with EDF (Department of Energy & Climate Change and Prime Minister's Office 2013); however, the government will never to directly support financially nuclear makes the UK policy "moderately pro nuclear". On the other hand, Germany, Italy and Spain have adopted an anti-nuclear position. In the case of pro-nuclear countries, we have added a "strike price" variable to describe the nuclear policy more accurately;

- Electricity market reform policy, which will have a direct influence on the investors' environment and the investors' profiles themselves. To elaborate our scenario, we included this driver in the second category: 'market driver'.

The market driver comprises several levels:

- Level of concentration and competition of the market that can be characterized by the number of players on the market and the Herfindahl-Hirschman Index (HHI[1]);
- Market policy led by the country, which will have an influence on both the market structure through market reform policy and market coordination, which is essential to investors' decisions.

As a first approach, we consider that the market reform policy is described by the choice to develop interconnections, and more generally, the electricity grid. The "market structure"

[1] HHI definition, with s_i the market share of firm i in the market, and N the number of firms:

$$H = \sum_{i=1}^{N} s_i^2$$

The lower HHI is, the more the market is competitive, while the higher HHI is, the more the market is concentrated.

driver is thus considered from both angles (concentration and interconnections). As for market coordination, investment coordination is described by the different financing methods: corporate financing, project financing, hybrid method mixing the last two, or other original financing methods (e.g. financing from the future customers) (OECD 2009; IAEA 2009).

The technical driver (regarding coal, gas, nuclear, hydro, wind, solar) includes i) building and generation costs, ii) load factors that will directly impact the expected profits, and iii) all the parameters that will make the technology more or less easy to acquire for the investor, i.e. the construction timescale, the average size of the plant for this technology, and the technology complexity. Since the perception of technology complexity depends on every company according to its own expertise, we did not include it in this technical driver, but in the drivers proper to the company.

The different decision variables corresponding to the three main drivers are listed in Table I.

Table I: Decision variables for each driver

N°	Variable	Related Driver
1	Carbon tax (€/tCO_2)	Policy Driver
2	CO_2 quota	
3	Feed-in tariffs for renewables (€/MWh)	
4	Green certificates for renewables	
5	Tenders for renewables	
6	Fiscal incentive for renewables	
7	Nuclear position	
8	Nuclear strike price (€/MWh)	
9	Stability of policy	
10	HHI concentration index	Market Driver
11	Development of grid and interconnections	
17	Corporate financing	
18	Project financing	
19	Hybdrid financing method (corporate and project financing)	
20	Other original financing method	
12	Construction costs (€/MW)	Technical Change Driver
13	Generation costs (€/MWh)	
14	Building period (year)	
15	Size of plant (MW)	
16	Load factor (%)	
21	Shareholding structure	Company driver
22	Market Capitalization	
23	Annual Production	
24	Generation Mix	
25	Market share	
26	Annual revenue	

2) Drivers based on the characteristics of companies

In order to understand investment choices, it is relevant to compare investor profiles and technology investment conditions: for instance, capitalistic investments such as coal or nuclear plants tend to be achievable only for companies with sufficient revenue and capitalization to support the building costs, while low-capital cost technologies such as small renewable facilities are accessible all investors. Nonetheless, the thorough investigation of investment conditions shows that original financing methods such as conjoint investment from a consortium of power generation companies or financing from long-term electricity purchasers can broaden the scope of companies able to make capitalistic investments.

The second step of our analysis thus consists in identifying the investors and determining how their characteristics will influence their own investment decisions.

Investor profiles can be analyzed through a few key characteristics that are:

- Shareholding structure, which generally determines the investment strategy of the company (private shareholders: institutional, public float, or state shareholders: state, ministry, local authority, and weight of the different shareholders);
- Market capitalization and annual revenue, which indicate the size of the company from a financial viewpoint and the size of the investments the company can support;
- Total annual production, which indicates the size of the company from an industrial viewpoint;
- Generation mix, which indicates the company’s fields of expertise;
- Market share on markets where the company is active, which indicates the international scope of the company.

An overview of the companies falling within our scope shows that most of the current power generation companies are former historical operators who used to be in a dominant market position (Grand and Veyrenc 2011). Their shareholders are state players (e.g. the government, a ministry, or local communities), institutional investors (e.g. banks and insurance companies), and private shareholders (public float), with the weight of each type of shareholder depending on the national position towards market reform and the specific history of the company. Their annual revenue and market capitalization represent several dozen billion euros and annual production of around a hundred TWh (EDF *et al.* 2012). Their dominant technologies are mostly coal and gas (and nuclear for EDF). Most of them have crossed the border of their initial market and have started targeting neighboring markets: e.g. EDF is present in the UK and Italy, and EOn in the UK, Italy and Spain. We can also observe concentrating movements between these companies: for instance, the Italian operator ENEL owns the Spanish Endesa, the French operator EDF owns British Energy, and the Spanish operator Iberdrola owns Scottish Power.

Yet another type of profile seems to be emerging with the market reform, that of small power companies. Such companies are generally young, dating back to the nineties or 2000 such as the wind operator Theolia or the solar operator Solaire Direct. Their shareholding structure boasts no state players; their revenue is usually a few million euros and their annual production less than 1 TWh. They mostly specialize in one technology since their size does not allow them to diversify, mostly in recent technologies such as renewables or CCGT. They can be local or international operators, representing minor market shares in any case.

As mentioned above, national positions regarding the market reform differ from one country to another, which affects the development of power generation companies. France, Germany and Spain tend to protect their historical operators on their domestic markets and promote their international development thanks to reform; the UK and Italy are really promoting competition on their own market, with Italy limiting market shares for the different players on the Italian market for instance. The development of investor profiles towards multinational concentrated companies or towards small power operators will depend on the changes to the global market structure in association with the market reform policies led in EU countries.

