The challenges of the French electricity generation sector: an analysis using ESDMA

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Abstract

Nuclear energy dependency, large vulnerability to socio-political factors, high wind and solar energy targets and progressive liberalization of the energy sector; those are some of the main challenges the French electricity sector is currently facing. This paper uses the multi-method Exploratory System Dynamics Modeling and Analysis to explore the future of the French electricity generation sector given its unique specificity and the wide range of deep uncertainties that this market contains. This methodology then allows the exploration of the complex interaction between socio-political parameters and the support for new nuclear energy installed capacity. The model used for this research was created by Pruyt, et al. (Energy Transitions towards Sustainability: A Staged Exploration of Complexity and Deep Uncertainty, 2011) and has been adapted to reflect the specific dynamics of the French electricity generation sector. The paper will end with a presentation of the work that will be carried out in the future for the purpose of this research.

Keywords. Exploratory Systems Dynamics Modeling and Analysis, French electricity generation, Nuclear energy, Renewables, Deep uncertainty

1. Introduction

The French electricity sector is characterized by its high specificity when compared to those of its neighboring countries. After the first oil shock of 1974, France decided to massively develop civil nuclear industry in order to benefit from an energy source that was less dependent on social and economic events in energy exporting countries. Currently, 40% of the energy consumed in France is produced by nuclear power plants, representing over 75% of the electricity consumption (RTE EDF Transport 2011). This politically driven investment has resulted in a high degree of specialization in this technology, leaving little room for innovation in other means of electricity generation. As a result of this specialization, nuclear energy has become an element of strength for the French economy for both the stability of the electricity price in the country and for the technology it enables to export (Teräväinen, Lehtonen and Martiskainen 2011). An illustration of this fact is the high number of nuclear power plants in Europe that were built by the French company Areva (Thomas 2009).

The current context however puts a threat on the dominancy of nuclear energy and challenges the French government to reconsider its energy policy. First, the Fukushima nuclear accident raised once again the question of the high risks associated with the production of nuclear electricity (Srinivasan and Rethinaraj 2013). As a result, many countries like Germany decided to end the utilization of nuclear energy and to progressively shut down their power plants (Evans 2011). Secondly the European Union, through the ‘climate and energy package’, has imposed renewable energy targets to be reached by 2020. This leaves France with a gap of 9.4% of the total electricity consumption to be covered by renewable power plants in less than eight years (RTE, Bilan électrique 2012 2013). Wind and solar energy are considered the two most interesting green energy sources in order to achieve this goal.

The future of nuclear electricity generation in France is hence subject to a great amount of complexity and deep uncertainty. This research aims to explore the future evolution of nuclear energies in France, given the specificities of the country's energy market, social and economic characteristics and the uncertainties contained by these parameters. Several scenarios will be inserted in the model to test the effect of possible nuclear incidents on the dominancy of this electricity source. This will enable the analysis of the impact of nuclear energy's evolution on renewable energies, keeping in mind the fact that France has installed capacity targets to achieve by 2020, and will probably receive supplementary goals for 2050. To perform this analysis, the system dynamics model created by Erik Pruyt, Jan Kwakkel, Caner Hamarat and Gönenç Yucel, presented at the 29th International Conference of the System Dynamics Society (Energy Transitions towards Sustainability: A Staged Exploration of Complexity and Deep Uncertainty 2011) will be utilized and adapted to the specificity of the French electricity generation sector. The methodology applied here is Exploratory System Dynamics Modeling and Analysis (ESDMA), a multi-method that uses both System Dynamics and the Exploratory Modeling Analysis methodology to explore the development of a system that is characterized by high complexity and contains deep uncertainties.

This paper is structured as follows. Section 2 provides more information about ESDMA and the model used for this research. Section 3 presents the dynamics that characterize the French electricity generation sector and demonstrates how they are inserted and represented in the model. In section 4 we analyze the behavior of the model and present the simulation outputs. In section 5, we present the future work that will be carried out in this research and section 6 will provide conclusions on the development of the different technologies in order to analyze the complexity of the evolution given the systems deep uncertainties.

2. Methodology: Exploratory Systems Dynamics Modeling and Analysis

The French electricity generation sector can be seen as a system that displays complex and dynamic behavior as a result of the wide range of variables that influence each other both positively and negatively. The evolution of this system is also dependent on factors containing deep uncertainties. An example is the economic development of the country, which greatly influences the amount of new generation capacity to be installed. The multi-method Exploratory System Dynamics Modeling and Analysis (ESDMA) is applied to deal with those characteristics. It offers interesting opportunities to test the deep robustness of potential policies to change the system's behavior (Kwakkel and Pruyt 2012) (Pruyt and Hamarat, The Concerned Run on the DSB Bank: An Exploratory System Dynamics Approach 2010).

ESDMA uses a dual methodology: System Dynamics (SD) and the research methodology Exploratory Modeling and Analysis (EMA). While the SD simulation is used to create a model which enables the generation of scenarios for the development of the system, the use of EMA offers the possibility to test and demonstrate the robustness of policy decisions. It will here generate a high number of plausible transient scenarios while varying the value of model parameters containing important uncertainties (Lempert, Popper and Bankes 2003). Thereby, this will give the possibility to test the effectiveness and robustness of different policies by taking into account the entire multi-dimensional uncertainty space bringing the outcomes into a very limited amount of output displays (Pruyt, Kwakkel, et al. 2011).

The EMA methodology consists of six steps: (1) conceptualization of the policy problem, (2) specification of the uncertainties and certainties that play a role for policy analysis, (3) development of a system model, (4) generation of thousands to millions of scenarios, (5) exploration and simulation of the outcomes of the computational experiments to analyze the system behavior and lastly (6) test and display of policy recommendations(Agusdinata 2008).

The model used in this research is based on a model created by Pruyt, Erik, Jan Kwakkel, Caner Hamarat and Gönenç Yucel, which has been presented at the 29th International Conference of the System Dynamics Society (Energy Transitions towards Sustainability: A Staged Exploration of Complexity and Deep Uncertainty 2011). This model shows the battle between old and new electricity generation technologies in the context of the current energy transition. Several elements drive the development of a certain technology. One of them is the progress ratio of this technology, which shows the remaining potential available to improve the efficiency of a type of electricity generation and thus how its marginal costs will decrease. The lower the progress ratio, the higher the future expected decrease of costs as a result of the utilization of this technology. More explanations about the use of this progress ratio will be given in section 3.b. To match the characteristics of the French electricity generation sector, the model created by Pruyt, et al. has been adapted by changing the values of certain variables, by making changes into the structure of certain dynamics and by adding new ones. The changes made to the model can be found in the same section (3.b).

3. Structure and specificity of the French electricity generation: application

a. Type of technologies

The model describes the evolution of several types of electricity generation in France: nuclear energy, wind energy, solar energy, hydroelectricity, and grey energy (electricity produced by coal and natural gas). The different types of electricity generation are here modeled by taking their specific functions in the French electricity network into account. For example, grey electricity (by means of gas turbines) and hydroelectricity are used to cover peak electricity demand; their cumulated share in the total capacity installed can therefore never decrease below a certain percentage to ensure a minimum reliability of the electricity supply. The following table shows an overview of each type of technology and the way it is utilized in the French electricity sector. Annex A provides more detailed information about the state of those technologies in France.

