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Nuclear energy policy in Belgium after Fukushima

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HIGHLIGHTS

- Belgium decided to close nuclear plants between 2015 and 2025 to promote renewables.
- Hopes for a technically acceptable schedule reduced after the Fukushima disaster.
- The Belgian electricity system has been modelled with system dynamics (SD).
- SD shows that nuclear plants will be mainly replaced by fossil-fuel plants.
- SD shows that it is better for renewables to delay shutdowns or to replace plants.

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ABSTRACT

The Belgian nuclear phase-out law imposes closing down in the 2015–2025 period seven nuclear power plants (NPPs) producing more than 50% of the domestic electricity. This creates an urgent problem in the country because of the absence of well-defined capacity-replacement plans. Though a safety-of-supply provision in the law allows for a delayed phase-out, hopes for a technically acceptable schedule have reduced after the Fukushima nuclear disaster in March 2011. In this article policy investigations are made with system dynamics. A significant finding from such modelling is that, in contrast to common expectations, a too early nuclear phase-out will not serve the deployment of renewable energy sources and rational use of energy. It is indeed found to primarily benefit to fossil fuel, creating unwanted drawbacks regarding safety of supply, dependency on foreign suppliers, price volatility, and increased use of non-renewable and CO_2-emitting fossil fuels.

1. Introduction

After the Fukushima disaster in March 2011 polemic discussions pro or against nuclear electricity production arose. Europe, Germany, Switzerland and Belgium confirmed the closing-down policies. In this article the authors present a system-dynamics (SD) modelling of the Belgian situation for getting a more systemic insight into this complex issue. Belgium produced in 2003 about 56% of the total electricity demand with seven nuclear power plants (NPPs); only France has a higher percentage production of about 75%. The phase-out law has been set in place in 2003 (BFG, 2003): it foresees the closure of all Belgian NPPs between 2015 and 2025 after 40 years operating time; nevertheless, a provision in the law permitted a renegotiation on the shutting-down schedule of NPPs in case of safety-of-supply difficulties, several times pointed out by the Regulation Committee of Gas and Electricity, most recently in CREG (2011a, 2011b). A major rationale for passing the law is that the phase-out is favourable to renewable energy sources (RES) considered as being presently 'crowded-out' by NPPs. Several studies were commissioned by the government before and after issuing the law, to verify the feasibility. An overview of these studies is given in Table 1, and their main recommendations are also provided. All studies prepared before the Fukushima disaster were basically favourable to adapting the shut-down calendar, because it is not dictated by technical or safety rationale's. The government set in place in 2012 eventually rejected these policy recommendations in the wake of the Fukushima disaster, maintaining most of the 2015 to 2025 phase-out programme. The present SD analysis has been started by Friesewinkel (2008) at Université Libre de Bruxelles (ULB); Brans and Kunsch (2010) presented headline results. Though five years have passed since inception, not much has changed and the study remains pertinent in 2013, two years after the Fukushima disaster. The article is structured as follows: Section 2 gives an overview on the System-dynamics (SD) methodology and references for energy modelling; it is also discussed why this approach has been chosen. Section 3 presents the general context of the problem; soft SD based on feedback analysis is giving first conclusions about the dynamic consequences of the unchanged

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Table 1
A survey of governmental studies on the electricity market in Belgium. (RES = renewable energy sources).

Study Year	Methodology	Phase-out recommendations
Ampère (2000)	Scientific analysis by university professors of the electricity-production potential in Belgium of traditional and non-conventional sources.	It is not indicated to discontinue the successful nuclear programme contributing to low costs and important CO_2 emission reduction.
CE2030 2007	PRIMES economic model of energy systems from the Belgian Planning Office using a number of scenarios with and without nuclear and different CO_2 reduction objectives.	RES are limited for fulfilling CO_2 emission reduction objectives; developing carbon capture and storage (CCS), and keeping operational NPPs beyond 2025 would bring a substantial relief.
GEMIX 2009 2012 (revision after Fukushima)	Comparison of several studies from Belgian and foreign sources, including Greenpeace (2011) in the 2012 revision. The whole energy system including transport is considered.	The deployment of RES is independent of other components in the energetic mix given the environmental constraints. The actual phase-out schedule may lead to a production deficit not necessarily covered by imports in the absence of available foreign capacities and interconnected transport grids.

phase-out law. These conclusions are strengthened by means of quantitative SD simulations in the following sections. The general structure of the quantitative SD model is described in Section 4 by detailing the supply and demand sub-models, and how they are connected; indicators for evaluating the merits of policies are introduced. Section 5 defines policies and their variants, the data and hypotheses made in the simulation model. Section 6 presents the main results of the simulations; policies are scored for ranking purposes, regarding their merits with respect to indicators. Section 7 gives conclusions, compares the results with other studies, and discusses the limitations of the model and possible future improvement work. Policy recommendations are given in Section 8.

2. System dynamics

2.1. Overview of SD

System Dynamics (SD), first developed by J.W. Forrester at MIT, Boston (Forrester, 1961), is a policy-aiding instrument for addressing socio-economic issues. SD is based on the principle that the dynamics of systems can be understood from internal structures while exogenous influences, privileged in econometric modelling, can influence the system, but do not explain its dynamic behaviour. Therefore feedback loops (FBLs) play a preeminent role. In the first '*Problem definition*' step modellers fix the system boundaries defining the validity domain of the model, and identify the problem symptoms; in the second '*Conceptualisation*' step, *influence diagrams* (*IDs*), also *called causal-loop diagrams*, are setup, starting from simple *mental model* with few key variables to more complex IDs containing more variables important for later modelling. Main feedback loops (FBL) are identified for establishing a *dynamic hypothesis*, and for eventually proposing structural changes. The ID in Fig. 1 describes the installation of new production capacities after a plant decommissioning. The gap-closing is done with one negative FBL, called a '*goal seeking loop*'. Some explanations on this diagram are as follows:

- A link between A→B is given a positive sign if a change in A produces a change in B in the same direction, e.g., increasing demand increases the gap, therefore (+); it is given a negative sign otherwise, e.g., increasing supply diminishes the gap, therefore (−).
- A closed loop, i.e., a FBL has the (+) polarity when it contains zero or an even number of (−) links; it has the (−) polarity when it contains an odd number of (-) links.
- Positive loops (+) are self-reinforcing or growth loops, the positive polarity is indicated in a curl spinning clockwise or counter-clockwise following the loop direction.

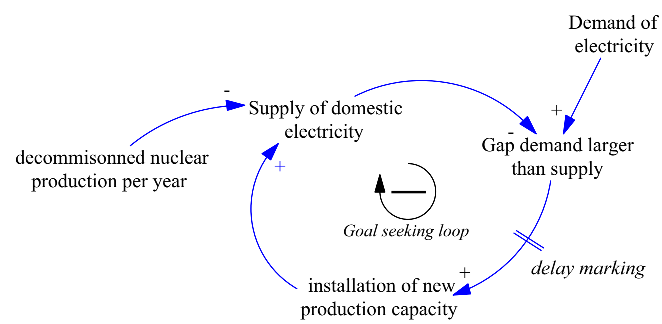

Fig. 1. An influence diagram with one negative goal-seeking feedback loop.

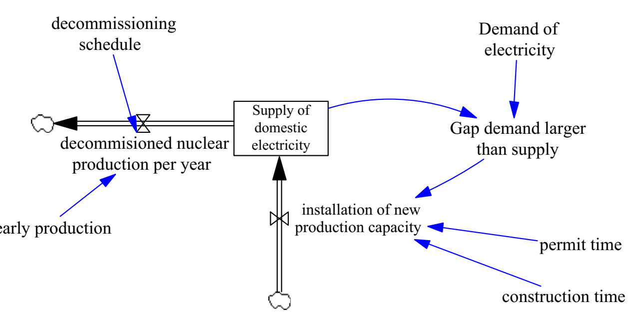

Fig. 2. The stock-flow diagram corresponding to the influence diagram in Fig. 1 with one stock, two flows, and a number of auxiliaries for calculating the flows. Clouds indicate the boundaries of the system.

- Negative loops (−) are self-correcting or *goal-seeking loops*: a change in any variable within the loop gets damped, e.g., the gap demand-supply is reduced. The negative polarity is again indicated in a spinning curl.