Table II: Company drivers

Shareholding structure	Company driver
Market Capitalization	
Annual Production	
Generation Mix	
Market share	
Annual revenue	

Table III: Matrix of direct influences

	1 : Carbon tax	2 : CO2 quota	3 : Feed-in tariffs for renewables	4 : Green certificates	5 : Tenders for renewables	6 : Fiscal incentive for renewables	7 : Nuclear position	8 : Nuclear strike price	9 : Stability of policy	10 : HHI	11 : Development of grid	12 : Construction cost Euro/MW	13 : Generation cost Euro/MWh	14 : Building period	15 : Size of plant	16 : Load factor	17 : Corporate financing	18 : Project financing	19 : Hybdrid financing method	20 : Other original financing method	21 : Shareholding structure	22 : Market Capitalization	23 : Annual Production	24 : Generation Mix	25 : Market share	26 : Annual revenue
1 : Carbon tax	0	3	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	0	3
2 : CO2 quota	3	0	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	0	3
3 : Feed-in tariffs for renewables	3	3	0	3	3	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
4 : Green certificates	3	3	3	0	3	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
5 : Tenders for renewables	3	3	3	3	0	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
6 : Fiscal incentive for renewables	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
7 : Nuclear position	P	P	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	0
8 : Nuclear strike price	P	P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	0	0	3	0	3
9 : Stability of policy	3	3	3	3	3	3	3	3	0	0	3	0	0	0	0	0	1	1	1	1	3	0	0	3	0	0
10 : HHI	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 : Development of grid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
12 : Construction cost Euro/MW	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	3	0	2	0	0
13 : Generation cost Euro/MWh	3	3	3	3	3	3	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	3	3	3	0	3
14 : Building period	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 : Size of plant	0	0	0	0	0	0	0	0	0	0	2	3	0	3	0	0	3	3	3	3	0	0	3	3	3	0
16 : Load factor	0	0	3	3	3	3	0	0	0	0	3	0	0	0	3	0	0	0	0	0	0	0	3	3	0	0
17 : Corporate financing	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
18 : Project financing	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
19 : Hybdrid financing method	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
20 : Other original financing method	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0
21 : Shareholding structure	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	3	3	3	0	3	0	3	0	0
22 : Market Capitalization	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3	0	3	3	3	3	3	0	0	0	0	0
23 : Annual Production	0	0	0	0	0	0	0	0	0	3	3	0	3	0	2	1	0	0	0	0	0	0	0	0	3	3
24 : Generation Mix	3	3	3	3	3	3	2	0	0	0	3	1	0	1	1	0	1	1	1	1	0	0	3	0	0	0
25 : Market share	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	3	3	3	0	0	0	0	0	0
26 : Annual revenue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	0	3	0	0	3	0

A. Analysis of interactions: matrix of direct influences and dependences

The MICMAC method consists in assessing the relative influence of all variables upon another[2] in order to fill a matrix called the 'Matrix of Direct Influences'.

[2] For each variable, its influence on every other variable is quantified from 0 to 3, the value 0 corresponding to no influence at all, and 3 to a strong influence. The letter P is used when a potential influence is sensed, but not clearly identified. In the matrix of direct influences, each line contains the values attributed to the variable's influence on every variable in the column. Therefore, the lines show how much influence the variables have on the others and the columns show how much the variables depend on the others.

Information collected from the literature review and interviews was used to fill in the matrix of direct influences and dependencies[3]. Since the experts would have required a training session and workshop in order to be able to fill in this matrix, it was not given to them but was instead filled in using a compilation of their answers and the results of the literature review.

The influence of a variable on another is considered direct if the value of the influencing variable appears in the definition of the influenced variable. For instance, feed-in-tariffs are designed according to technology generation costs, revenues of power generation companies are partly determined by incentives (feed-in-tariffs, fiscal incentives, carbon price or carbon tax). It is important to note that filling in the matrix is about identifying crossed influences between the variables in our list. It does not mean that the variables depend exclusively on other variables from the list. The paragraph below details how the matrix was filled in.

Policy drivers

Incentives for renewable and carbon are designed based on the global policy of the country regarding this matter, which means that all climate policy incentives are influenced by one another and are influenced by the global stability of climate policy. The costs of technologies have a direct influence on shaping incentives (FiT, price of carbon, fiscal incentive, etc.) so that the incentive plays its role well. The technical characteristics affecting the production and thus revenue are also influential (in particular, the load factor influences shaping FiT or other incentives, especially for renewables that face intermittency issues; however it does not influence carbon prices which are defined as a cost per metric ton of CO_2 so that the company's carbon costs remain proportional to its carbon emitting generation). Incentives are also shaped according to the existing mix in the country that the policy wants to change, i.e. the generation mix of all power generation companies. Since all these influence are direct and very obvious,

[3] According to observations by Godet (2001), an optimal filling of the matrix corresponds to approximately 20%; our matrix has a filling rate of 27.8%, which is reasonably close.

they are assessed with the maximum value of 3.

Carbon incentives may be influenced by the country's nuclear stance, since a pro-nuclear stance can favor a low carbon policy: potential influence.

The nuclear stance is a long-term political decision that goes back to the 80s & 90s and the inertia of which is hardly likely to be influenced by other listed drivers. However, some drivers have a moderate or weak influence on it: sometimes it can be part of a low-carbon policy. It is influenced by the stability of policy (in the US, the possibility of a radical change in energy policy makes it impossible to have a strong pro-nuclear policy); the profile of shareholders from power generating companies may have more or less influence on the political opinion on nuclear since the presence of government entities in the shareholders supposes common interests or at least closer interaction between the state and the company. Moreover, the existing generation mix of companies influences the state's nuclear stance, since the lifespan of power plants induces a certain level of inertia. A national electricity mix relying on nuclear for 75% of the generation is less likely to switch to an anti-nuclear position than a mix with 20% nuclear share.

The nuclear 'strike price' depends on the state's nuclear stance and the stability of its policy, as well as being designed according to the generation cost.

Policy stability influences many other drivers rather than depending on them, but no direct influence from the other drivers has been identified. Policy stability actually depends on many factors, some of them outside the scope under investigation, like the political context and organization of the country, and is mostly the result of indirect influences of others drivers.

Market drivers

The HHIs depend on the market shares of the companies that can be calculated using the production or company size, which is why the corresponding indicators were also listed as influential on the HHI.

The grid development depends on: 1) the stability of policy since real perseverance is needed to establish new lines; 2) the concentration of the market since the multiplication of players will make more interconnections necessary; 3) the size of plants since it is an indicator of a centralized or decentralized market (smaller plants means more plants and therefore more interconnections); and 4) the load factors: a low load factor means there is a need for more capacity and more interconnections.

The choice of a financing method is mostly influenced by the financial indicators of the size of the company: market capitalization, market share and annual revenue to a lesser extent. The choice is also influenced by:

- Shareholding structure of the company: the private or public profile of the company offers different kinds of financial guarantee and thus leads to different financing methods;
- Size of the project, which determines the total investment cost and building time, and therefore the payback period;
- Existing mix, since it shows the company's field of expertise and can orientate the choice of financing method;
- Policy incentives: supporting incentives since they can offer financing structures (such as tenders) or financial security (feed-in tariffs/strike price, fiscal incentive, green certificates);
- Carbon-related incentives, since they increase risk on profitability.

It is also important to mention that the cost of financing will depend on the generation cost, investment cost, and all policy incentives including carbon incentives. However, it is not the cost of financing that is examined here, but the choice of financing method.