Type of technology	Situation in the French market	Function in the model
Nuclear energy	- dominant source of electricity (49% of the installed capacity in 2012) - vulnerable to discontinuous level of socio-political trust	- relatively profitable (due to feed-in tariff) - reliable production of electricity - inflexible electricity production - relatively high progress ratio (rather little efficiency improvements expected)
Wind energy	- an upcoming electricity source - quasi non-existing installed capacity in 2000	- relatively profitable (due to feed-in tariff) - unreliable electricity (production fluctuation) - rather low progress ratio (rather highefficiency improvements expected)
Solar energy	- an upcoming electricity source - very small installed capacity in 2000	- highly profitable (due to feed-in tariff) - unreliable electricity (production fluctuation) - low progress ratio (huge efficiency improvement expected)
Grey electricity	- 21% of the installed capacity - used to cover the daily intermediate and peak demand - no feed-in tariff	- not really profitable and low investment security (no feed-in tariff) - reliable production of electricity - flexible electricity production - high progress ratio (very little efficiency improvement expected)
Hydro-electricity	- 19.5% of the installed capacity - used to cover the daily intermediate and peak demand	- rather profitable (feed-in tariff), but nearly all possible construction place for dams already used - reliable production of electricity - flexible electricity production - high progress ratio (very little efficiency improvement expected)

Table 1: Characteristics and functions of the different technologies in the French electricity generation sector

b. Dynamics of the system

The following subsection provides an overview of the main dynamics of the model that have been added to or changed in the model of Pruyt, et al. The overview given here will show the influence of those dynamics on the system by means of causal relations and feedback loops. Also, because of its importance in the model, a description of the effects of the technology's progress ratios(already present in the model of Pruyt, et al) will be provided. Lastly, this section shows a list of all the dynamics present in the model.

New technology cost

A progress ratio has been assigned to each technology. The progress ratio "derives from historical data inexperience curves (and) are used for forecasting development of many technologies as a means to model endogenous technical change in for instance climate–economy models" (Sark 2008). It thus represents the speed of learning of a technology's exploitation. The progress ratio influences the new cost of the technology through a negative logarithmic function ('-log') and then through a negative exponent ('a^[-X]'). The change in the new capacity costs is measured by the following formula:

$$C(x_t) = C(x_0)\left(\frac{x_t}{x_0}\right)^{-b}$$

Where $C(X_t)$ is the cost of the technology. $C(X_0)$ is the cost of the technology at the starting point. X_t and X_0 are then respectively the cumulated production at time t and time 0. B is the learning parameter (Ferioli, Schoots and Zwaan 2009). The new cost of the technology thus also depends on the installed and decommissioned capacity.

A higher progress ratio means a lower experience curve parameter (which is calculated by the negative logarithmic function) and therefore a slower reduction of the new technology costs. The height of the new technology costs then increases the expected earnings for the new power plants and thus the preference for the technology. An example of a technology with a high progress ratio is hydroelectricity, which is a technology that has been exploited for a long time and which is not expected to have significant technological progress.

The new cost of the technology is then used to calculate the expected earnings for the electricity producer when using the specific technology to build a power plant. Other parameters are used to calculate the expected earnings: electricity average market price, average production per year, variable costs and the lifetime of the technology installed. The expected earning per MW shows the total profit (during the total lifetime of the power plant) that the company will make by installing the technology. This variable is then compared to the expected earnings of the other technologies, which allows it to become more or less preferable in comparison to its 'rivals'. The comparison is made by computing the fraction of expected earnings of a specific technology on the sum of the expected earnings of all technologies.

Dynamics leading a nuclear incident

Commonly, there is a tendency to think that an industrial incident is the result of one main factor that is responsible for the sudden failure of the system. In the case of Chernobyl, the accident could essentially be explained by an operational error made by technicians who had a lack of knowledge in the operation of nuclear power plants.

However, when studying those types of accidents, more interactions can be found with factors that are not immediately expected to have a significant impact on the system but still correlate significantly with the event. In their article about air transport safety, Ale et al. investigate the elements leading to the occurrence of an air crash incident by using a causal model (Ale, Bellamy, et al., Towards a causal model for air transport safety - an ongoing research project 2006) (Ale, Bellamy, et al., Further development of a Causal model for Air Transport Safety (CATS): building the mathematical heart 2009). In their model, they show that the increased probability of an air crash accident can be traced back to a more complex succession and combination of several minor events that aren't solely technical. On the same basis, the Chernobyl event can be linked to a higher accident probability that correlates among others with socio-political factors like the declining performance of the national economy, the decreasing degree of the country's specialization in this technology (due to a lack of investment in new nuclear power plants in the years preceding the incident) and the diminution of public attention towards this sector (Qureshi 2007).

In this research, four factors that together could increase the possibility of the occurrence of a nuclear incident have been identified:

- Factor 1 - *the state of the national economy*: an economy that is not performing well has less capacity to invest in infrastructure maintenance.
- Factor 2 - *the amount of new nuclear energy capacity installed in recent years*: a low investment level in new nuclear energy capacity leads to a reduction of the specialization of the energy sector in this technology and therefore to a decrease of knowledge in how to manage nuclear energy.
- Factor 3 - *temporary excessive electricity demand*: difficult electricity production conditions during winters (due to a high heating demand) and during summers (due to a high cooling demand and the difficulty to cool power plants down) increase the chance of operational incidents.
- Factor 4 - *public and political attention*: high public and political attention is considered to encourage investments in the operational safety of nuclear power plants.

By using lookup functions, each factor creates a nuclear incident probability parameter. All four probability parameters are multiplied together and in case a certain threshold is reached, a nuclear energy incident happens. The fact that the multiplication of these four probability parameters determines the occurrence of an incident means that all four factors are needed (i.e. have to be sufficiently high) in order to create a nuclear incident. Four thresholds have been created. If only the lowest threshold is reached, an INES 4 level nuclear incident will occur (IAEA 2013). If the highest threshold is surpassed, an INES 7 level nuclear incident is simulated.

Factor 1 is modeled as a stock that 'accumulates' the last five years monthly economic development figures. A low average economic development score in the last 5 years will strongly increase the nuclear incident probability parameter of factor 1.

Similar to factor 1, factor 2 is modeled as a stock that 'registers' how many new nuclear energy capacity has been installed in the last 5 years. A low level of investments increases the nuclear incident probability parameter of factor 2.

Factor 3 is modeled as a sinus function. The assumption has been made that a temporary excessive electricity demand only happens twice a year: one time in the winter and one time in the summer. The sinus function is written as follows:

*Factor 3 incident probability parameter = ABS(Randomiser extent of the electricity demand*SIN((3.1415*2)*(Time-2000)))*

The sinus part of the function is multiplied by a random parameter that increases or reduces the extent of the electricity demand. 2000 is the start time of the model.

Factor 4 is part of a negative feedback loop that is influenced by the level of trust in nuclear energy within the country. In case a nuclear incident occurs, the public attention increases and the chances that a second nuclear incident occurs strongly decrease.