Quantitative SD modelling strengthens soft FBL analyses by performing numerical simulations. Detailed IDs with quite more variables are then needed, and physical units are given to each variable. State variables are called 'stocks': they are represented by rectangular reservoirs. The variation rates of stock per unit of time are called 'flows': they are represented as an ingoing or outgoing valve, according to the sign. 'Auxiliaries' are added to the model to calculate the flows. Initial values are provided to compute the stocks by numerical integration from initial time t_0 (here 2005) to current time t. The authors used VENSIM DSS32 (1988–2002) for setting up IDs, modelling and simulations. Tests were performed to verify both validity and numerical accuracy, and the coherence of physical units. Fig. 2 shows the stock-flow diagram – also called Forrester diagram, corresponding to the ID in Fig. 1. It is seen that additional auxiliaries are needed for setting up equations for the links and for flow calculations.

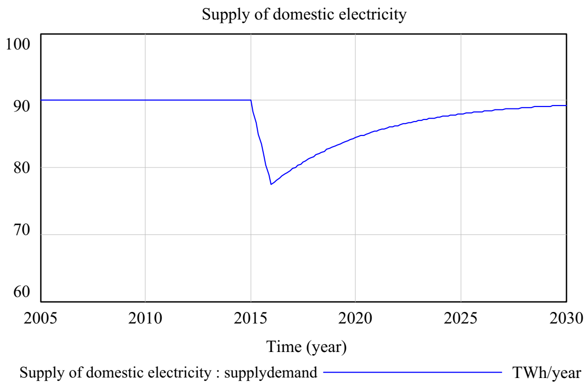

Fig. 3. The simulation using the stock-flow diagram in the time period [2005–2030].

The time graph of supply [TWh/year] appears in Fig. 3.

The replacement of 1,730 MWe decommissioned nuclear capacity is now simulated as an example, assuming a load factor of 90% (7884 h/year). (*S*) denotes a stock; (*IF*) an ingoing flow increasing the stock; (*OF*) an outgoing flow decreasing the stock; (*A*) auxiliaries. *INTEG*(,) stands for the flow integration to the current time *t*, given the initial t_0 value in the second argument.

Permit time = 2 [year] (*A*)
Construction time = 3 [year] (*A*)
Decommissioning schedule = *STEP*(1, 2015) – *STEP*(1, 2016*)* [*Dmnl* = *dimensionless*] (A)
Decommisioned nuclear production per year = 1730 × 7884 × 1*e* – 006 [TWh/year] (OF)
Demand of electricity = 90 [TWh/year] (A)
Gap demand larger than supply = *demand of electricity* – *supply of domestic electricity*[*TWh/year*](*A*)
Installation of new production capacity = *gap demand larger than supply*/(*permit time* + *construction time*) [TWh/year²] (IF)
Supply of domestic electricity = INTEG (*installation of new production capacity* – *decommisioned nuclear production per year*,90) TWh/year(*S*); *initial value is* 90 [TWh/year]

2.2. SD for energy planning

SD has been used for strategic energy planning and policy for more than forty years (Bunn and Larsen, 1997), including the revised 'World dynamics' model (Meadows et al., 1992) following numerous energy-focused models in the 1970s and 1980s; SD is actively used: many articles are available and freely downloadable from the web site of the system dynamics society (SDS)[1]; Sterman (2000) is a useful textbook. The first author also developed energy models (Kunsch and Springael, 2005, 2008; Ben Maalla and Kunsch, 2008). Teufel et al. (2013) reviews about 80 SD publications about the electricity market modelling. Jäger et al. (2009) presented before Fukushima an impact study of economic and related constraints on the German electricity spot market. Four factors were considered: (1) environmental regulations, (2) fuel prices, (3) electricity demand, and (4) extended nuclear life-time. Regarding electricity prices the ranking from more to less important is (1), (2), (3), and (4); for CO_2 emissions the ranking becomes (1), (4), (3), and (2). Only a limited number of SD publications have been devoted to the nuclear phase-outs after Fukushima. Table A1 (Appendix A) presents such references on SD modelling of the energy transition in Germany and Switzerland, the two other European countries which did confirm a nuclear phasing-out after Fukushima. Why using SD to model energy markets? Teufel et al. (2013) enumerates six major characteristics considered by SD modellers to giving comparative advantages to other methodologies, like econometric modelling or optimisation: (1) capability of including delays important for planning, approval and building processes; (2) opportunity to model bounded-rationality processes with imperfect information; (3) modelling descriptively behaviours of system agents rather than normative optima (Jäger et al., 2009); (4) modelling of uncertainties due to imperfect foresight by means of scenarios and Monte Carlo simulation; (5) modelling of non-equilibrium conditions in markets and non-linearity, not considered in most economic equilibrium or optimisation models; and (6) focussing on causal relationships rather than fitting data to observations, so that qualitative influences are easily incorporated into models. Though any SD model is no more than a gross simplification of the observed system, rich insights into structural and causal mechanisms can be gained from SD modelling, while policies to pilot the system are elaborated and tested (Randers, 1980; Sterman, 2000). Regarding the objective and the validity of SD models in correctly representing real-world systems, it is important to be aware of the kind of predictions or forecasts expected from SD models: quoting Keating (1998, p. 19): "while econometricians seek to make 'point predictions' (i.e., fitting past data series to make future forecasts), system dynamists seek to predict 'qualitative changes in reference modes' (i.e., evaluate existing patterns and how they may change in the future)". Quoting further Forrester (2013, pp. 2010–2011): 'There is no reason that a generic model should reproduce any specific historical time series. Instead it should generate the kind of dynamic behaviour that is observed in the systems […]. The dynamic character of past behaviour is very important, but the specific values at exact points in time are not'.

[1] http://www.systemdynamics.org

3. Analysis of the Belgian energy problem

3.1. Policy requirements

Fig. 4 shows the shut-down planning in the phasing-out law (BFG, 2003) of the seven operating Belgian NPPs: the initial 5.93 GWe capacity will be progressively shut down till 2025, i.e., after 40 years of operation.

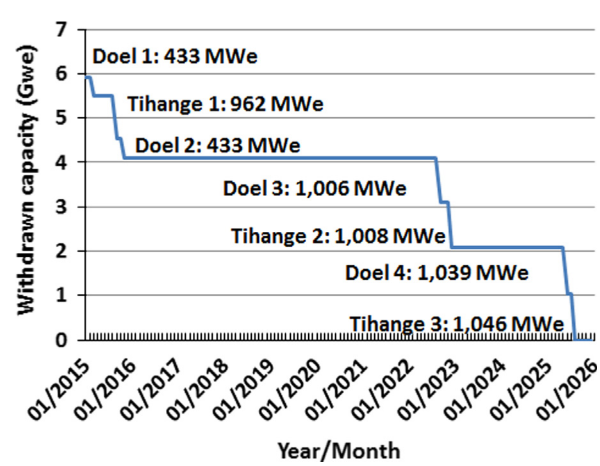

Fig. 4. The time planning defined in the phasing-out law (CREG, 2011a): 5930 MWe nuclear capacity are withdrawn from 2015 to 2025. Three units are shut-down in Tihange (Tihange 1, 2, and 3) and four units in Doel (Doel 1, 2, 3, and 4) following the schedule on the horizontal axis. Capacities in MWe are indicated next to the unit names.

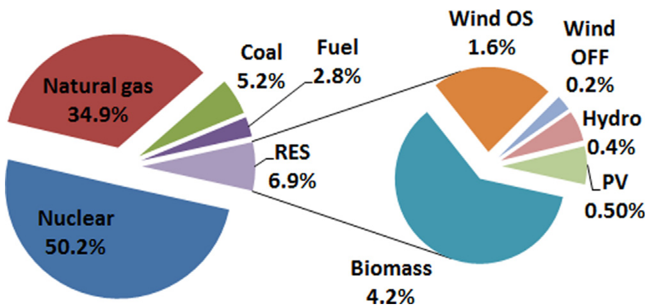

Fig. 5. Use of primary resources for electricity production in Belgium at the end of 2010 (CREG, 2011a). RES=renewable energy sources; OS=on-shore; OFF=off-shore; and PV=Photovoltaic cells.