Technical drivers

The MW construction cost can vary depending on the construction timescale since the longer it lasts, the higher the €/MW cost and the size of the plant, due to a potential scale of economies.

The MWh generation cost is influenced by the construction cost of the MW and the generation capacity (to evaluate variable costs). Generation costs also depend on others parameters that were not identified as drivers *per se*: cost of fuel, cost of workforce, etc. (they are all included in the ‘generation cost’ driver).

The construction timescale mostly depends on the size of plant but also – to a lesser extent – on the existing mix of the generation companies, since it indicates their level of expertise in the different technologies.

The load factor is mostly a technical parameter imposed by the technology: base technologies such as coal and nuclear are required to have an approximate load factor of 80%, while intermittent renewable technologies have an average load factor of 20-25%. According to variations in demand, however, this load factor can be changed: it is particularly true for peak technologies such as gas or hydro, but it can also affect base technologies. This is why the company’s production is considered to have a weak influence on the load factor.

Company drivers

The shareholding structure, which will keep the same company profile over time (public/private), can be mostly influenced by policy stability. It can also be influenced by the size of the capital, i.e. the market capitalization, since a large company is more likely to be a former state-owned company with government entities still counted among the shareholders, rather than a small company born with the liberalization process. Lastly, shareholding structure can be influenced by the policies and incentives in general.

The market capitalization can be calculated by different methods. Since the calculation depends on shareholder expectations, it mostly depends on the shareholding structure of the company. And since it involves the company’s profits in most methods, revenues and costs are considered to be highly influential. Financing choices are considered to influence costs so they are listed as having a small influence. As said above, other costs such as fuel costs are influential but they do not appear here since they have already been included in generation costs.

The value of annual production of a company is above all conditioned by demand and its capacity. On a more detailed level, it depends on:

- Generation mix;
- Size of the plants and their load factors, since the plants will generate more or less electricity over the Year according to their capacity and the type of technology (base, intermittent, peak);
- Generation costs of the technologies;
- Grid constraints;
- Incentives for carbon emissions (to a lesser extent).

Positive incentives on renewables and nuclear are not considered influential since the renewable technologies considered here are intermittent and thus have priority to sell, as well as the fact that nuclear is supposed to work on a base load. Since coal is also a base-load technology, this means that generation from gas could mostly be impacted.

The generation mix depends on the installed mix and how it can be used to respond to demand and thus is influenced by:

- Size of plants (they define the installed mix);
- Load factors of the technologies in the mix (since they give the actual generation of the installed capacity);
- Generation costs (merit order);
- Investment costs, thus involving the size of plants and MW investment costs (since the need to make an investment profitable can condition the load factor);
- Incentives to use some technologies rather than others: support incentives for renewables or nuclear, or negative incentives for fossil technologies.

The market share of a power generation company is usually calculated in terms of installed capacity or generation (e.g. calculation of HHI indicators in European Commission reports);

the traditional definition of a market share is based on the company's revenue. The market share thus depends on the size of plants (installed capacity), the annual generation or the annual revenue (for the theoretical definition).

The annual revenue is influenced by the annual production and all the incentives affecting the revenue.

IV. RESULTS: BUILDING SCENARIOS FOR GENERATION IV

A. Development assumptions for all drivers

In order to build investment scenarios based on these drivers, it is necessary to extract assumptions from our previous analysis regarding their development over the timescales of our study. Low and high assumptions for each dimension of the policy driver have been formulated.

We have identified a strong climate policy scenario and a moderate climate policy scenario that can be quantified by their carbon price ranges, with carbon pricing being the key tool of climate policy. Today EU ETS has had low carbon prices around a dozen US$/metric ton CO_2 for a few years. Strong climate policy would imply increasing this price, which could be achieved by reforming the carbon market or by applying a carbon tax. Given the European objectives of 3x20, carbon prices are expected to rise although the question remains as to how much. The moderate climate policy would consist in pursuing the EU ETS system with reforms, leading carbon pricing to increase from a dozen $/metric ton to $45/t$CO_2$ in 2040. A strong climate policy would increase the carbon price up to 120 $/t CO_2 in 2040 (IEA 2012). The renewable policy is closely related to the carbon policy, as detailed in the European Climate-Energy Package. Therefore, a strong climate policy scenario corresponds to strong incentives both in terms of long-term support and high amounts of emissions reductions, whereas the low assumption would correspond to current trends (Bordier 2008). We assume that nuclear policies do not change within the considered period[4].

In theory, liberalization should lead to market decentralization, which is far from being obvious in the case of the European electricity market. In this article, we have described concentration assumptions using the HHI; as in the European Commission guidelines on competition, a market in which the HHI is below 1000 is considered to be competitive and low concentrated, whereas a market in which the HHI exceeds 2000 is considered to be highly concentrated. By observing the HHI of different European countries, we can see that some countries have managed to fall under 1000 (UK, Italy), whereas others remain very concentrated (France's HHI is above 7000). Concentration movements since the beginning of the liberalization process are not in favor of deconcentration in Europe. For this reason, we have provided both a high and a low concentration assumption.

A high concentration assumption implies a low development of interconnections; a low concentration market with a strong development of interconnections. It should be pointed out that development of interconnections is an issue due to systematic strong local opposition. As for the different financing methods, we consider the flexibility of choices in financing as a static decision variable and thus we make no assumption regarding their potential development.

Among the technologies being studied, coal, gas, hydro and nuclear are considered to be time-tested and expect less progress than wind and solar[5]. The technical driver thus corresponds mostly to the expected technical change for these two recent renewable technologies, wind and solar. For this driver, we made a high technical change assumption and a low technical change assumption. The technical change would impact the construction costs, generation costs and

[4] This assumption may be considered a limit in the elaboration of scenarios; nevertheless, such political stances commit long-term industrial behaviors, which is why it is relevant to assume a certain degree of inertia in the pro or anti-nuclear stance.

[5] It is true that nuclear technologies are still experiencing innovation, but even new generations of nuclear reactors (Generation III, Generation IV) are based on tried-and-tested concepts: pressurized water reactors for Generation III, which is one of the most current concepts in operation today, and sodium-cooled fast reactors for Generation IV, the technology was experimented in France in the eighties with the Phenix and Superphenix demonstrators, while Russia is currently operating a few fast reactors (BN-600, BN-800).

technical constraints of each technology: load factor, average size of plants, construction time. WEO 2011 scenarios allow us to estimate the expected cost reduction (IEA 2012). Since the impact on these different costs is quite homogenous according to the expected progress for one technology, overnight investment cost reduction is a relevant indicator. **Table IV** gives the orders of magnitude of investment cost reduction for the two assumptions, which shows that progress is mostly expected for solar technologies (PV and CSP).