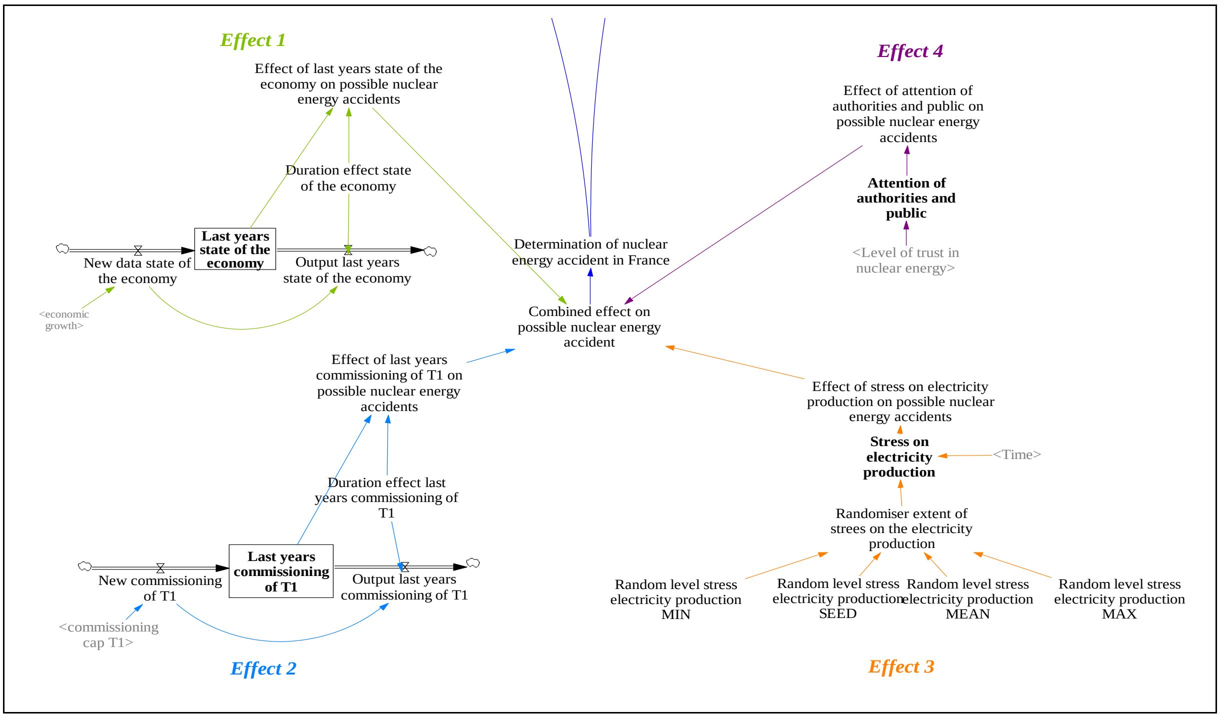

Figure 1: Overview the modeling of the dynamics leading to a nuclear incident

Finally, when a nuclear incident occurs in France, two variables are influenced. First a share of the nuclear energy capacity is removed depending on the extent of the incident. Secondly the level of trust in nuclear energy decreases, which means that new investments in nuclear energy are partly blocked.

As mentioned before, this study uses the INES scale used by the International Atomic Energy Agency to create different size nuclear incidents. An article written by D.Smythe provides estimations of the occurrence frequency of each INES scale incident (Smythe 2011). Although these frequencies are not used as fixed numbers in the model and have been included in a uniformly distributed uncertainty range, these figures contain a large amount of uncertainty which will thus have consequences for the interpretation of the model results. Many other parameters included in the variables (and among other thresholds) and stocks are not strongly based on proven data since no data for that kind of simulation is available yet. For the purpose of this research, work is still needed to deal with and interpret these uncertainties.

Dynamics leading to a decrease of trust in nuclear energy

The level of trust in nuclear energy is influenced by two factors: potential nuclear incidents in France and potential nuclear incidents in foreign countries. Nuclear incidents in other countries are here assumed not to lead to removals of nuclear energy capacity in France and have a lower impact on the level of trust. The level of trust in nuclear energy is modeled as a stock that is constantly filled up by a confidence return rate, and 'emptied' by successive nuclear incidents of different sizes (including very low size incidents). Figure 2 provides an overview of the behavior of the level of trust in the nuclear energy stock.

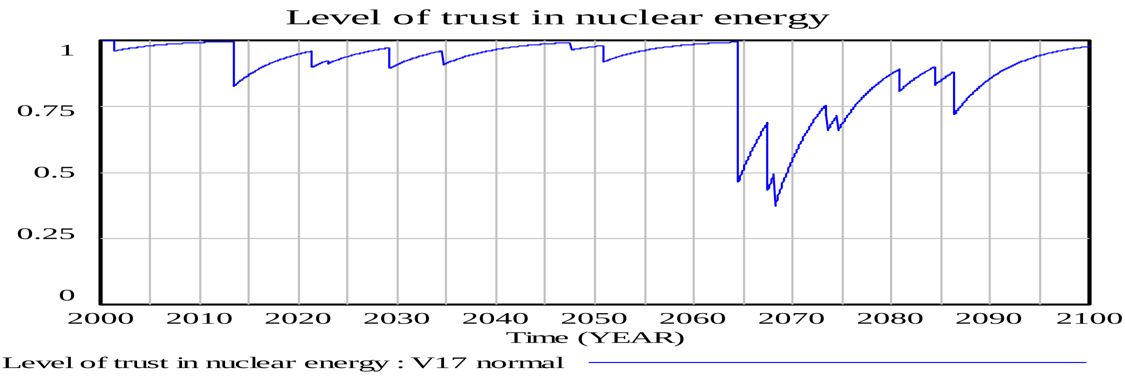

Figure 2: overview of the behavior of the level of trust in nuclear energy stock

Influence of the European development of renewable energies

The dependency between European energy markets is high, and therefore the French energy system cannot be considered to evolve fully independently. The fact that a specific technology is relatively new in neighboring countries (and thus a low number of mature companies in this sector) decreases the speed at which the same technology is developed within France. Because the incorporation of other countries' energy systems would add an even higher amount of uncertainty into the model, a theoretical evolution of wind and solar energy on European scale has been created to simulate the effect of this development on the French electricity market. The formula used is the following:

$$Level\ of\ technology\ specilisation\ in\ Europe = 1/(1 + \left(\frac{1-\frac{C0}{pC}}{\frac{C0}{pC}}\right)e^{-k(t-t0)}$$

Where *C0* is the European installed capacity of the technology in the year 2000, *pC* is the theoretical potential European installed capacity of the technology, *k* is the adoption rate, *t* is the current time and *t0* is the start time of the model.

Parameters	Wind energy	Solar energy
European capacity in 2000	12.887 MW	2.000 MW
European potential capacity	297.500 MW	988.000 MW
Adoption rate	0,258	0,219
Percentage when market considered mature enough	15%	15%

Table 2: Parameters for European influence on French wind and solar energy market

Summary of the model dynamics

Dynamic	Effect in the model
Industry specialization	Preference for a certain technology due to the intensity of its utilization in the past
Expected progress performance	Preference for a certain technology as a result the expected decrease of its costs
New capacity costs	Decrease of the capacity costs due to its utilization
New technology cost	Preference for a certain technology due to its costs compared to other technologies
Dynamics leading a nuclear incident	Effect of the simultaneous occurrence of 4 factors that lead to the occurrence of a nuclear energy incident
Dynamics leading to a decrease of trust in nuclear energy	Effect of previous nuclear energy incidents that decrease the preference of nuclear energy
Influence of the European development of renewable energies	Preference for a certain (RE) technology resulting from the investments made on European level
Demand for reliable electricity sources	Effect of the need for a minimum level of reliable electricity source for the good functioning of the electricity sector
Demand for peak load installed capacity	Effect of the need for a minimum level of flexible energy generation for the good functioning of the electricity sector

Table 3: summary of the dynamics present the model

c. Input data

Parameter	Unit	Nuclear energy	Wind energy	Solar energy	Grey electricity	Hydro-electricity
Capacity in 2000	*MW*	63000	61	120	27000	25000
Cumulative decommissioned capacity in 2000	*MW*	0	0	0	2000	10000
Lifetime	*yr*	[30 - 50]	[20 - 30]	[20 - 30]	[15 - 40]	[30 - 50]
Technology cost	*10^6€/MW*	1.8	1.5	7.6	1.2	0.5
Progress ratio		[0.85–0.95]	[0.85 – 0.95]	[0.85 – 0.95]	[0.85 – 0.95]	[0.85 – 0.95]
Feed-in tariff	*€/MWe*	42	82	300	/	60.7
Average production per year	*MWe/MW*	8000	2000	1250	3000	2770
Variable cost	*€/MWe*	28.4	2	5	46	43
European technology adoption rate	*%*	/	0.219	0.258	/	/
European potential capacity	*MW*	/	197500	988000	/	/
European capacity in 2000	*MW*	/	12887	2000	/	/
Average planning and construction periods	*yr*	[1 - 5]	[1 - 5]	[1 - 5]	[1 - 5]	[1 - 5]

Table 4: Input data of the five technologies

Parameter	Unit	Value
Economic growth	*%/year*	[-1 ; +3]
End value of electricity intensity of economic growth	*%/year*	[40 ; 100]
Average electricity price	*€/MWe*	[40 ; 70]
Average selling price grey energy	*€/MWe*	[55 ; 100]

Table 5: Other input data of the model

Some of the parameters' values are highly or even fully predictable. This is for example the case of the installed capacity of each technology in the year 2000 and their average production per year. However, other parameters are highly uncertain (in table4 and 5 specified by ranges). The progress ratio is for example a theoretical calculation of the estimated progress that a technology could reach through higher efficiency and price decrease. Another example is the forecasted economic growth of the country. Those parameters will have a major impact on the outcomes of the model and are deeply uncertain. It is then by using the EMA methodology that it will be made possible to include those ranges in the model, and explore their effect on the overall system by running the model thousands of times.