Fig. 5 shows the primary resource usage for electricity generation in Belgium at the end of 2010, i.e., about 93 TWh/year in total. Nuclear generation represents roughly half of electricity production and natural gas about one-third (CREG, 2011a, 2011b). At the model starting date in 2005, less than 5 TWh/year of demand (5.4%) was supplied by electricity imports; fossil resources have to be imported throughout. The European Union (EU) has set three key targets for 2020 the so-called '20-20-20' targets (EC, 2010a, 2010b), i.e., on average a 20% reduction in EU greenhouse gas emissions from 1990 levels, a 20% raising of the share of renewable energy source (RES) in the EU energy mix; and a 20% improvement in the EU's energy efficiency thanks to rational use of energy (RUE). In the case of Belgium the RES target is about 15% of the electricity demand. But regarding the RES development there are technical constraints: the replacement of NPPs capacity by hydraulic energy and pumping storage stations is small due to the low land elevation; the available surface for implementing on-shore windmills and biomass is limited by high population density, about 11 million inhabitants for a total surface of 30,500 km^2; finally the country has a short coastline limiting the development of off-shore wind farms. RES represented in total only about 7% in 2010 (see Fig. 5); most optimistic forecasts from pro-renewable organisations announce a maximum of about 32 TWh/year, i.e., about less than 35% of total demand in 2010 (EDORA et al., 2007). A more pessimistic value by De Ruyck (2006) in a preparatory report to CE2030 (2007) amounts to only 15 TWh/year, which is about the total RES target of Belgium. The Belgian Federal government has thus three main objectives: maintaining the electricity price at reasonable level, while achieving as much as technically feasible RES targets, and keeping a satisfactory level of safety of supply.

3.2. Soft SD analysis with feedbacks

The ID of Fig. 6 indicates the general structure of the full simulation model, and allows a first 'soft' analysis based on FBLs. It is centred on two goal-seeking loops (GSL) for fossil and RES: both energy sources are competing to fill the phase-out gap. The positive learning loop induces a RES production-cost decrease with installed renewable capacities; but after some delay; RES growth is limited by availability and growth constraints. The choice of new investment on RES or fossil is influenced by the relative importance given to cost or CO_2-emission reductions. The 'Fuel' and 'RES' loops are indicated by reinforced lines; they have ambiguous signs depending on the relative fossil and renewable percentage contributions in production and on their respective unit production costs. The electricity market price also depends on the importance of incentives to RES and RUE, and to the payment of carbon taxes for fossil fuel. The price is expected to increase with the phase-out, because nuclear production today is the cheapest (see Table B1 in Appendix B). Considering an early phase-out in 2015–2025, fossil fuel, and especially natural gas, clearly has an advantage in the GSL competition. RES are heavily subsidised to become competitive, increasing herewith consumer prices. This situation is unlikely to change for some time, before learning effects can lower the production costs; RES are also limited by many constraints – including NIMBY observed in Germany (Der Spiegel, 2013). The market price is thus expected to increase with an early phase-out in case RES is deployed in priority, while it could be stabilised by more fossil production. On the short to medium term, the market trend is to decreasing fossil-fuel prices due to the development of non-conventional oil and gas in USA and Canada and several EU countries (IEA, 2012). Even if more weight is given to CO_2 reduction objectives, investment in fossil-fuelled power plants will still outweigh RES investment in the shorter term. In such 'crowding-out' situation the 'Fuel' loop is positive inducing more fossil gap-filling production; in synergy the associate 'RES' loop is on the contrary negative, meaning less RES production. In summary, the simple, but common message may be wrong that RES will be developing by priority because of the nuclear phase-out. Quantitative SD modelling is presented in the next sections for verifying under which conditions RES may develop.

4. Quantitative SD modelling

4.1. General structure of supply and demand

The model has two sub-systems: electricity supply side and electricity demand considering different sectors: households, services, industry, and agriculture. Actors from both sub-systems influence the whole evolution and react to changes in the environment:

- Electricity producers adopt a goal-seeking behaviour taking into account economic and environmental constraints for adjusting production capacities.
- Consumers also adopt goal-seeking behaviours when reacting to changes in electricity prices and investing into efficiency technologies (RUE) within existing constraints to reduce their energy bills.

In the following sub-sections the structures of the supply and demand sides and of their links are described. Numerical values are presented in Section 5 and in Appendix B.

4.2. Structure of the supply side

The ID in Fig. 7 gives an overview of the behavioural model of centralised producers when making investment decisions. The key variables will be detailed later on. Exogenous variables like investment, running costs, and subsidies are also indicated. The decision process starts with calculating the electricity production costs. The sources include nuclear, fossil fuels (coal, natural gas, and fuel) and RES: wind (on-shore and off-shore productions), solar, hydro and biomass. By comparing the costs producers determine the relative source attractiveness. Sources are limited by constraints, either due to a limit in the yearly installed capacity, or to a maximal production potential. Behind these structures appear stocks-and-flow diagrams: Fig. 8 shows the calculation of the stock 'New production needed'. The equations of the flows 'change in production needed' attached to this stock are the same for all sources, so that such equations are vectorised as follows:

$$\textit{New production needed}\,[\textit{source}] = \textit{INTEG}\,(\textit{change in new production needed}\,[\textit{source}],\ \textit{initial value}_{2005}) \qquad (1)$$

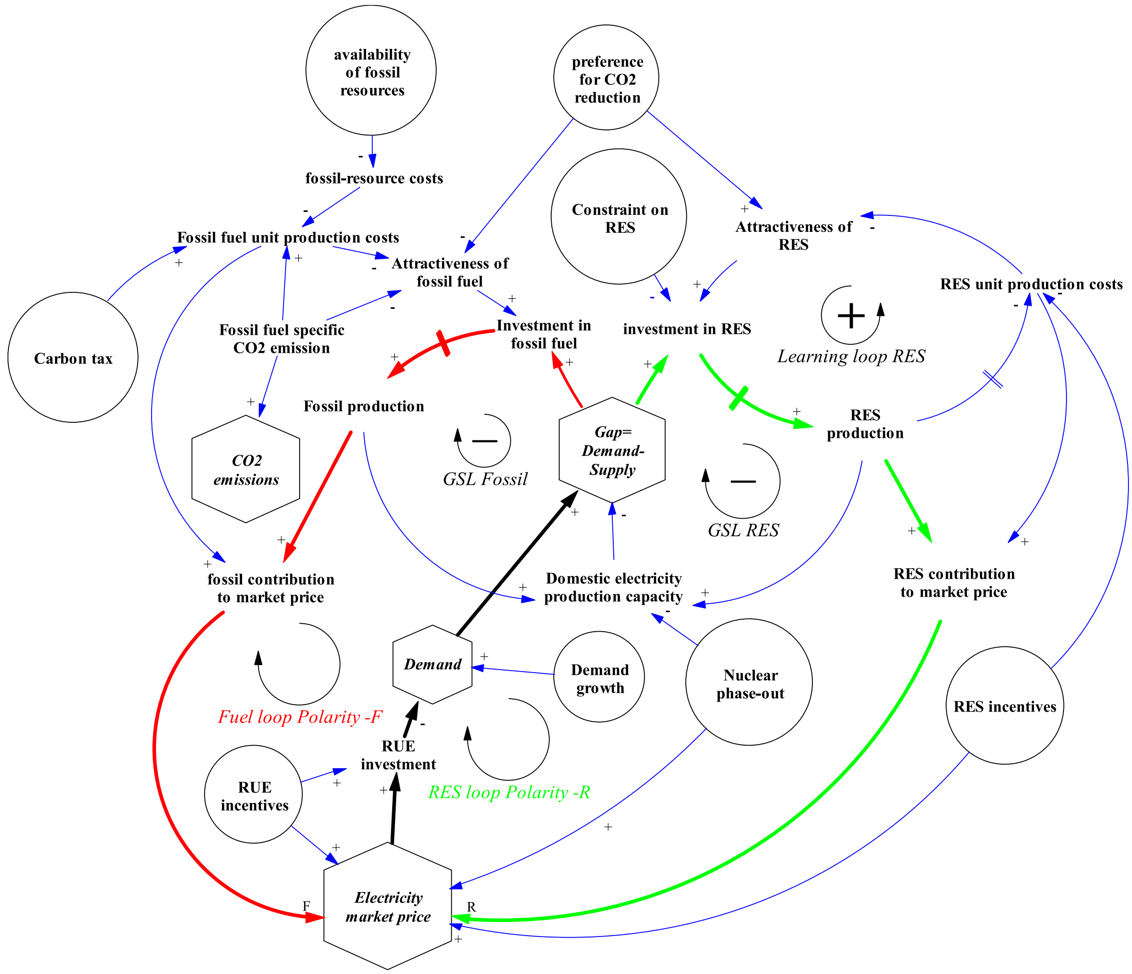

Fig. 6. The basic ID of the nuclear phase-out and its impact on renewable energy sources (RES) and rational use of energy (RUE). Exogenous variables, constraints or policies are represented in circles; four indicators appear as hexagonal shapes; delays are indicated by the ‖ symbol on links (GSL = goal-seeking loop).