Table IV: Investment cost reduction between 2010 and 2040

Technology	Low technical change	High technical change
Onshore wind	10%	20%
Offshore wind	25%	50%
Solar PV (utility and rooftop)	50%	75%
Concentrated solar power	40%	90%

Table V: 24 possible scenarios

Scenario 1a	strong climate policy	low technical change	concentrated	strong pro-nuclear
Scenario 1b	strong climate policy	low technical change	concentrated	moderate pro-nuclear
Scenario 1c	strong climate policy	low technical change	concentrated	anti-nuclear
Scenario 2a	strong climate policy	low technical change	not concentrated	strong pro-nuclear
Scenario 2b	strong climate policy	low technical change	not concentrated	moderate pro-nuclear
Scenario 2c	strong climate policy	low technical change	not concentrated	anti-nuclear
Scenario 3a	strong climate policy	high technical change	concentrated	strong pro-nuclear
Scenario 3b	strong climate policy	high technical change	concentrated	moderate pro-nuclear
Scenario 3c	strong climate policy	high technical change	concentrated	anti-nuclear
Scenario 4a	strong climate policy	high technical change	not concentrated	strong pro-nuclear
Scenario 4b	strong climate policy	high technical change	not concentrated	moderate pro-nuclear
Scenario 4c	strong climate policy	high technical change	not concentrated	anti-nuclear
Scenario 5a	low climate policy	low technical change	concentrated	strong pro-nuclear
Scenario 5b	low climate policy	low technical change	concentrated	moderate pro-nuclear
Scenario 5c	low climate policy	low technical change	concentrated	anti-nuclear
Scenario 6a	low climate policy	low technical change	not concentrated	strong pro-nuclear
Scenario 6b	low climate policy	low technical change	not concentrated	moderate pro-nuclear
Scenario 6c	low climate policy	low technical change	not concentrated	anti-nuclear
Scenario 7a	low climate policy	high technical change	concentrated	strong pro-nuclear
Scenario 7b	low climate policy	high technical change	concentrated	moderate pro-nuclear
Scenario 7c	low climate policy	high technical change	concentrated	anti-nuclear
Scenario 8a	low climate policy	high technical change	not concentrated	strong pro-nuclear
Scenario 8b	low climate policy	high technical change	not concentrated	moderate pro-nuclear
Scenario 8c	low climate policy	high technical change	not concentrated	anti-nuclear

Regarding the company drivers, the change in the size of companies naturally follows the assumptions on market concentrations and the HHI. However, since the aim of the study is to assess the reaction of companies to investing conditions and to observe how the development of their mix could be affected, no assumption is made on company drivers.

A total of 24 different scenarios is possible as a result of the number of assumptions:

- High and low assumptions for the climate policy driver, market driver, and technical change driver;
- High, low and medium assumptions for the nuclear policy.

It may be irrelevant to describe all 24 scenarios without any kind of sorting: among the identified drivers for investments, we wanted to identify those that were the most relevant to scenario building. This was possible by processing the structural analysis results using the MICMAC tool.

B. Sorting key drivers as a result of structural analysis

Based on the matrix of direct influences, the MICMAC tool was used to generate a graph of direct influences and dependences, as shown in **Figure 1**. According to this chart, when a variable is further along the x-axis, it is more dependent on the other variables; when a variable is further up the y-axis, it has more influence on the other variables. Therefore, the variables contained in the upper left corner of the chart have influence on the others, but they do not depend on them and are thus exogenous: they are called “input variables”. They tend to condition the system’s dynamics. The variables in the upper right corner of the chart, which have influence and depend on other variables, are called “intermediate variables”. They can sometimes be considered as the most important variables of the set since any action on these variables has a domino effect on the rest of the system. The variables in the bottom right corner depend on other variables, but have no influence on them: they are called “output variables”. Their behavior explains the impact from input and intermediate variables. The variables in the bottom left corner of the chart have no influence on other variables and they do not depend on them: they are called “excluded variables” and they are less important. They often describe inertial trends that change little over time. Lastly, the “clustered variables” are those that are insufficiently influential or dependent to be included among the previous classifications.

Figure 1: Chart of direct influences and dependences (empty)

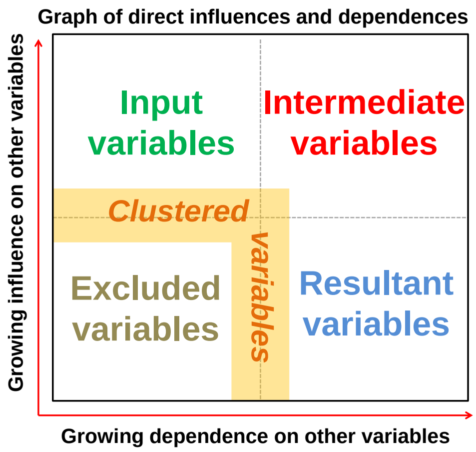


Figure 2: Chart of direct influences and dependences (external and internal variables)