4. Results

This chapter will present three different types of results. The first part (4.a) shows the development of the five installed capacities (nuclear energy, wind energy, solar energy, grey electricity and hydroelectricity) without any nuclear incident being generated. The second part (4.b) shows the effect of nuclear energy incidents on the installed capacity of nuclear energy, when the dynamics leading to a nuclear incident are taken into account (see chapter 3.b.). The third part (4.c) presents a comparison of the effects of a large nuclear incident in France in 2020 and 2060 using the five different technologies.

To generate these outputs, the model has been run 1000 times by using among others the uncertainties mentioned in section 3.c. The envelopes hereunder give an overview of the technologies' evolution for a period of 100 years starting from the year 2000. In each envelope, 25 randomly chosen lines show the installed capacity over time. An end state distribution of the installed capacity in 2100 is provided on the right side of the envelope.

a. Development of the different installed capacities (without nuclear incident)

Development of nuclear energy

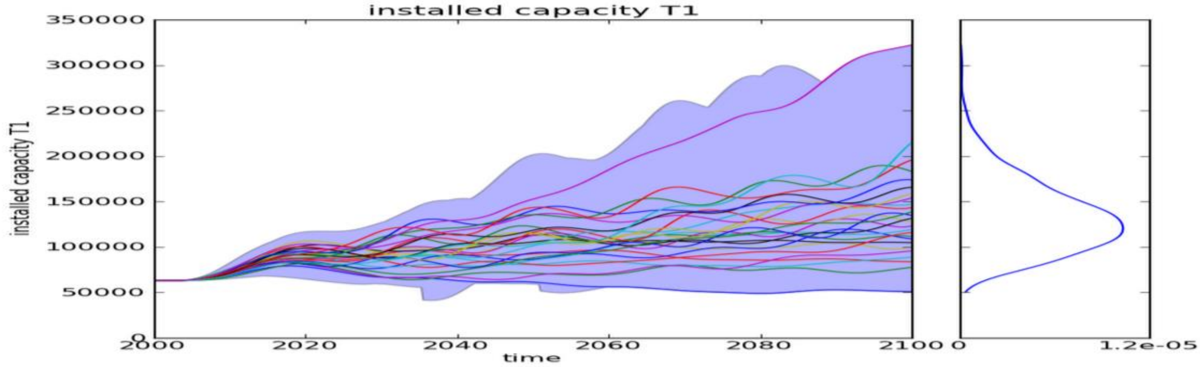

Figure 3: the development of nuclear energy

The envelope shows a rather wide possibility of outcomes. The installed capacity never decreases below 50 GW and in some occasions, it even rises above 325 GW in 2100. The installed capacity however seems to concentrate between 100 and 150 GW. It seems that the uncertainties inserted into the model parameters play an important role in determining the evolution of nuclear energy capacity. Observing the lines, it can be observed that in most cases the installed capacity of nuclear energy rises between 2010 and 2040. This is a trend that can also be observed in the wind energy envelope. The period between 2010 and 2040 is thus a moment where, according to the model, the demand for new generation capacity is high, and where nuclear and wind energy are seen by the model as the two preferred types of electricity source. The period between 2040 and 2100 however displays a stabilization of the total nuclear energy capacity, except in some rare cases where the share of installed capacity increases constantly.

Development of wind energy

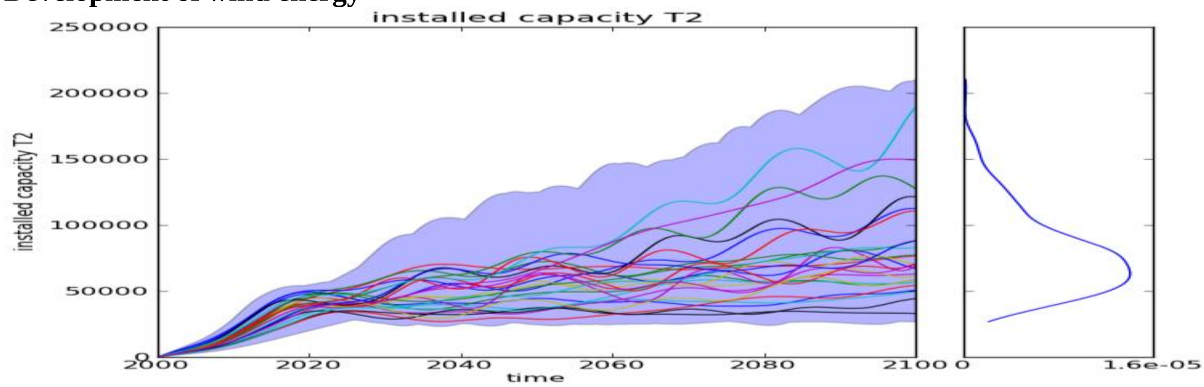

Figure 4: the development of wind energy

The envelope describing the wind energy evolution displays a minimum installed capacity of 30 GW and a maximum of 210 GW by 2100. The installed capacity concentrates around 80 GW but in each case, wind energy succeeds in developing and grabbing a strong part of the total installed capacity. Analyzing the outcomes, it seems that two different types of lines can be observed: lines that remain constant after 2040 and those that continue to increase. The same observation can be made for the development of solar energy. The second type of lines has the tendency to fluctuate more whereas the first type of lines has a more steady development. The period between 2020 and 2040 plays an important role. If wind or solar energy succeed in pursuing their development after 2020 (i.e. after the feed-in tariff is removed), they will continue to compete strongly with the other technologies which creates this fluctuating pattern. If not, they will enter an equilibrium state and keep their level of installed capacity until 2100.

Development of solar energy

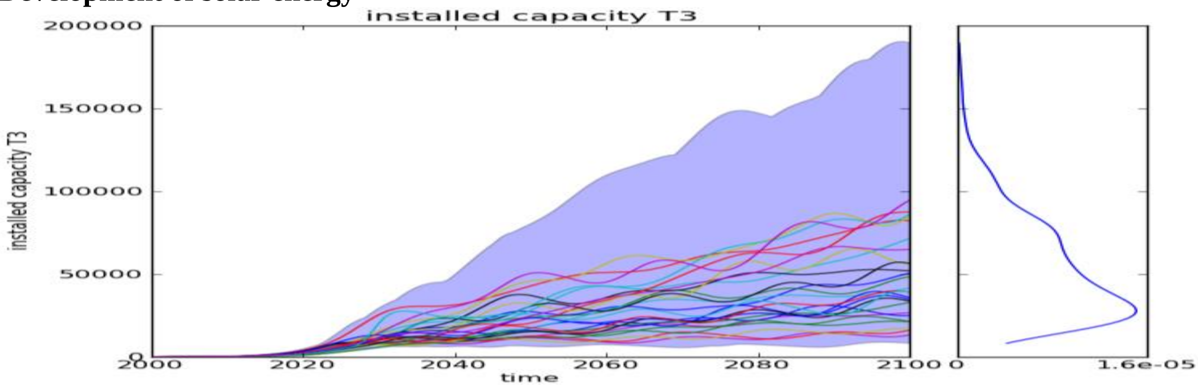

Figure 5: the development of solar energy

According to the simulation made by running the model, solar energy does not succeed in developing to the same extent as wind energy, even if the technology has a greater expected progress. Whereas wind energy uses the period between 2000 and 2020 to gain a large share of the installed capacity, solar energy only begins its development later since the solar technology is less mature than wind energy technology. Therefore solar energy only succeeds in becoming an important electricity source in a few cases. Figure 6 shows that, whatever the winner between solar and wind energy, the end state distribution of the renewable energies fraction has the tendency to concentrate around 40 %.