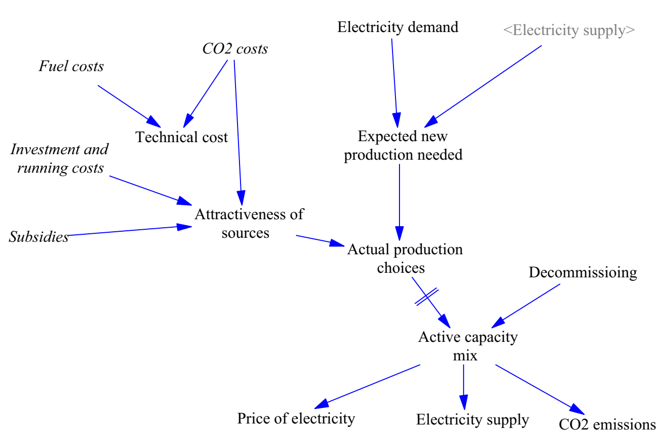

Fig. 7. ID of the supply side leading to an active capacity mix able to meet the demand.

The stock-and-flow diagram in Fig. 9 is associated to the active capacity mix; it is similar to the one shown in Fig. 2.Let us detail few of the composite variables vectorised per source in Fig. 7:

$$\begin{aligned} &\textit{Fuel and } \mathrm{CO_2} \textit{ cost} = \textit{net investment required} \times \textit{annuity/load factor} \\ &\quad + \textit{primary fuel costs/conversion efficiency} \\ &\quad + \mathrm{CO_2}\textit{abatement costs} \times \textit{specific emissions} - \textit{subsidies} \end{aligned} \tag{2}$$

$$\begin{aligned} &\textit{Net investment cost} = \textit{initial net investment cost (weight domestic} \\ &\quad \times \textit{domestic learning effect} \\ &\quad + \textit{weight nondomestic} \times \textit{nondomestic learning effect)} \end{aligned} \tag{3}$$

$$\begin{aligned} &\textit{Effect of domestic learning} = \textit{relative increase in cumulative capacity} \\ &\quad \times \textit{domestic learning rate} \end{aligned} \tag{4}$$

'Effect of domestic learning' is endogenous learning proportional to the increase in capacity on the domestic market. 'Effect of non-domestic learning' is given as a yearly decreasing rate thanks to technology improvements in outside countries – e.g., on wind mills in Germany (see Table B3). Investment choices are made on the basis of an attractiveness formula for attributes to be minimised, here producer prices, and specific CO_2 emissions:

$$\textit{Attractiveness}\,[\textit{investment}, \textit{attribute}] = \frac{\underset{\textit{all investments } I}{Max}(\textit{attribute}\,[I]) - \textit{attribute}\,[\textit{investment}]}{\underset{\textit{all investments } I}{Max}(\textit{attribute}\,[I]) - \underset{\textit{all investments } I}{Min}(\textit{attribute}\,[I])} \tag{5}$$

The combined attractiveness of some investment is then given by the weighted average:

$$\textit{Attractiveness}\,[\textit{investment}] = \sum_{\textit{all attributes}} \textit{weight}\,(\textit{attribute}) \times \textit{attractiveness}\,[\textit{investment}] \tag{6}$$

Weights are scenario-dependent, as explained later. Capacity constraints on new production capacities come in the model from

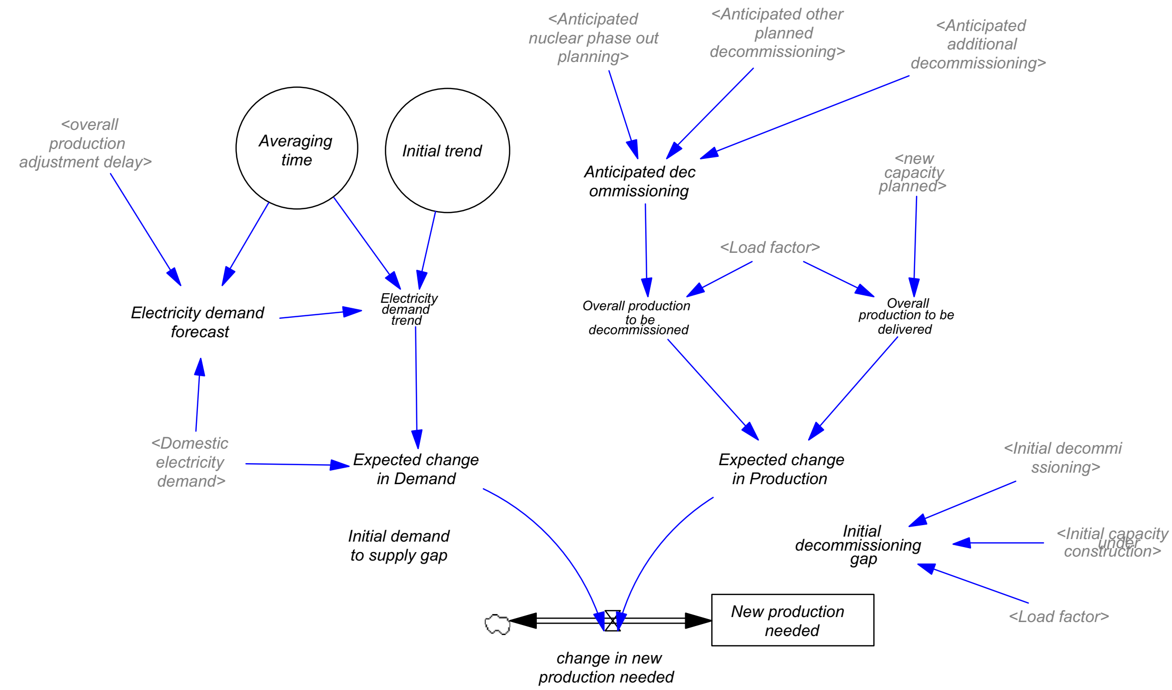

Fig. 8. Stock-and flow diagram of the 'New production needed'.

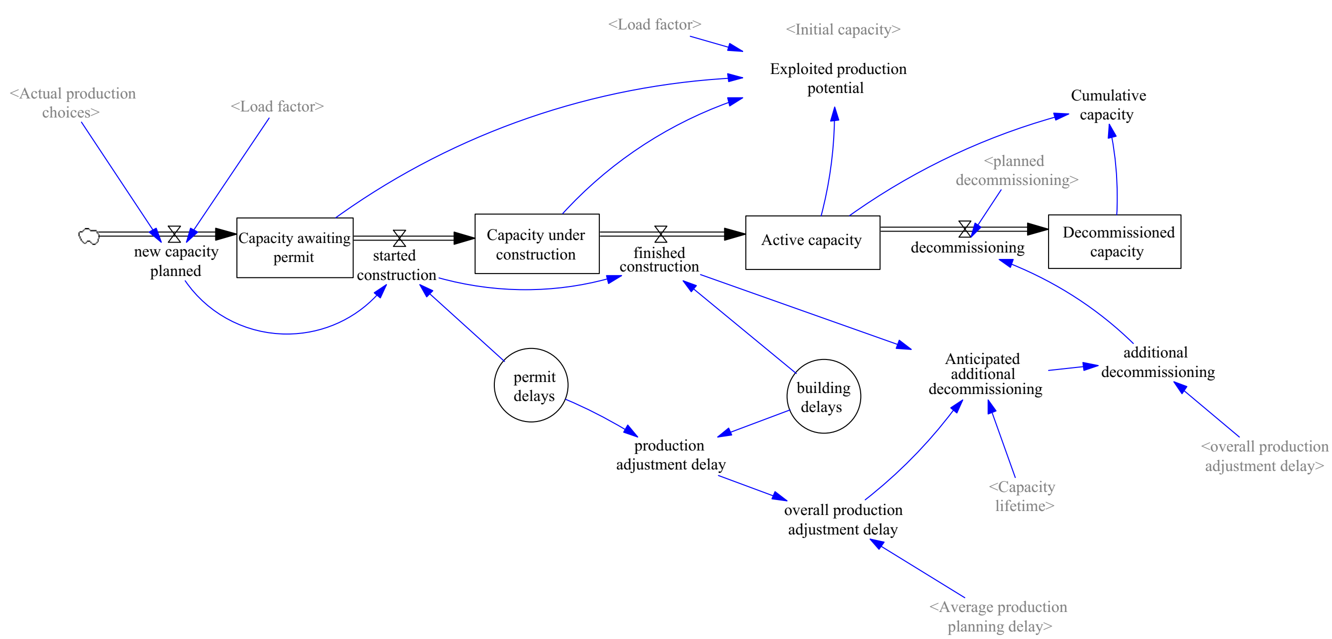

Fig. 9. The stock-and-flow diagram for setting up active capacities of various sources.

three origins: (1) physical boundaries, giving per source a maximum 'Technical production potential', for instance the physical production limits on wind farms; (2) the economic boundaries limiting the yearly building rate of new production capacities; (3) other legal constraints, for instance the federal phase-out law. Within these constraints the new capacity is allocated to different sources in decreasing order of attractiveness: when the most attractive source is not bounded by capacity constraints, it gets 100% of the new capacity.