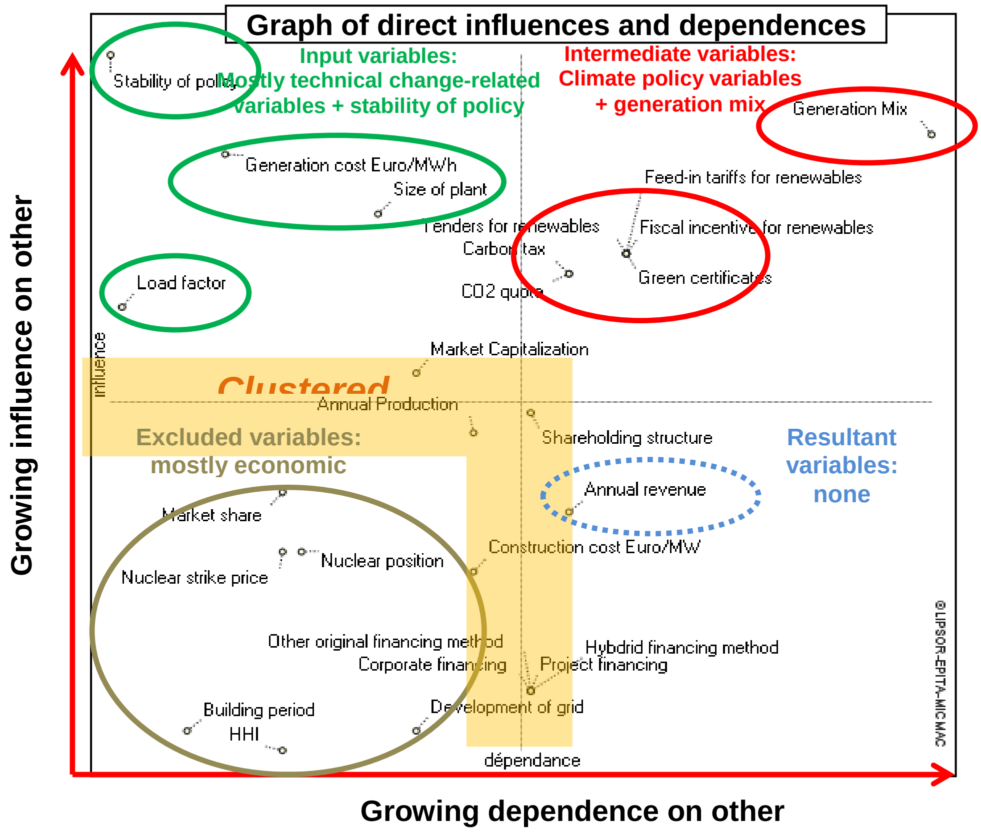


Figure 2 shows that input variables are policy stability and technical variables (generation costs, size of plant, load factor). Intermediate variables are all the climate policy variables and the generation mix. This is predictable since it means policy instruments are designed according to the technical characteristics of the technology. Nonetheless, technology changes cannot be seen as a direct result of policy (results of encouraging incentives are not direct enough). Generation mix is also a result of the technical characteristics of the technology and policies, as well as influencing the energy policy choices in return.

There are no resultant variables, except for the annual revenue that may be considered as one. This is not surprising since the annual revenue results from 1) the technology's characteristics such as generation costs, load factor and installed capacity (size of plant), 2) the company's generation mix, and 3) the policies adding or lessening the revenue. The annual revenue also results from electricity prices, which was not listed among our drivers.

Excluded variables are most of the market driver-related variables: financing methods and the HHI, but also the 'construction timescale' technical variable and nuclear policy-related variables. This is coherent with our previous assumption according to which nuclear policy is invariant over time.

One striking result of this analysis is that all variables of the market driver (the HHI, financing methods and grid development) have no influence whatsoever on the system and are excluded variables. This does not mean that they are not important individually for the investor when it comes to making a decision, but that they do not interact with other variables in the system composed of the identified drivers. Given the little direct interaction that the market structure has with the other decision drivers, this means it will not change significantly over time. The financing methods tend to concern a more general issue of industrial financing (not only energy, not only electricity). This means that they are more related to trends in the field of finance and banking.

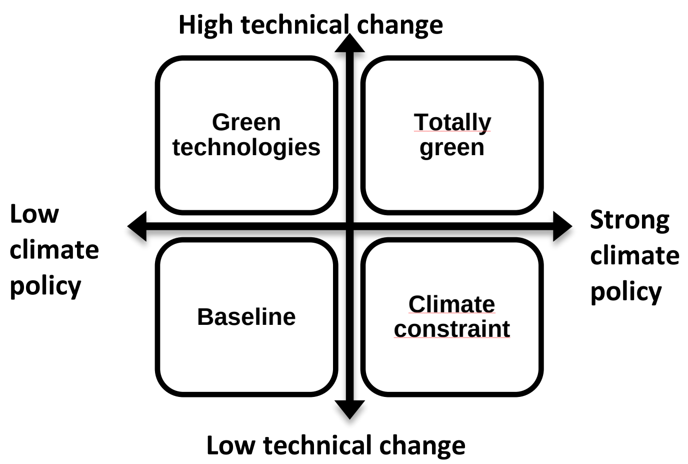
Another striking result is that the company drivers are mostly clustered variables: this means that they have unclear influences which could not be elucidated by our structural analysis (one of the limits of the tool). One counter-intuitive result is to have €/MW investment costs as a clustered variable and not as an input variable like generation costs. The role of clustered variables is not easily interpreted. However, this could mean that it is not the cost per MW that makes the investment capital-intensive, but the size of the plant, together with the fact that the load factor indicates how fast the investment will be profitable.

Lastly, the fact that there are practically no resultant variables seems to indicate that no variable can be influenced without a domino effect on other variables. In our investment choice problem, this means that there is no parameter easy to target to obtain a clear effect: a change in a policy or a technical driver will not have a clear and direct result on another driver, except for the revenue. This is consistent with the difficulty of defining efficient policies or predicting the effects of technical progress.

C. 4 Relevant types of scenarios

Relevant drivers to be applied when building scenarios are thus the climate policy and technical change, which leads to 4 main types of scenarios:

Figure 3: Main types of scenarios



In the baseline scenario, neither climate policy nor renewables undergo any significant upheaval. Carbon emission reduction is still addressed by the EU ETS market with low prices up to 4US$/metric ton CO_2, which is no strong incentive for carbon, except for the UK which created a carbon tax that will increase as planned by the UK government. Current incentives for renewables will be pursued, with some of them having already being abandoned (e.g. the solar FiT in Spain). It is the least favorable scenario for low-carbon technologies, but favorable to coal and gas. It consists in pursuing the same trends in all five countries: nuclear and fossil fuels with a minor share of renewables in the UK and France, renewable and fossil fuels with a minor share of renewables in Germany, Italy and Spain, thus meaning high carbon emissions. Fossil resources make it possible to continue using fossil-fueled electricity over the timescales considered (three decades). Nuclear development prospects will only concern France and UK (through the construction of EPRs), motivated by the need to decommission old plants, but the share of nuclear in their generation mix is not likely to grow. The possibility of fast reactor penetration will exist in France if the Astrid project goes according to plan. In the end, nuclear development is only supported by pro-nuclear policies in the UK and France.

The "green technologies" scenario states that renewables have achieved economic competitiveness through technical change, and there is a low climate policy. This scenario introduces highly competitive renewables (those predicted by the most optimistic assumptions) in the baseline scenario. Since the results of the structural analysis suggest that technology characteristics are the inputs for policy design, the incentives for renewables are made unnecessary by the economic competitiveness.

Like the baseline scenario, the "green technologies" scenario is favorable to coal and gas investments but includes a "green" component. It is still favorable to renewables due to the technical change factor; gas investment will be promoted since it is a low-capital, flexible technology that is technically suited to be a back-up capacity to renewables and is economically suited to low load factors. More generally, among low-carbon technologies, this scenario tends to reduce nuclear investment in favor of gas and coal. For nuclear development, the same conclusion can be drawn, except that nuclear investments are less attractive given the new competitive technologies on the market: nuclear is expected to lose market shares even in pro-nuclear countries.