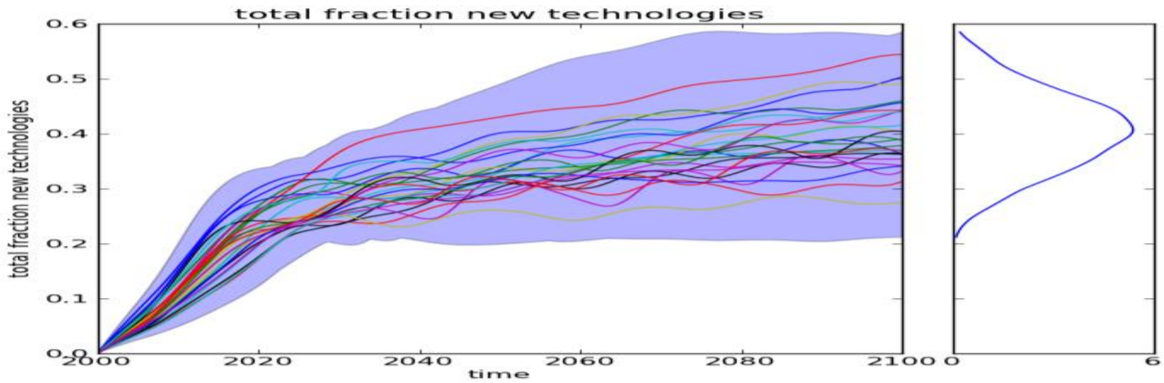

Figure 6: the development of the fraction of renewable energies

Development of grey electricity

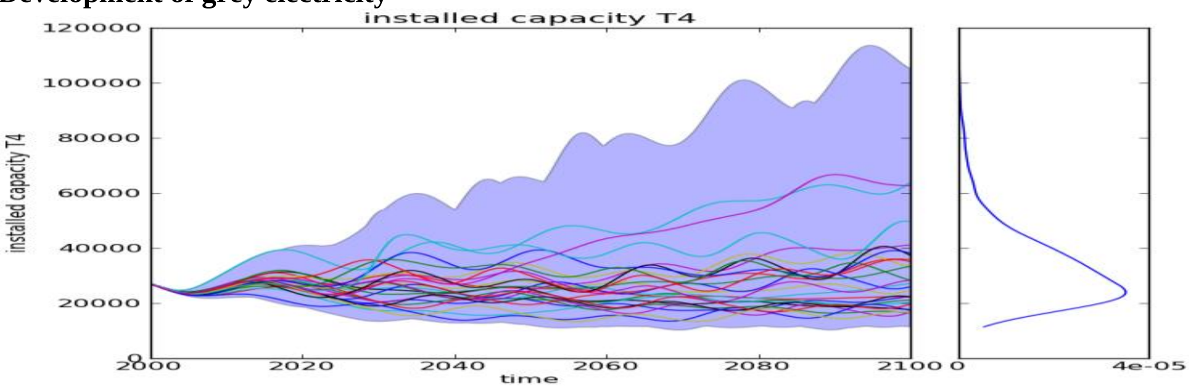

Figure 7: the development of grey electricity

According to the model grey electricity is not expected to become as important as nuclear energy. The end state distribution displays a range from 12 GW to 100 GW but the final installed capacity concentrates between 12 GW and 40 GW. An increase of the installed capacity between 2020 and 2040 can enable grey electricity to become an important energy source but in many cases the amount of installed capacity in 2000 and 2100 does not differ widely.

Development of hydroelectricity

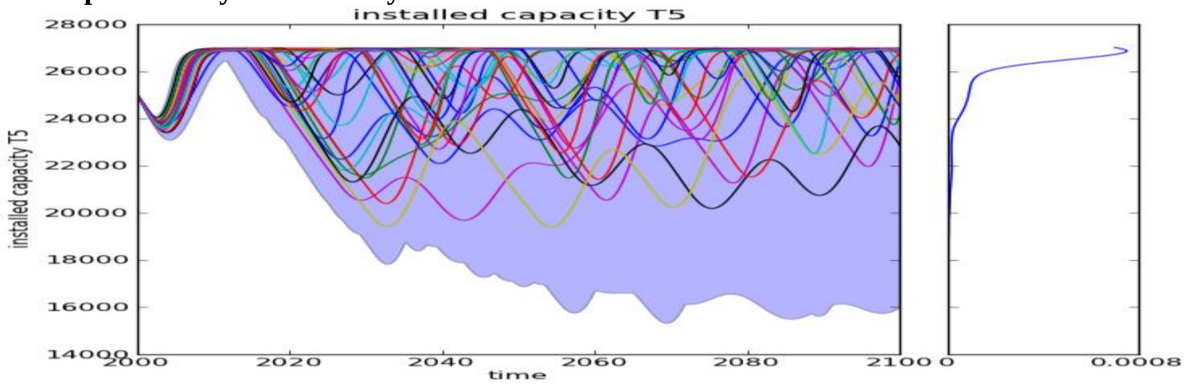

Figure 8: the development of hydroelectricity

The physical boundary that constrains further development of hydroelectricity prevents this technology to take over an important share of the total installed capacity, but its low cost and utility in the electricity generation market ensure that in most cases the capacity is utilized at full potential.

b. Effect of incidents in France and foreign countries on the nuclear energy installed capacity

Chapter 3.b explains how the dynamics leading to a nuclear incident have been modeled. Figure 9 provides an overview of its effect on the installed capacity of nuclear energy and compares it to the case when no nuclear incidents are generated.

The second part of the graph clearly shows one case (blue line) when two nuclear energy accidents happen (one just after 2040 and one just after 2080). These nuclear incidents both happen after a period in which no (or very little) new investments in nuclear energy have been made (the blue line was progressively decreasing) and the economic development was low or even negative. These are two of the factors that increase the chance of a nuclear incident.

However the end state distributions are very similar which firstly means that, given the parameters that were used in the model, the amount of times that nuclear energy incidents happen is low and secondly that nuclear energy often succeeds in taking back the installed capacity 'lost' after a nuclear energy incident.

As mentioned above, more work is needed to identify the factors (and their interdependencies) and increase the certainty of the parameters used currently to determine whether a nuclear energy accident is likely to occur.