4.3. The demand side

This part of the model describes the behaviour of households as electricity consumers. Services are assumed to be fully correlated to households. Other sectors are not modelled, their growth rates being exogenous variables for sensitivity calculations. Households use energy in the form of two vectors, electricity and fossil fuels, for two usages electrical and heating (transport is not included). Energy bill reduction is made possible thanks to efficiency technologies, either for energy savings, e.g., efficient light-bulbs, or for substitution within the energy vector, i.e., transferring some of the consumption from one vector to the other one, e.g., micro-heat-power cogeneration (micro-CHP) increases fossil fuel consumption, but decreases electricity consumption. The more a technology reduces the bill, the more it is attractive. Fig. 10 indicates the model structure on the demand side. Similar to the case of the supply side there exist technology constraints visible on the right in Fig. 10, for instance for installing solar heaters on roofs. The

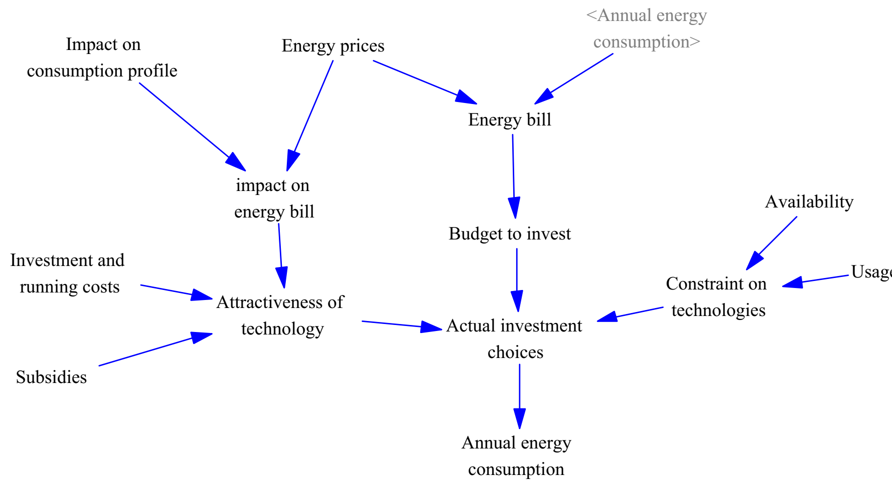

Fig. 10. The ID of the demand side.

Table 2
Baseline policies and variants.

Baseline policy (1) law	**Baseline alternative policy (2) Alternative**
Nuclear phase-out law implemented as such in 2015–2025	Based on: Baseline policy (1)
Limited RES incentives	
Conservative constraints on potential and new installations of RES	More efforts are made to promote renewables: softer constraints on potential and new installations of RES
Constant fuel prices	Higher subsidies for RES
Constant CO_2 prices	Higher CO_2 prices
Constant industry demand	
Variant 1 soaring fuel prices Variant 2 growing industry demand	
Policy (3) imports	**Policy (4) delayed phase-out**
Based on: baseline policy (1)	Based on: baseline alternative policy (2)
Producers can buy electricity from an 'imports' source at lower price.	Extend the lifetime of Belgian nuclear power plants by 20 years; no new plants are allowed.
Policy (5) replacement-soaring	
Based on: delayed phase-out policy (4) with soaring fuel prices and replacement of decommissioned nuclear capacity, but without capacity increase.	

availability level is the percentage of households that have access to the technology at any given time; the usage level is the percentage of households that are actually equipped with the given technology at any time. The difference between both levels gives the remaining availability: combining the availability with the investment cost and the installation rate of the technology gives a range of maximum average spending budget by technology as a constraint for the feasible maximum yearly investment. Given an estimate of the range of energy-bill impact of the technology, the attractiveness of investing in some technology is estimated according to (5) for the attribute 'Net impact on the electricity bill'.

4.4. Linking supply and demand

Linking variables are the price of electricity on the market in Euro/MWh and the supply and demand of electricity in the Belgian market in MWh/year. In the present model it has been assumed that prices are set by the Belgian producers alone (see Section 5 and Appendix B for cost data), deliberately ignoring the complex real-time price building on internationally intertwined liberalised markets, not relevant for the present long-term SD modelling. Supply and demand are combined into one indicator, 'Demand to supply gap' representing the imported part of the demand. Three other indicators, 'Domestic demand', 'Market price', and 'Yearly CO_2 emissions' are also computed in a straightforward way. The last indicator 'Dependency on external markets' is obtained by integrating the imported or fossil production over the whole simulation period.

5. Policies, data and hypotheses

5.1. Overview of policies and variants

A baseline policy corresponds to a basic scenario, in which fuel price, generating technologies, and electricity demand do not change abruptly, but in a smooth way from the initial 2005 conditions. Variants in which some important parameters experience more important changes are used for sensitivity testing: policies and variants are described in Table 2. Three additional policies are tested: allowing imports, shifting for 20 years the phase-out, and replacing shutdown NPPs.

The nine contrasted scenarios are chosen out of fifteen possible combinations of five policies with three variants in order to test them with SD simulations under a wide range of conditions. All policies, except for baseline law (1) and variants promote RES as much as technically feasible. Decreasing fossil-fuel price scenarios are not considered, because they are not likely in the long term. Additional Monte-Carlo simulations on growth rates, carbon price, number and values of green certificates, RES growth constraints, CO_2 attractiveness weight in (6), etc., were performed in addition to test the robustness of observed dynamic behaviours. Space is not available to detail them all here, but it is enough to mention that the system dynamics in different scenarios does not radically change within realistic value ranges. In the following sub-sections more details on hypotheses, parameters and data of the nine scenarios are given.

5.2. Details of policies and variants

5.2.1. Baseline law policy and variants

The baseline policy law (1) is a 'Business as Usual' scenario used for comparisons, rather than a politically valid choice, because of the conservative RES deployment in terms of feasible resources and limited financial promotion. On the supply side, Table B1 gives the elements of costs of sources for computing the market price of electricity, and CO_2 emissions per source. Table B2 gives information about initial production and capacity-growth constraints. Learning effect parameters are given in Table B3. Data on CO_2 abatement costs and green certificates, and RES technical potential and growth rates are found in Table 3. The obtained technical costs are compatible with international studies (IEA, 2007) and (EUSUSTEL, 2007). On the demand side, electricity demand has been split into five sectors (initial demand in TWh/year in 2005): energy (13.0); industry (41.1); agriculture (0.4), services (12.7); and households (26.0). The average electricity demand in 2005 of about 4.4 million households (BMEA, 2005) is calculated to be about 5.9 MWh/year. The demand growth rate of all sectors is 0%/year in the baseline case, assuming that any growth in demand is compensated by increased efficiency. The average fossil fuel consumption per household (including heating) is 24.4 MWh/year. The average household energy bill is computed from the consumption of electricity and fossil fuel multiplied by the corresponding prices. Using again the data from BMEA (2005) the total energy bill of 1635 $Euro_{2005}$ has been used as an initial value, found to be consistent with other Belgian sources. The impact of the energy bill on household and service sectors has been modelled by introducing four efficient technologies with data from ENC (2007) and Ben Maalla and Kunsch (2008):

1) Efficient lighting (compact fluorescent lamps and LEDs) decreasing the electricity consumption by 5%.
2) Behavioural energy savings leading to savings of about 15% in electricity and 10% in heat.
3) Solar heaters producing heat with little additional electricity consumption; and
4) Micro-cogeneration units producing electricity and heat at decentralised level with high efficiency.

In the variant 'Soaring fuel prices', the following assumptions have been used for the primary fuel costs growth rate in %/year (CE2030, 2007): Coal 1%/year; Fuel 2%/year; and Gas 2%/year. The rationale is that the pressure on fuel and gas is higher because their reserves are more limited than coal. In the variant 'Growing industrial demand' the following assumptions are made (CE2030, 2007): Energy sector 2%/year; Industrial sector 2%/year; and Agriculture 0%/year.