The “totally green” scenarios, in which a strong climate policy is combined with high technical progress for renewables, are the most favorable for renewables and carbon emission reductions. Carbon prices will rise up to thanks to carbon taxes or carbon market reform. Renewable costs will decrease and be supported by strong incentives in the beginning, which should attract investments. Support policy is rendered useless when renewables become competitive, so incentives are expected to disappear after 20 years at the latest. It is favorable to investment in both renewables and nuclear in France and the UK, and favorable to invest in renewables in Germany, Spain and Italy. In all countries, fossil-fuel-based technologies will lose market shares according to these scenarios. This means that back-up generation due to renewable intermittency will be ensured by non-intermittent hydraulic power and nuclear power. It is necessary to point out that such a situation means a lower load factor for nuclear power and thus an important loss of competitiveness on generation costs (OECD and Nuclear Energy Agency, 2012). As a consequence, such massive low-carbon investment situations would only be possible if climate policies and renewable competitiveness were strong enough to maintain nuclear investment attractive compared with fossil fuels and especially gas, or if technical change could bring solutions to intermittency such as the good management of long-term storage or interconnections between numerous sources. In terms of policy, the dynamics of the ‘totally green’ scenario would become similar to the ‘green technologies’ scenario in the last decade of the considered period, except for the carbon policy which would stay stronger, and renewable penetration would be lower in the ‘green technologies’ than in the ‘totally green’ scenario since it would not be helped by incentives. As for nuclear development, interest in nuclear would be stronger than in the baseline scenario for France and the UK. It would thus make development of fast reactors more likely in France and encourage pending investments in the UK through the renewal of 20 GW of nuclear power and the potential replacement of decommissioned coal fired power plants by nuclear (up to 8.3 GW).

The “climate constraint” scenario in which a strong climate policy faces low technical change in the renewables is favorable to low carbon time-tested technologies like nuclear and hydropower. However, in the five countries studied here, hydraulic capacities are already well developed and subjected to strong environmental constraints and local opposition, which considerably limits investment in new build. Considering the nuclear policies in the different countries in question, it is thus favorable to nuclear in France and the UK. In Germany, Italy, and Spain, this scenario should be favorable to renewables through climate policy incentives and despite their limited competitiveness. This scenario thus implies the use of expensive renewable energies or the use of fossil fuels combined with high carbon prices for Germany, Italy and Spain. In any case, domestic electricity generation will be achieved at high costs. Nevertheless, the artificial maintenance of technologies that have not achieved economic profitability in the long term is questionable. As the results of the structural analysis suggest, technology characteristics are the inputs for policy design. This means that within a period of 20 years (which corresponds the longest lifetime of the incentives identified), the support for renewables should decrease. A strong climate policy means that support could go to newer technologies like CCS or geothermal energy. Still, since such technologies are further from maturity than wind and solar, their penetration would not be as good as that in the ‘totally green’ scenarios. An alternative solution could be found in electricity imports, depending on the development of the grid, being costly itself. This scenario is the one where there is the strongest interest in nuclear energy and thus in fast reactors. In France, the nuclear capacity would definitely be maintained and investment in FRs confirmed. Nuclear investments in the UK could cover not only the renewal of 20 GW of nuclear power and the replacement of 8.3

GW of coal-fired power plants, but also investments to respond to the increasing demand and thus gain significant market shares. Investment in FRs could thus be considered. As for Germany, Italy and Spain, the anti-nuclear stance could be questioned.

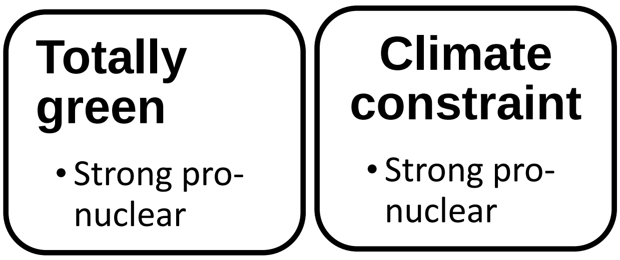
D. 3 Scenarios for Gen IV integration

1. **Identification of scenarios favorable to fast reactors**

Among all types of scenarios, the "climate constraint" type of scenario is thus the most favorable to nuclear investment and thus to FR integration. Let us clarify our point of view taking into account the neglected variables, market driver and nuclear policy: given that in the "climate constraint" context, nuclear seems the most viable solution, both moderate pro-nuclear and strong pro-nuclear stances would constitute favorable scenarios to nuclear development including FRs. In the market-related drivers, the most crucial ones are the financing methods that can, if well chosen, reduce the financial risk for investors. Market concentration factors will not be influential in this case since nuclear policy is supposed to ensure market coordination. Grid development is not an issue for centralized production means like nuclear plants.

"Totally green" scenarios are also favorable to nuclear investment, with the reserve expressed in subsection III. C. about their technical compatibility with intermittent technologies. It would need a strong pro-nuclear policy to allow for nuclear development until the stage of the next generation of reactors.

Figure 4: Three scenarios favorable to FR investments



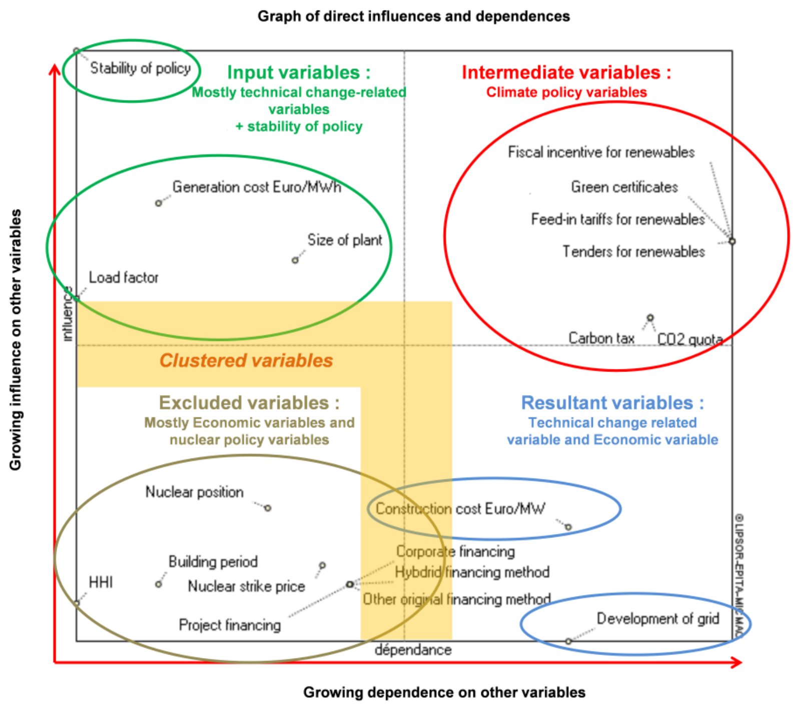
We have thus identified the three scenarios that are the most likely to provide a favorable environment for investment in FRs. Let us not forget that these scenarios correspond to "necessary conditions" for FR development within our framework of assumptions, but not "sufficient conditions".