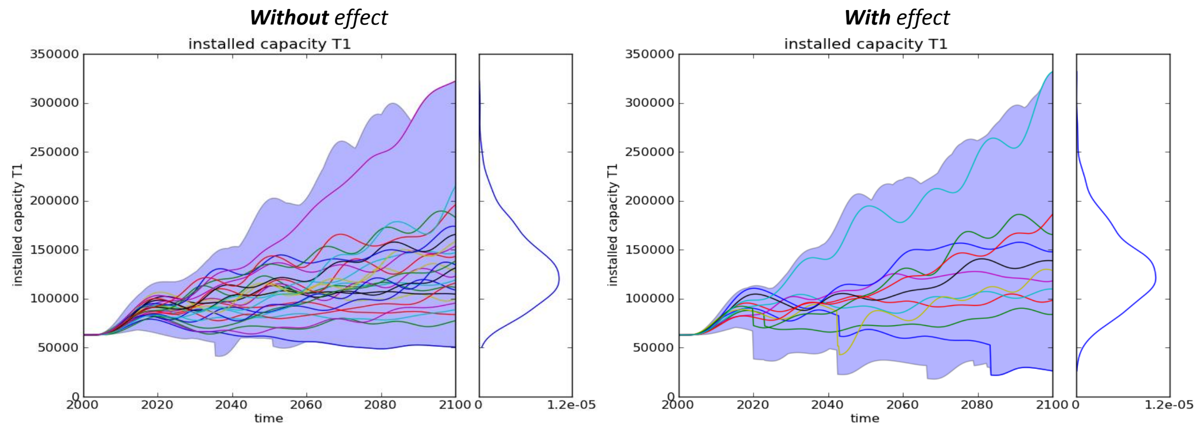

Figure 9: comparison of the installed capacity of nuclear energy without and with potential nuclear energy incidents

c. Comparison of the effects of a large nuclear incident in France in 2020 and 2060

To study the effect of a nuclear energy incident on the five electricity sources, two ‘large’ nuclear energy incidents have been simulated in 2020 and in 2060. In each case the amount of nuclear energy removed is randomly chosen between a 40 and 60 percent). Additionally, the preference for nuclear energy is reduced by 50 to 90% and then slowly returns to its initial value according to the confidence return rate.

By looking at the results, the following conclusions can be drawn:

- In many cases, nuclear energy succeeds in taking back a great amount of installed capacity after an accident. This is strongly explained by the specialization of the industry in this technology. The higher the amount of nuclear energy before the crisis (and thus the higher the specialization of the industry in this technology), the better and faster is the recovery after the accident (both in 2020 and 2060).
- Secondly, solar energy is able to take over a greater share of the total installed capacity in 2060 than it does in 2020. This is explained by the fact that in 2060, the solar energy technology is more mature. Unlike solar energy, wind energy is able to take a more important share of the installed capacity left over by nuclear energy in 2020.
- The nuclear accidents create disturbances and fluctuations in the installed capacity of each technology, but in general each level of installed capacity of each technology is tending towards an equilibrium state: none of the technologies disappear or become insignificant as a result of their competition.

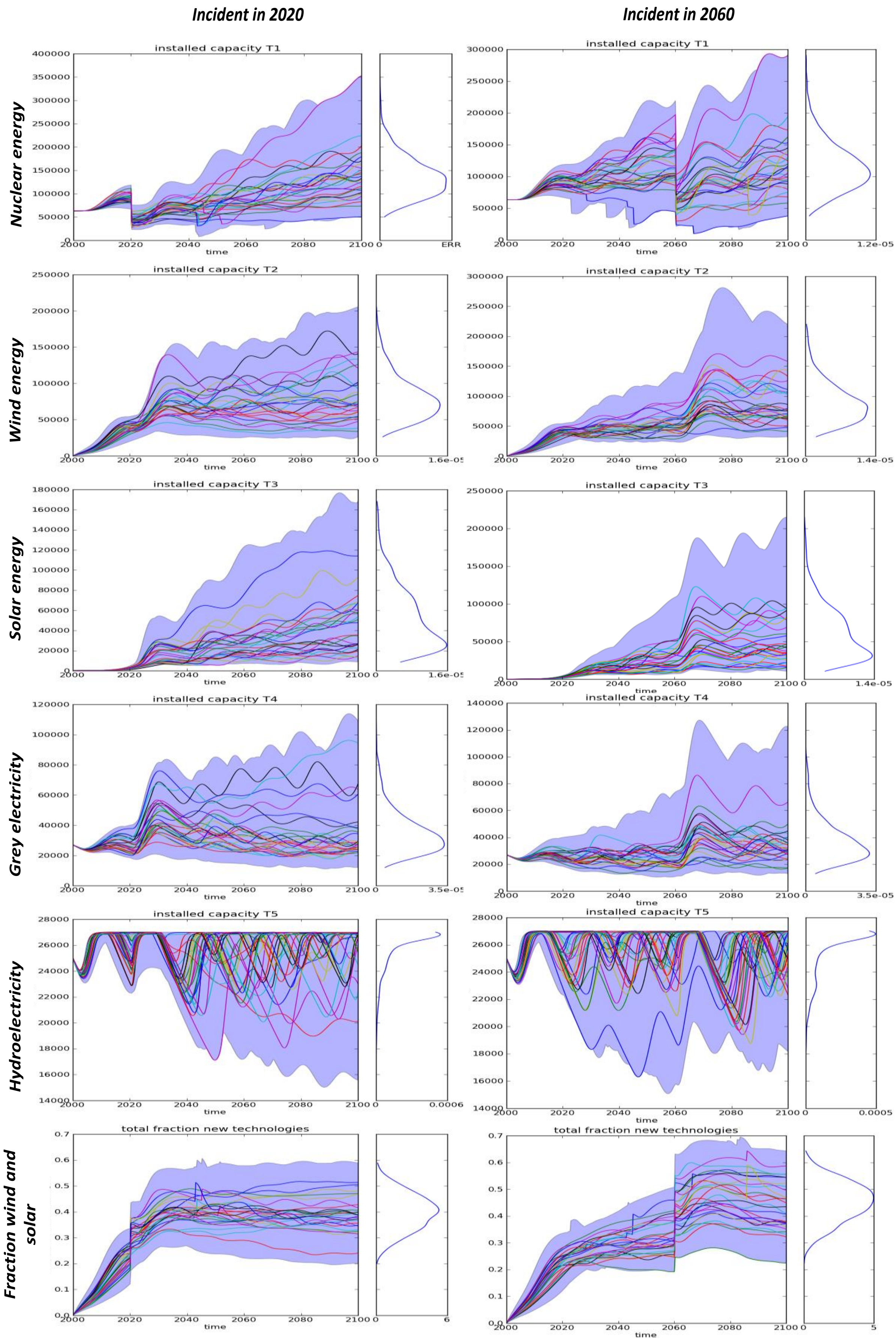

Figure 10: Simulation of nuclear energy incidents in 2020 and 2060

5. Future work

Dynamics of socio-political mistrust in nuclear energy and impact on electricity generation
Nuclear energy is highly vulnerable to fluctuations in the level of socio-political trust towards this technology. In the research that is currently conducted, the focus lies on the dynamics of public and political support for nuclear energy as a result of different system factors and on the way it affects the new installed capacity rate.

There is for example a correlation between the demand for electricity and the speed at which society trust nuclear energy again after an accident (Pligt, Eiser en Spears 1984). In France, the investments in nuclear energy stopped in the 80s due to the social impacts of the sequential incidents of Three Mile Island, Saint-Laurent-des-Eaux (France) and Chernobyl. It took over twenty years before the decision was made to make new investments in nuclear energy. While the argument of social impact is surely valid, the reason why no investments have been made in the technology within this period can also be explained by the low demand for new installed capacity. By the end of the 80s, there was so much new nuclear energy capacity installed that no further investment was really needed. In the case of Japan however, two years after Fukushima, the new government has already announced its intention to review its initial plans of abandoning nuclear energy generation (BBC News Asia 2012).

The model will be adapted by introducing a population of convinced and unconvinced citizens and politicians. Several types of variables will then influence the rate at which people move from one side to another (Pligt, Eiser en Spears 1984):

- People's beliefs about the economic advantages of nuclear power (influenced for example by the energy demand);
- People's beliefs about the safety of nuclear energy (influenced among others by the duration between the last nuclear incident and the present time); and
- People's beliefs about the socio-political implications of nuclear power (partly influenced by the rate at which new capacity is installed in comparison to development of renewable energy).