5.2.2. Baseline alternative policy and variants

The Alternative policy (2) is designed with pro-active RES promoting assumptions. The RES technical potential is significantly increased, and the constraints on new installations are raised to enable faster penetration, when RES become competitive with fossil sources in terms of costs. The comparison of RES data with the baseline law (1) is given in Table 3, reflecting the views of Belgian pro-renewables (EDORA et al., 2007).

5.2.3. Imports (no variants)

In this policy it is assumed that electricity may be imported at conditions comparable in terms of costs to domestic nuclear power, i.e., from France with easy cross-border transport capacities but with 20% additional increase for transport losses, charges and taxes; the availability time as the sum of permit delay and building delay of nuclear capacity (IEA, 2007) has been reduced from 8 years to 3 years, because production can be more rapidly adjusted.

5.2.4. Delayed nuclear phase-out (no variants)

In this policy the Belgian government is assumed to extend the authorised lifetime of Belgian nuclear power plants by 20 years, so that the shut-down period would be shifted to 2035 till 2045, but without replacing or adding new nuclear capacities. It is also assumed that this is done concurrently with the RES pro-active Baseline alternative policy (2) in favour of RES.

5.2.5. Replacement of nuclear power plants with soaring fuel prices (no variants)

This policy is based on the Alternative policy (2) with reinforced RES measures, and the variant with soaring fuel prices, with a nuclear lifetime of 60 years like in the delayed nuclear phase-out, with replacement of the shut-down capacities, but no additional nuclear capacity.

6. Results of the SD simulations on policies and variants

6.1. General information

Fig. 11 shows the production mixes except for Import (3). Tables 4 and 5 give all results described in detail in the following sub-sections; the comparison and ranking of policies is discussed in Section 7. In all scenarios supply is adjusted to demand at any time by goal-seeking FBLs: the nuclear shut-down shocks are visible in Fig. 11. The demand to supply gap is kept small all the time, while fluctuations dampen over time. RES and fossil fuel develop whenever some capacities are decommissioned: as illustrated the decommissioning planning and the corresponding addition of RES capacity in the baseline law (1) is shown in Fig. 12, and in Fig. 13 for the alternative baseline (2).

6.2. Electricity production mix

The composition of the electricity mix in 2050 across the policies and their variants is given in Table 4, see also Fig. 11. There is very small import in any policy/variant in 2050, except for import policy (3). In law policy (1) and variants, the production

Table 3
Values of parameters modelling the alternative policy (2) in favour of RES. Corresponding values in the baseline law (1) are shown in brackets.

Variable	Units	Value	Source
Maximum capacity growth/year	%/year	Solar and Wind 50 (15); Biomass 20 (10); Hydro 10 (10)	EDORA et al. (CE2030)
Total production potential	TWh/year	Wind 21.3 (6.2); Solar 2.9 (0.2); Biomass 6.7 (6.6); Hydro 0.8 (0.5)	EDORA et al. (CE2030)
CO_2 abatement cost, Growth rate	Euro/tCO2	40 (20)	CE2030, GEMIX
	%/year	3 (0)	Own assumption
Market value per green certificate	Euro	90 (65)	ENC
Importance of CO_2 for attractiveness	% in (6)	80 (20)	Sensitivity parameter

The two variants are the same as in the Baseline policy Law (1).

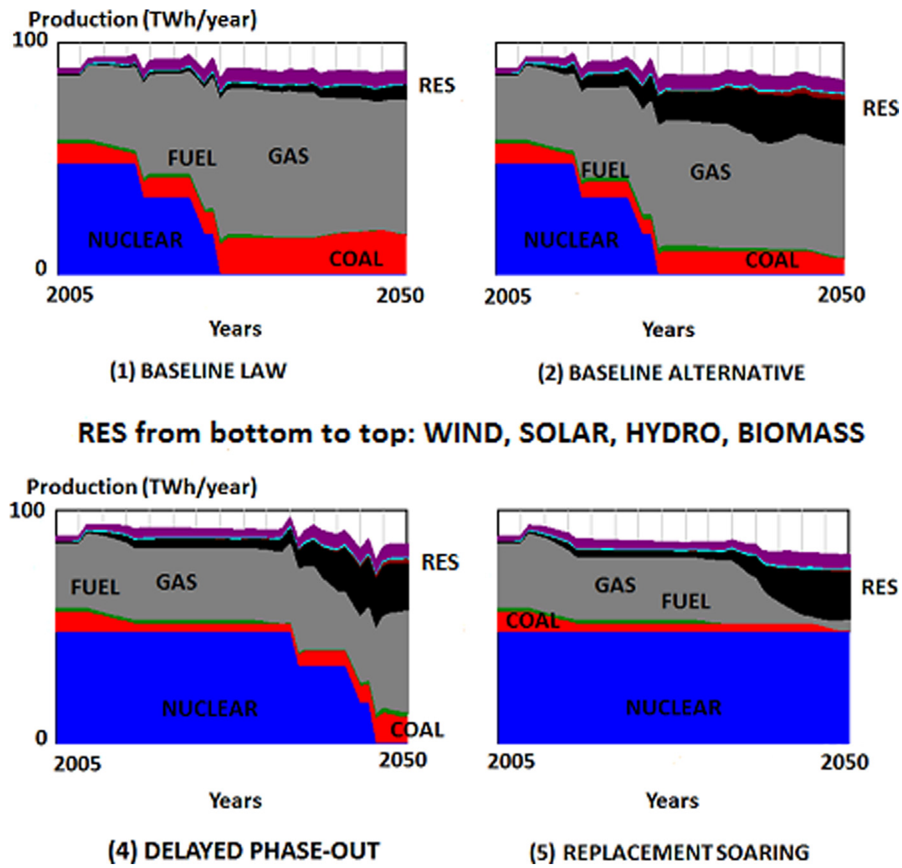

Fig. 11. The energy production in TWh/year is shown for four baseline policies (1); (2); (4); and (5), see Table 2 for a description of policies and variants.

Table 4
The energy mix in 2050 for the five baseline policies and their variants when applicable.

Policies	NPPs (%)	Coal (%)	Fuel (%)	Gas (%)	RES (%)	Imports (%)
(1) Law		19		66	14	
Law-soaring		50		36	15	
Law-industry growth		30		62	**7**	
(2) Alternative		8		58	34	
Alternative soaring		7		57	35	
Alternative-industry growth		18	3	62	**17**	
(3) Import				1	12	**86**
(4) Delayed phase-out		13	2	51	34	
(5) Replacement soaring	59	0	0	6	35	

mix is dominated by fossil sources (85–90%) of production. Baseline alternative (2), delayed phase-out (4) and replacement-soaring (5), all give a full deployment of RES in 2050 (34–35%) thanks to the pro-active RES policy. The industry growth variants apparently give the smallest percentages of RES in 2030: 7% (1); 17% (2). The same variant effect would appear for policies (4) and (5): smaller percentages appear because of the important demand growth between 2005 and 2050: but in fact RES grow more rapidly, due to the increasing gap, and reach their full potential between 2020 and 2030, before a slight decrease occurs due to more gas and coal.

6.3. *Electricity demand*

Table 5 shows that demand decreases most (−14%) in the soaring variants of policies law (1) and alternative (2), and in soaring-replacement (5), because of important investing into efficient URE technologies. A somewhat smaller demand decrease is obtained in baseline (2), also in the phase-out policy (4) thanks to the high carbon cost alone. The poorest performance is achieved in the baseline (1) because fuel prices are stable and the carbon price is smaller (see Table 3).

6.4. *Market price of electricity*

As seen in Table 5 electricity prices in 2050 ($Euro_{2005}$/MWh) range from 50 in the import policy (4) to about 140, in alternative (2) industry-growth variant. In law (1) industry growth variant, electricity prices stabilise around 70. In baseline alternative (1) and delayed phase-out (4), prices are also high around 125 due to the high CO_2 costs. Finally, the replacement-soaring policy (5) sees electricity prices first increase up to 80 until 2035 as a result of CO_2 costs and remaining natural gas in the production mix (see Fig. 11), then it drops to about 60 in 2050 with the development of RES.