The next stage of the analysis consists in testing the robustness of these results by observing what happens when we remove the clustered variables from the system.

2. Further analysis without the internal decision variables of investors

This section excludes the company drivers since these variables are mostly clustered variables. The matrix of direct influences and dependences is the same as in used in Table I, with the first 20 lines and first 20 columns[6]. Figure 5 shows the results of the MICMAC simulation performed without these variables (20 variables instead of 26).

Figure 5: Chart of direct influences and dependences (external variables only)



The main tendencies of **Figure 2** are clearly maintained, giving the same results regarding the relevant drivers for scenario building and confirming the robustness of the approach. However, two clustered or excluded variables appear here as resultant variables: construction costs and grid development. This means that the grid development will only be

[6] The filling rate of the matrix is 22.8%, which is close to the optimal filling recommended by Godet (2001).

the result of policies and technology changes. It must be pointed out that in this chart, the €/MW investment costs are considered as a resultant variable and are still not considered as an input variable like generation costs. This confirms that it is not the cost per MW that really makes the investment capital-intensive, but the size of the plant, with the load factor indicating how fast the investment will be profitable.

V. CONCLUSION

This study identifies the key drivers behind the choices of investors and construction scenarios for the European generation mix based on the development of these drivers in the future: 1) policy (divided into climate policy and nuclear policy), 2) technical change and 3) market drivers. The results of the structural analysis and scenario discussions show that pro-nuclear policies are insufficient to promote nuclear development in Europe: business-as-usual scenarios are not favorable to FRs; climate policy appears to be the *sine qua non* condition for further nuclear development. Surprisingly, the market driver is negligible compared with the two others. In the end, both strong and moderate pro-nuclear policies are compatible with FR investment in the “climate constraint” scenarios, where nuclear is the only economically viable alternative. The “totally green” scenarios combined to a strong pro-nuclear policy assumption are also favorable to FRs in a context of flourishing renewables. Three scenarios favorable to FR investment have thus been identified regardless of the market driver; that is to say, they combine the necessary conditions for FR investments.

Climate policy changes are thus decisive for nuclear investment within our European scope. On a broader scale, the climate policy of Europe is decisive for the whole international climate policy: the achievement of its objectives would be a catalyst for an international climate policy, whereas its failure would discourage further attempts to build an international climate policy. Nevertheless, this does not mean that international FR development is bound strongly to Europe. Other drivers such as a strong electricity demand due to quick industrialization could create an environment favorable to FRs for instance in Asia, even in case of unfavorable scenarios in Europe.

There are though a few limits to be mentioned: these scenarios only combine the necessary conditions for the emergence of FRs. There is also an indirect driver - “public acceptance of the technology” - that is currently included in the nuclear policy driver. However, public rejection could appear for renewables as well because of land use and landscape transformation. Among technologies omitted from this study, carbon capture and storage could change the attractiveness of fossil fuel in the “climate constraint” and “totally green” scenarios, while the development of FRs in the form of small modular reactors could change the analysis since the market concentration factor and, above all, grid development would mostly likely become more important.

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REFERENCES

Allais, M. [1943] *A la recherche d’une discipline économique*, Impr. Industria.

Alvarez, S.A. and Barney, J.B. [2007] 'Discovery and creation: alternative theories of entrepreneurial action,' *Strategic Entrepreneurship Journal* 1:1-2: p.11–26.

Arrow, K.J. [1965] *Aspects of the theory of risk-bearing*, Yrjö Jahnssonin Säätiö.

Baumol, W.J. [1977] 'On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry,' *American Economic Review* 67:5: p.809–22.

Bergman, J., Viljainen, S., Kässi, T., Partanen, J. and Laaksonen, P. [2006] 'Managing the exploration of new operational and strategic activities using the scenario method—assessing future capabilities in the field of electricity distribution industry,' *International Journal of Production Economics* 104:1: p.46–61.

Bibas, R. [2011] 'Dynamiques d’investissement et de maîtrise de la courbe de charge dans le système électrique français,' Available at: http://www.modelisation-prospective.org/journee_chaire_2011.html [Accessed October 2, 2013].

Bland, J. and Westlake, S. [2013] *Don’t stop thinking about tomorrow*, NESTA. Available at: http://www.nesta.org.uk/library/documents/dont_stop.pdf [Accessed September 18, 2013].

Boiteux, M. [1956] 'Sur la gestion des monopoles publics astreints à l’équilibre budgétaire,' *Econometrica*.

Bordier, C. [2008] 'Développement des énergies renouvelables: quelle contribution du marché du carbone?,' *CdC Climat Recherche, Point Climat* :16. Available at: http://www.caissedesdepots.fr/fileadmin/PDF/finance_carbone/etudes_climat/note16_energies_renouvelables.pdf [Accessed October 2, 2013].

Chabaud, D. and Messeghem, K. [2010] 'Le paradigme de l’opportunité. Des fondements à la refondation,' *Revue française de gestion* 36:206: p.93–112.

Chick, M.C. [2007] *Electricity and Energy Policy in Britain, France and the United States Since 1945*, Edward Elgar Publishing.

Coates, J., Durance, P. and Godet, M. [2010] 'Strategic Foresight Issue: Introduction,' *Technological Forecasting and Social Change* 77:9: p.1423–1425.

Da Costa, P., Zagamé, P., Le Mouel, P., Garbi, O. and Pratlong, F. [2009] *Macroeconomic assessment for the EU ‘Climate Action and Renewable Energy Package’*, Foresight and ASSessment for

Environmental Technologies Integrated Project. Available at: http://www.webmeets.com/files/papers/EAERE/2009/917/eaere.pdf [Accessed October 2, 2013].

Department of Energy & Climate Change and Prime Minister's Office [2013] 'Initial agreement reached on new nuclear power station at Hinkley - Press releases - GOV.UK,' Available at: https://www.gov.uk/government/news/initial-agreement-reached-on-new-nuclear-power-station-at-hinkley [Accessed November 6, 2013].

Durance, P. and Godet, M. [2010] 'Scenario building: Uses and abuses,' *Technological Forecasting and Social Change* 77:9: p.1488–1492.

EDF, E.On, RWE, EnWB, Vattenfall, Enel, Eni, Endesa, Gas Natural Fenosa, EDP, Iberdrola, SSE and Centrica [2012] *Annual report*, Available at: Companies' websites.