Development of different nuclear accident scenarios
Further research and modeling will be done by creating different scenarios and investigating their impact on the French electricity generation sector. For example, different nuclear crises on different scales will be simulated at different points in time to investigate the effect on the total amount of installed capacity available and the evolution of the other technologies. The occurrence of a large nuclear accident just before a period of high demand for new installed capacity could play a decisive role in the dominancy of this technology in France, since other electricity sources will then be prioritized. Nuclear energy will also be separated in the four different technologies that are currently used for electricity generation in France: CPO-CPY, P4-P'4, N4 and EPR (World Nuclear Association 2013). This will allow exploring the effect of a sudden failure of one of those technologies (for example as a result of a reactor incident which leads to the prohibition of the usage of this particular technology) on the development of the entire French electricity generation diversity. The prohibition of CPO-CPY nuclear power plants (mostly power plants installed between 1977 and 1988)would lead to a high amount of installed capacity to be replaced, while forbidding the use of the EPR technology (newest generation, no installed capacity yet but one power plant under construction) could put a threat on the future usage of nuclear energy in France.

The study and incorporation of those three elements in the model will enable a better understanding of the impact of a country's high dependency towards one unique technology in a world that sees a fast development of renewable energies and in which the risk of nuclear energy's utilization will probably never fully be eliminated.

6. Conclusions

This paper investigates the challenges of the French electricity generation sector and focuses particularly on the dependency of the country towards nuclear energy and its effect on the evolution of the other types of energies. By using the ESDMA multi-method, the development of the five types of electricity sources has been explored by considering the most important system uncertainties. The following observations about the model outcomes can be made.

According to the model and the uncertainty inserted, the period between 2020 and 2040 is a decisive moment for each technology. Whether one types of electricity source has an important place in 2100 depends upon its success during the second twenty years period of the model.

An important observation provided by the model's outcomes is that nuclear energy is expected to keep an important role in the French energy sector, given the uncertainties included in the parameters. The scenarios created in future work will test the robustness of this dominancy on its ability to survive the socio-political consequences resulting from a nuclear accident.

The outcomes of the model also shows that wind and solar act as competitors. The fact that wind energy is a more mature technology plays a decisive role in the success of its development by 2100.

The research results presented here also show that more work is needed on three different domains. First more work has to be done to understand and use the dynamics leading to the occurrence of a nuclear incident, both qualitatively and quantitatively. Secondly, the confidence return rate, which currently is a constant parameter, can be replaced by a variable in order to include new feedback loops in the model (effect of the state of the economy, the electricity demand and the installed capacity of renewable energies). Lastly, the nuclear energy capacity can be divided in 4 different technologies which are currently used in France. This will allow investigating the effects of the failure of one particular nuclear energy technology according to the age of the power plants.

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Annexes

Annex A – Sources used for the specification of model parameters

Nuclear energy
The biggest source of electricity in France is nuclear energy. In the year 2000, the installed capacity was 63000 MW and has remained unchanged since then (RTE, Energie Electrique en France 2000 2001)(RTE, Bilan électrique 2012 2013). Nuclear energy is thus the dominant source of electricity and is in this model challenged by the other upcoming means of production (wind and solar). In this model, it has been considered that the average lifetime of a nuclear power plant was 45 years (Bataille and Birreaux 2003). Even if the price a nuclear power plants have dropped a little in the past year, a megawatt was in the year 2000 worth 1.8 M€ (Gupta and Thompson 1999). The progress ratio of the technology was also considered by many scientific articles to lie between 0.96 and 1 (Lund University 2006). In order to protect the development of nuclear energy, the French has set up a feed-in tariff. For each MWe produced, a fixed selling price of 42 € is afforded (Le Monde 2011). Other specificities of nuclear power plant are the large average production per year, 8000 MWe/MW (DGEC 2008), and a variable cost of 28.4 €/MWe (DGEC 2008).

Wind energy
Wind energy has developed very lately in France. In 2000, the capacity didn't exceed 61 MW (RTE, Statistiques de l'Energie Electrique en France 2002 2003) but has however reached 7.500 MW in 2012 (RTE, Bilan électrique 2012 2013). Still, the progress ratio was rather high (between 0.90 and 0.96) since the technology was already been used intensively in Spain and Germany (Lako 2010).The price for a megawatt wind energy was approximately 1.5 M€ (Lako 2010).

As it did in the case of nuclear energy, the French government also came with a feed-in tariff in order to encourage the development of wind energy. Each wind energy producer is rewarded with a feed-in tariff of 82 €/MWe during the ten first year of the power plant. According to the production of the power plant during those ten first years, a new feed-in tariff between 28 and 82 €/MWe is then decided for an extra five year (IEA 2010). In this model, it has been considered that the average new feed-in tariff was 62 €/MWe (the mean between the maximum feed-in tariff, 82 €/MWe, and the average market price, 42€/MWe).

In the model, a wind energy power plant is considered to have a lifetime of 25 years (Lako 2010), an average production per year of 2000 MWe/MW (Blanco 2009) and a variable cost of 2 €/MWe (Lako 2010). In order to compute the theoretical development of the European wind energy market, the European potential capacity had been set to 197500 MW (Lako 2010). The potential capacity is the capacity that could be achieved in 2050. The European capacity in 2000 was 12887 MW (EWEA 2011) with an adoption rate of 0.258 (Lund 2006).

Solar energy
The solar energy capacity was in 2000 much higher than wind energy: 120 MW (RTE, Statistiques de l'Energie Electrique en France 2002 2003). A megawatt could be bought for 7.6 M€ (Lako 2010). The fact that solar energy didn't developed as fast as wind energy is partly to be explained by the fact that the solar energy European market wasn't as advance as the one of wind energy. The European capacity in 2000 was approximately 2000 MW (SETIC 2008). Still solar energy has a great potential in Europe: 988000 MW by 2050 (Lako 2010). The adoption rate is 0.219 (Lund 2006).

Other specificities of solar energy power plants are an average lifetime of 30 years (Lako 2010), and average production per year of 1250 MWe/MW (ADEME 2011) and variable costs of 5 €/MWe (Lako 2010). The progress ratio is estimated to be between 0.77 and 0.84 (Lako 2010).

The feed-in tariff offered for solar energy producers is 300 €/MWe during the first 20 production years of the power plant (IEA 2010).

Grey electricity
In the 70's, the French authorities decided to invest massively in nuclear energy in order to reduce the energetic dependence of the country. Therefore, grey electricity didn't develop so rapidly as in other countries. Still, it always played a significant role in order to fulfill the deficiencies of nuclear energy (mainly dealing with flexibility). In 2000, the total capacity of grey means of production was 27000 MW (RTE, Energie Electrique en France 2000 2001). The cost of a megawatt was 1.2 M€ (Croezen and Slingerland 2005) and the variable costs were 46 €/MWe (DGEC 2008). Since the different technologies are since long used, the progress ratio is very high: between 0.93 and 0.99 (Lund University 2006). No feed-in tariff is offered for grey electricity in France. Since the technologies does not function as base loads (a role that is fulfilled by nuclear energy), the electricity produced is only sold whenever the selling price is higher than a certain point. In France, the average production per year of grey means of production is 3000 MWe/MW (DGEC 2008). The lifetime of the power plants is in average 30 years (Croezen and Slingerland 2005)

Hydroelectricity
As grey electricity, hydroelectricity is mainly used to fulfill the deficiencies of nuclear energy in production flexibility. It thus plays an important role in the French electricity sector and has the advantage not to produce any greenhouse gases. Therefore, the French state has set up a feed-in tariff of 60.7€/MWe (IEA 2010).

Hydroelectricity represented in 2000 a capacity of 25000 MW (RTE, Energie Electrique en France 2000 2001). A turbine for hydroelectricity is considered to have a lifetime of 45 years (Lako 2010). The cost of the technology is relatively low (0.5 M€/MW) since the dams are already built (no extra dam can be added in France) (Lako 2010).A investment in hydroelectricity thus only means the replacement of the turbines.

The progress ratio of hydroelectricity is estimated to lie between 0.95 and 0.99 (Lako 2010), the average production per year is in France 2770 MWe/MW (RTE, Energie Electrique en France 2000 2001) and the variable costs lies around 43 €/MWe (Lako 2010).