6.5. *CO_2 emissions*

Table 5 shows that, depending on the policy and scenario, emissions from the electricity sector in 2050 range from 25 $MtCO_2$/year (+30% from initial 19 $MtCO_2$/year) for the baseline alternative (2) to about 80 $MtCO_2$/year in the variant of law (1) with industry soaring (+312%). Except for replacement (5) where -90% is achieved in 2050, and imports (−97%), rather large annual CO_2-emission levels must be expected.

6.6. *Dependency on fossil fuel*

Table 5 shows the ratios of the relative integrated fossil domestic productions from 2005 to 2050 with respect to the

Table 5
Results of simulations and ranking of policies by means of merit scores S_1 to S_5. Note that the 'industry growth' variant is not taken into account in % changes of 'Domestic electricity demand'; the 'soaring price' variant is not taken into account in % changes of 'market price'.

Relative changes in 2050 from 2005 (%), Merit scores (S_1–S_5) [1 Best – 5 Least good]	Domestic electricity demand (2005: 93.2) (TWh/year)		Market price (2005:64.2) (EUR_{2005}/TWh)		Annual CO_2 emissions (2005:19.4) (10^6 tCO_2/year)		Gap = (Demand – Supply)/Demand (2005: 0) (%)		Ratios of imported fossil fuel 2005–2050 to (5) = 100% (%)		Total score	Ranking
	%	S_1	%	S_2	%	S_3	%	S_4	%	S_5		
(1) Law	– 14 to – 7	2	10–13	2	92–312	5	~0	1	200–308	4	14	IV
(2) Alternative	– 14 to – 13	1	90–119	5	30–229	2–3	~0	1	177–262	4	13–14	III
(3) Import	0	5	– 21	1	– 97	1	84	5	NA	5	17	V
(4) Delayed phase-out	– 9	2	96	5	42	2	~0	1	131	2	12	II
(5) Replacement soaring	– 14	1	– 6	1	– 90	1	~0	1	100	1	5	I

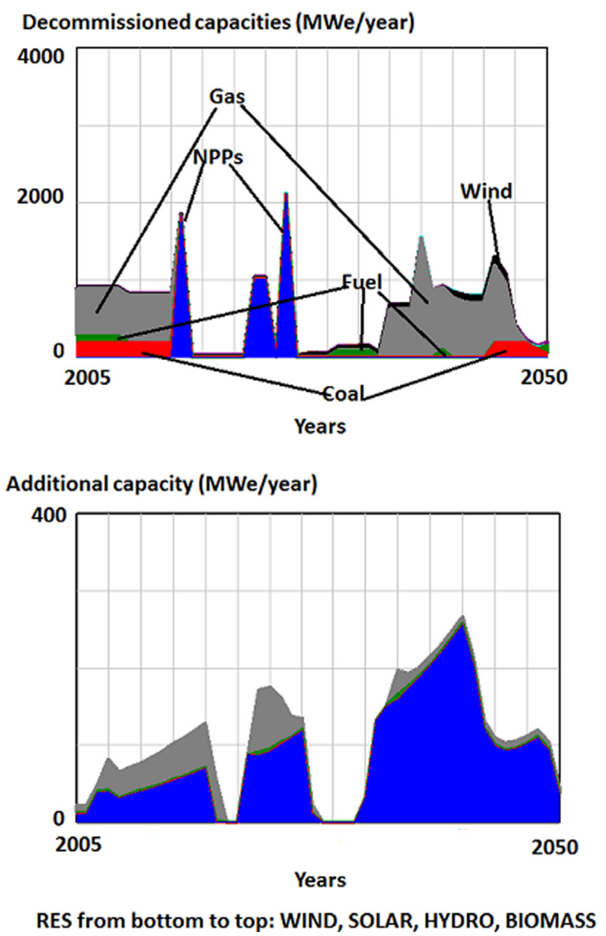

Fig. 12. (above) The decommissioning planning in the base law policy (1) and (below) the addition of RES capacity as decommissioning proceeds (MWe/year).

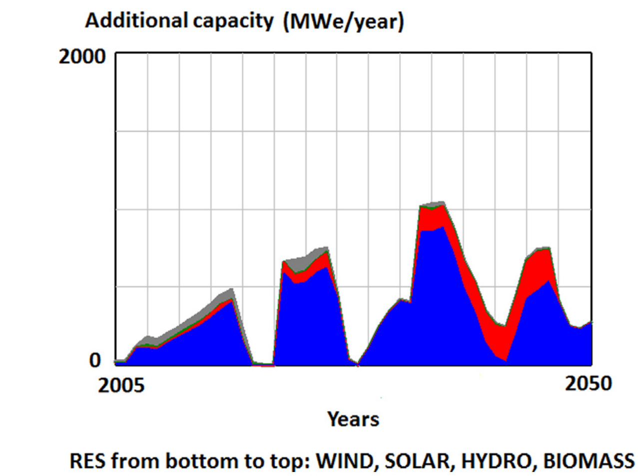

Fig. 13. The addition of RES capacity (MWe/year) as decommissioning proceeds in baseline Alternative (2) (note the difference in scale with Fig. 12).

(smallest of all) value obtained for the replacement policy (5) (ratio = 100%). These ratios give a measure of dependency regarding external markets, and thus at the same time they measure the sensitivity with respect to exogenous evolutions of fossil-fuel market prices. Law policy (1) and its variants show the largest dependency in the range 200–300%. Alternative (2) is less dependent, but still in the range 180–260%. Delayed phase-out (4) shows the smallest degree independence of about 130% just after replacement (5) (100% by definition). The ratio is meaningless for import (3) because most electricity is produced elsewhere, but as the most external dependence exists in this case, the worst $S_5 = 5$ score is given in Table 5, so that this policy cannot be considered as being politically valid.

6.7. *Household energy bills*

The values of the average household energy bills in Euro/year fluctuate in 2050 between 2,000 and 3,600 $Euro_{2005}$/year depending on the policy. The demand reduction obtained by investing into efficiency technologies to reduce energy bills vary between 7% and 14% as seen in Section 6.3.

7. Conclusions and future work

For evaluating the different policies a merit score is given to each one. Because the human mind is limited when comparing too many performance echelons, the 7 ± 2 golden rule (Miller, 1956) has been applied, and accordingly five pseudo-ordinal judgements only were assumed with the same content for all indicators: **1 Best; 2 Rather Good; 3 Average; 4 Poor; and 5 Worst.** The best score is '1' is at the same time the best position in ordinal ranking. Individual scores have been attributed by indicator as follows: policies close to Best get '1'; policies furthest away from Best get '5', and other policies get intermediate scores '2', '3', '4' according to their approximate positions with respect to '1' and '5'. Scores are combined by a weighed sum, being evaluated on the same dimensionless (Dmnl) scale. Assuming that all weights are equal, the total score is the sum of the individual indicator scores: the resulting global ranking from I (First) to V (Last) is in the far-right column of Table 5, i.e., for the three valid policies: **I Replacement (5); II Delayed phase-out (4); and III Alternative (2).** All three policies impose reinforced RES measures to comply with the environmental concerns: they actually achieve about the full feasible RES potential in 2050. Today Replacement (5) is not politically acceptable, two options are left: Alternative (2) and Delayed phase-out (4); both lead to comparable electricity prices, but annual CO_2 emissions are much larger in (2), and so is the dependency on fossil fuel, and thus the sensitivity to fuel prices for most of the simulation period. Some conclusions valid for the very different German case from Jäger et al. (2009) remain true (see Section 2.2): the phase-out is relatively unimportant for influencing the market price (it comes in fourth position in this analysis, fuel price being second), but it takes the second important position regarding CO_2 emissions, fuel price being then fourth. In all cases environmental targets are the most important factors for developing RES. Delaying the nuclear phase-out would thus not really hinder the eventual technically feasible development of RES, or significantly increase market prices, but it would reduce the risk of natural gas becoming the most preferred energy source, and therefore the risk of unacceptable CO_2 emissions. The recent study in Knopf et al. (2012) comes to similar conclusions regarding the German phase-out: based on a mixed integer optimisation technique, the scenario evaluations estimate the impacts of the phase-out on electricity prices, CO_2 emissions, and the European electricity market. In particular two phase-out dates are compared: the currently decreed 2022 exit date after Fukushima, and the previously planned 2038 exit date. It is again shown, as confirmed by several other studies used for comparison, that the gas price has more influence that the exit date, though the increase caused by the latter remains significant; moreover 'the year of the nuclear phase-out has a clear impact on CO_2 emissions' (quote); it is also remarked that 'Exit 2038 … would have indeed facilitated the road into the age of renewable energies…' (quote). To conclude, the SD model of the Belgian electricity market produces policy recommendations similar to those obtained by the previous studies (CE2030, 2007; GEMIX 2009, 2012) (see Table 1). The Regulation Committee of Electricity and Gas also warned for a capacity deficit in 2011–2020, and recommended to postpone the most-ancient-reactor decommissioning (CREG, 2011a, 2011b). An agreement may thus exist in this country that the 2015–2025 phasing-out timing is too early: it is not necessary to rush for shutting down NPPs, as long as this source remains safely and cheaply available. Life extension to 60 years seems to be feasible and safe (IAEA, 2003). Moreover, it is shown in (GEMIX, 2012) that extended lifetimes would not increase the radioactive-waste issue in a significant way.