Friedman, M. and Savage, L.J. [1948] 'The Utility Analysis of Choices Involving Risk,' *Journal of Political Economy* 56. Available at: http://ideas.repec.org/a/ucp/jpolec/v56y1948p279.html [Accessed July 12, 2013].

Godet, M. [2001] *Creating futures: scenario planning as a strategic management tool*, Économica.

Godet, M. [2010] 'Future memories,' *Technological Forecasting and Social Change* 77:9: p.1457–1463.

Godet, M. [2008] *Manuel de prospective stratégique Tome 2*, Paris: Dunod.

Godet, M. [2000] 'The Art of Scenarios and Strategic Planning: Tools and Pitfalls,' *Technological Forecasting and Social Change* 65:1: p.3–22.

Godet, M. [2002] 'Unconventional wisdom for the future,' *Technological Forecasting and Social Change* 69:6: p.559–563.

Godet, M. and Roubelat, F. [2000] 'Scenario Planning: An Open Future,' *Technological Forecasting and Social Change* 65:1: p.1–2.

Gonod, P. [2006] *Contribution de Pierre Gonod aux concepts clés de la prospective*, Collège Européen de la Prospective Territoriale. Available at: http://www.foresight-college.eu/IMG/pdf/PFG_contributions_total_p_copie.pdf [Accessed October 2, 2013].

Gonod, P.F. and Gurtler, J.-L. [2002] 'Evolution de la prospective,' *Oléagineux, Corps Gras, Lipides* 9:5: p.317–28.

Grand, E. and Veyrenc, T. [2011] *L'Europe de l'électricité et du gaz* Econometrica., Hansen, J.-P., Percebois, J., Boiteux, M. and Tirole, J. [2010] *Energie économie et politiques,* Bruxelles: De Boeck.

Henry, C. [1974] 'Investment Decisions Under Uncertainty: The ‘Irreversibility Effect.’,' *American Economic Review* 64:6: p.1006–12.

Hicks, J.R. [1939] 'The Foundations of Welfare Economics,' *The Economic Journal* 49:196: p.696.

Hines, A. and Bishop, P.J. [2006] *Thinking about the future: guidelines for strategic foresight,* Washington, DC: Social Technologies.

Hughes, N. and Strachan, N. [2010] 'Methodological review of UK and international low carbon scenarios,' *Energy Policy* 38:10: p.6056–6065.

Hughes, N., Strachan, N. and Gross, R. [2013] 'The structure of uncertainty in future low carbon pathways,' *Energy Policy* 52: p.45–54.

IAEA [2009] *Issues to Improve the Prospects of Financing Nuclear Power Plants*, Available at: http://www-pub.iaea.org/books/IAEABooks/8183/Issues-to-Improve-the-Prospects-of-Financing-Nuclear-Power-Plants [Accessed October 2, 2013].

IEA [2012] *WEO*, Available at: http://www.worldenergyoutlook.org/publications/weo-2012/#d.en.26099 [Accessed October 2, 2013].

Joskow, P.L. and Parsons, J.E. [2012] *The Future of Nuclear Power After Fukushima*, MIT CEEPR. Available at: http://dspace.mit.edu/handle/1721.1/70857 [Accessed October 2, 2013].

Markard, J., Stadelmann, M. and Truffer, B. [2009] 'Prospective analysis of technological innovation systems: Identifying technological and organizational development options for biogas in Switzerland,' *Research Policy* 38:4: p.655–667.

Massé, P. [1953] 'Les investissements électriques,' *Revue de Statistique Appliquée* 1: p.119–129.

Ministère du Développement durable [2013] 'Les réacteurs nucléaires de génération 4,' Available at: http://www.developpement-durable.gouv.fr/Les-reacteurs-nucleaires-de.html [Accessed October 3, 2013].

Neumann, J.V. and Morgenstern, O. [1944] *Theory of Games and Economic Behavior*, Princeton University Press.

OECD [2009] *The Financing of Nuclear Power Plants,* Available at: http://www.oecd-nea.org/ndd/reports/2009/financing-plants.pdf [Accessed October 2, 2013].

OECD and IAEA [2012] *Uranium 2011: Resources, Production, Demand*, Available at: http://www.oecdbookshop.org/oecd/display.asp?LANG=EN&SF1=DI&ST1=5K9778108FR8 [Accessed October 2, 2013].

OECD and Nuclear Energy Agency [2012] *Nuclear Energy and Renewables*, Paris: Organisation for Economic Co-operation and Development. Available at: http://www.oecd-ilibrary.org/content/book/9789264188617-en [Accessed July 31, 2013].

Pigou, A.C. [1924] *The Economics of Welfare*, Transaction Publishers.

Rogner, H.-H. and Langlois, L. [2001] 'The Economic Future of Nuclear Power in Competitive Markets,' *Energy Studies Review* 10:1. Available at: http://digitalcommons.mcmaster.ca/esr/vol10/iss1/3.

Samuelson, P.A. [1943] *Foundations of economic analysis*, Harvard University Press.

Schenk, N.J. and Moll, H.C. [2007] 'The use of physical indicators for industrial energy demand scenarios,' *Ecological Economics* 63:2–3: p.521–535.

Venkataraman, S. [1997] 'The Distinctive Domain of Entrepreneurship Research,' *Advances in entrepreneurship, firm emergence and growth* 3: p.119–138.

Wang, G., Wang, Y. and Zhao, T. [2008] 'Analysis of interactions among the barriers to energy saving in China,' *Energy Policy* 36:6: p.1879–1889.

Weisbrod, B.A. [1964] 'Collective-Consumption Services of Individual-Consumption Goods,' *The Quarterly Journal of Economics* 78:3: p.471–477.

VI. ANNEX: INTERVIEWS OF ENERGY ECONOMY EXPERTS – QUESTIONS

This annex lists the questions asked during the semi-directive interviews:

- Do you think the liberalization of European market is favorable to nuclear/other technologies?
- What are proper policy instruments to encourage nuclear investments on this market?
- According to you, what is the optimal technology portfolio?
- According to you, how accurate/useful is LCOE?
- Do you think the liberalization of European market is compatible with CO2 emission reduction objectives? And with the CO2 emission trading scheme?
- What policy instruments other than permit trading and carbon tax could be effective?
- When it comes to investing in a new power plant, who are the decision-makers? What is the risk distribution and is it efficient?
- What are the current financing methods for power plants? What are the consequences on technology choices?
- Do you know of other original financing methods? Do you think they will spread in the future? What will be consequences on technology choices?
- Regarding future generations of nuclear reactors and especially Generation IV, what is the current state of research and development in Europe/France to your knowledge? Are there programs to develop such technologies? On what financing schemes?