Annex B – Model quantitative pattern behavior comparison

Output	Correlation	Um	Us	Uc	Utotal
Nuclear energy	0.229	0.88	0.12	0.00	1.00
Wind energy	0.993	0.25	0.65	0.10	1.00
Solar energy	0.924	0.18	0.08	0.69	0.95
Grey electricity	0.764	0.23	0.06	0.37	0.67

Table6: Summary of the 'Theil inequality statistics' test

The quantitative pattern behavior comparison uses the 'Theil Inequality Statistics' (University at Albany 2010). First the test shows the correlation coefficient between the curve produced by the model and the curve observed in reality. The correlation is thus a measure of the relation between a certain numbers of variables and determines to which extent the variables are proportional to each other. A correlation test assumes there is a certain linear relation between the variables, which is not always the case. Secondly, it does not reveal at which point the two curves differs (or not) from each other. This is why the 'Theil Inequality Statistics' also shows the constant deviance towards the average (Um), the deviance towards the amplitude (Us) and the deviance towards the phase (Uc). Those three terms are called the 'inequality proportions'. Theoretically, the sum of the Um, Us and Uc should be equal to 1.

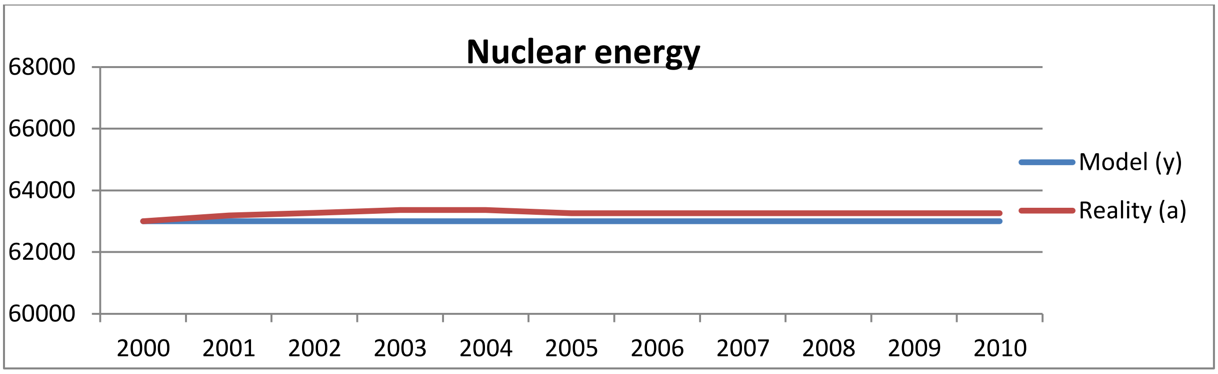

Figure 11: Quantitative pattern behavior comparison of nuclear energy

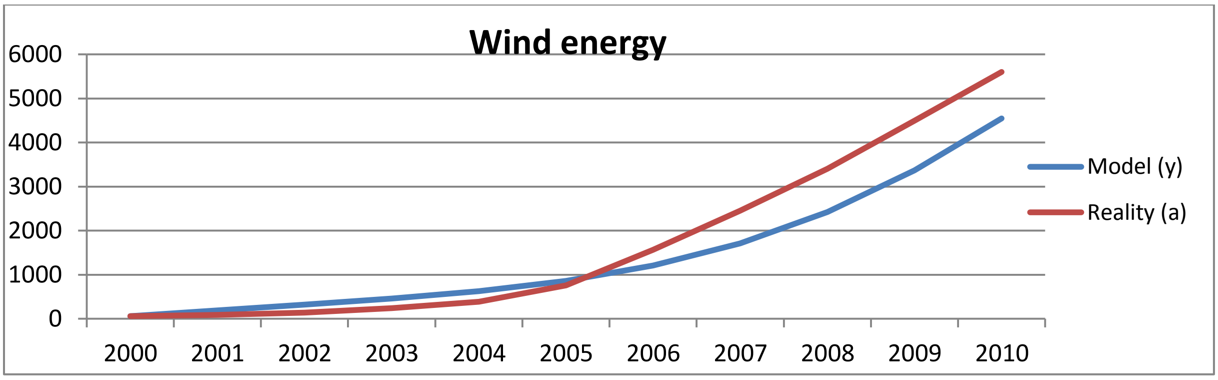

Figure 12: Quantitative pattern behavior comparison of wind energy

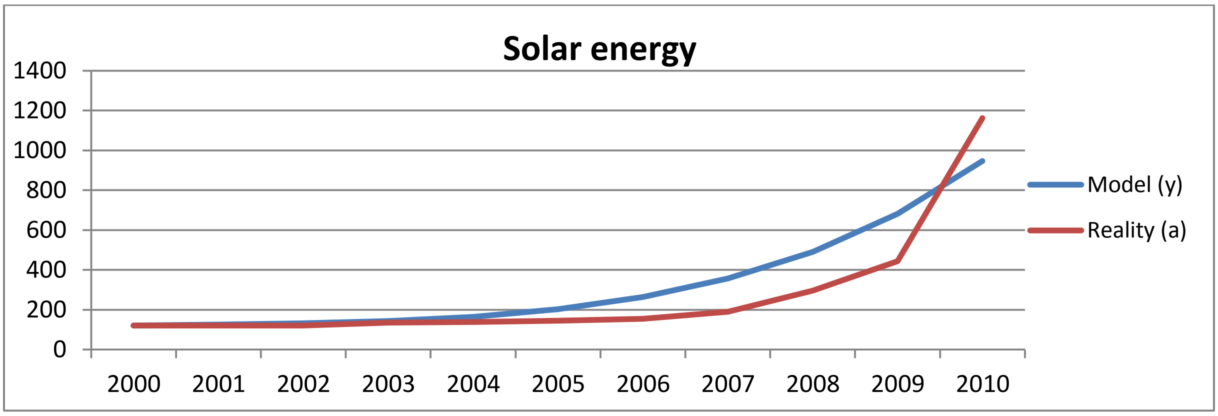

Figure 13: Figure 3: Quantitative pattern behavior comparison of solar energy

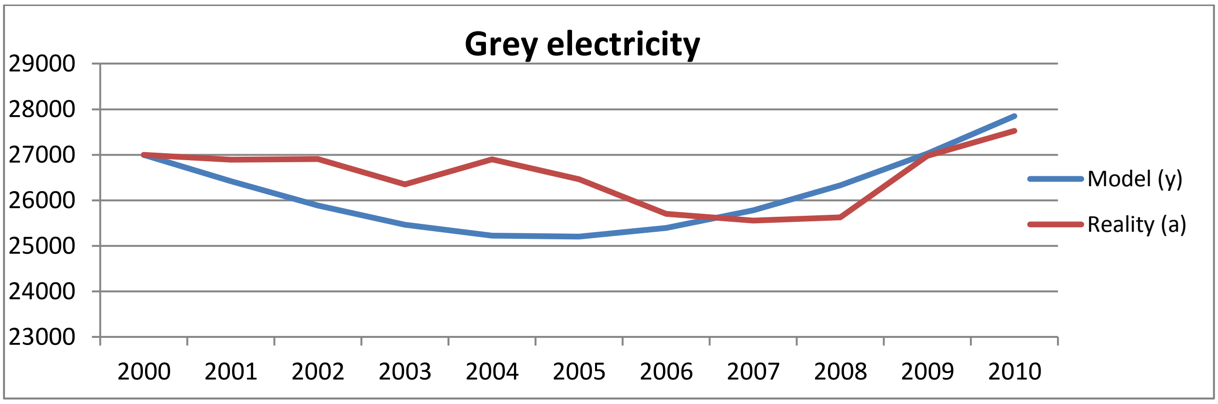

Figure 14: Figure 3: Quantitative pattern behavior comparison of grey electricity