The authors are aware that the present model has limitations. Some are due to the SD methodology itself:

- Stocks and flows are modelled as continuous variables in SD, while power plants have well-defined capacities. This affects the results only in the short run, and is less important when considering long-term strategies.
- In modelling producers' behaviours capacities are added only when they are needed to meet electricity demand without foresight and anticipation. Again this is relatively unimportant for evaluating the long-term energy mix.

  Other limitations arise from the simplified modelling. Some of these shortcomings could be the object of future developments and refinements:
- Advanced technologies for electricity production, such as carbon capture and storage, geothermal energy, tidal-wave energy, accelerator-driven nuclear reactors, etc., are not considered, nor are electricity storage and transport networks across Europe. These innovative technologies will probably still need much more time before becoming operational.
- Load curves in the energy demand are not explicitly modelled. The model is therefore rather optimistic regarding the RES contributions, because electricity cannot be stored, and thus part of the intermittent solar and wind production is presently lost.
- Households are assumed to invest in RUE when their energy bill increases. Other investment behaviours triggered by environmental consciousness, word of mouth, etc., might be modelled as well. Higher flexibility in the modelling of exogenous variables, which are today treated as being constant, would permit to test from within the model boundaries the effectiveness of subsidy or tax policies.

Table A1
Review of recent articles referring to modelling with SD energy transition issues in Switzerland and Germany (EU=European Union; RES=Renewable Energy Sources; RUE=Rational Use of Energy; and SDS=System Dynamics Society).

Reference	Objective	Tool	Findings
Page (2012). Liberalisation, competition and welfare effects of the Swiss electricity market reform, University of Fribourg, Fribourg, Switzerland.	Impact of different policies considering the Swiss nuclear phase-out after 50 years operation between 2019 and 2034 (Belgian law foresees 40 years).	SD analysis of likely market responses, updating (Ochoa, P., Van Ackere, A., 2009. Policy changes and the dynamics of capacity expansion in the Swiss electricity market. Energy Policy, 1983–1998).	*International electricity exchanges are important but explicit policies are needed to avoid import dependence*
Leopold et al. (2012), 2012. Germany's Electricity Industry in 2025: Evaluation of Portfolio Concepts, SDS conference, Sankt-Gallen, Switzerland.	Study of different long-term development scenarios of the electricity industry in Germany.	Simulation of production-mix portfolios to mitigate emissions and reduce fossil use through a production/consumption SD model.	*RES load management permits to significantly reduce the total production costs and CO_2 emissions*
Schmidt et al. (2012). The Transition of the Residential Heat Market in Germany – A Dynamic Simulation Approach. SDS Conference, Sankt-Gallen, Switzerland.	Study of the residential heat market regarding the EU 2020 targets in Germany	Study of different policies for the promotion of RES and RUE by means of (Vogstad (2005). A system dynamics analysis of the Nordic electricity market: The transition from fossil fuelled towards a renewable supply with a liberalised energy market, Department of Electrical Engineering, Norwegian University of Science and technology, Trondheim, Norway).	*The EU targets for heat demand reduction and CO_2 emission would not be met; the share of RES and RUE seems to be achievable.*
Hu et al. (2013). Transition Towards Renewable Energy Supply – A System Dynamics Approach, In: Cuaresma et al. (Eds.), Green Growth and Sustainable Development, Dynamic Modeling and Econometrics in Economics and Finance 14, Springer, Heidelberg, Germany, pp. 217–226.	Development of the energy market in an aggregated form in Germany.	Comparison with SD modelling of different pathways of the impeding energy transition.	*Despite the high costs due to the planned huge electricity storage capacity, only 31% CO_2-emission reduction will be achieved in 2025*

Table B1
Cost and emission data in 2005.

Quantity	Units	Nuclear	Coal	Oil	Gas	Wind	Solar	Hydro	Biomass	Imports	Source
Price of fuel incl. cycle	Euro/MWh	0.30	3.62	43.10	18.04	0	0	0	25.86	0.36	CE2030 / ENC / IEA(2007)
Conversion efficiency	%	34%	42%	48%	55%	20%	12%	85%	40%	34%	Ampère / ENC
Specific emissions	tCO_2/MWh	0	0.8	0.5	0.4	0	0	0	0	0	Ampère / Greenpeace
Permit delays	Year	3	1	1	1	1	1	1	1	1	CE2030 / IEA(2007)
Construction time	Year	5	3	2	2	1	1	2	2	2	CE2030 / IEA(2007)
Load factor	Hours/Year	8000	4500	4000	4500	2300	1000	5000	7000	8000	CE2030/CREG
Investment	10^6Euro/MWe	2.40	1.00	1.00	0.8	1.20	5.00	4.00	1.80	2.88	CE2030 / ENC / IEA(2007)
Capacity Lifetime	Year	40	40	25	30	20	25	50	40	40	CE2030 / ENC / IEA(2007)
Investment costs	Euro/MWh	26.24	19.44	24,23	16.39	54.73	484.50	68.41	22.49	31.49	Calculated
Operations and Maintenance costs	Euro/MWe/Year	45,000	40,000	40,000	26,000	12,500	30,000	40,000	40,000	54,000	IEA(2007)
Operations and Maintenance costs	Euro/MWh	5.63	8.89	10.00	5.78	5.43	30.00	8.00	5.71	6.75	Calculated
Other costs	Euro/MWh	2.50	0	0	0	0	0	0	0	3.00	CE2030 / IEA(2007)
Producer price of MWh	Euro/MWh	42.30	63.54	160.83	75.57	72.20	617.40	91.69	111.44	50.76	Calculated

Table B2
Initial productions in 2005 and maximum yearly capacity increase.

Variable in model	Units	Nuclear	Coal	Oil	Gas	Wind	Solar	Hydro	Biomass
Initial capacity (BMEA/CREG)	MWe	5947	1830	435	6100	200	10	100	320
Initial production (BMEA/CREG)	GWh/Year	47,576	8235	1740	27,450	460	10	500	2240
Maximum new on-line capacity per year MWe/Year (CREG)	MWe/year	1000	1000	100	1000	See annual maximum growth rates in Table 3			

Table B3
Learning of different sources (Dmnl=dimensionless).

Quantity	Units	Nuclear (%)	Coal (%)	Oil (%)	Gas (%)	Wind (%)	Solar (%)	Hydro (%)	Biomass (%)	Imports (%)	Source
Domestic learning rates	Dmnl	10	10	10	10	20	20	10	20	10	CE2030
Relative cost in 2050 vs 2000	Dmnl	100	83	100	95	75	25	100	60	100	CE2030
Effect of non-domestic learning	1/Year	0.0	0.4	0.0	0.1	0.6	2.7	0.0	1.0	0.0	CE2030
Relative importance of domestic learning	Dmnl	20% for all sources									Own assumption

- Adding other efficiency technologies would be easy, as well as modelling industrial actors' behaviours.
- A future version of the model could include the energy needs for transport, and model additional energy vectors, such as hydrogen.

Though there are such limitations and improvement possibilities, important recommendations for Belgian policy-makers have been obtained with the present model.

8. Recommendations for the Belgian energy policy

With the support of system-dynamics analyses confirming previous studies, the authors come to the firm belief that the nuclear phase-out schedule should be reconsidered by the Belgian government. Nuclear power should be kept as a transition source, until the renewables become more competitive and can provide a more significant share of Belgian energy. This helps limiting the environmental impacts of electricity production, and reduces the dependency on external markets for importing electricity and fossil fuel. This also leaves more time for R&D to develop new technologies, such as carbon capture and storage systems and large-scale electricity storage. Also in the meantime the grid technology and the interconnections between European countries will certainly develop permitting to reduce inconveniences due to the intermittency character of wind and solar energies.

Appendix A

See Table A1

Appendix B. Assumptions and data

See Tables B1–B3

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