The EU-25 Power Sector: a System Dynamics Model of Competing Electricity Generation Technologies

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Abstract

The main goal of this paper is to explore the transition of the EU-25 electricity generation system towards a more sustainable system characterised by lower CO_2 emissions by means of a system dynamics model of the EU-25 electricity generation sector. In this paper, the model and the resulting dynamics are explored by means of base case simulations, policy simulations, scenario analyses and (univariate and multivariate) sensitivity analyses. Finally, some conclusions, ex-post criticisms and directions for future research are discussed.

Keywords: Electricity Generation Technology, Europe, Transition

1 Introduction

1.1 Transition of the EU Energy System

Nowadays, the transition of energy systems towards more sustainable energy systems is a very hot issue. The European Commission (2007) recently published its European Energy Policy focussed on three important objectives: the environment (combating climate change), security of supply (limiting the European external vulnerability to imported hydrocarbons) and economic-social welfare ('promoting growth and jobs, thereby providing [...] affordable energy to consumers').

Much attention is paid –in that and other reports– to the transition of the electricity subsystem towards a sustainable electricity subsystem because (i) the electricity sector is currently responsible for large amounts of CO_2-equivalent (CO_2eq) emissions, (ii) it has the leverage to contribute substantially to these three objectives and (iii) electricity is generally believed to become an even more important form of energy than it is today.

Today, the transition of the European electricity system towards a more sustainable system is perceived –by the European Commission, the European electricity industry (Eurelectric) and green NGOs alike– to be feasible because of several reasons. First, the electricity industry is believed to possess the leverage to drastically reduce emissions over time through fuel switching, demand reduction, efficiency improvements, and a more revolutionary transition towards a CO_2-poor generation mix consisting of new renewable technologies, new nuclear generation technologies and the use of carbon capturing and storage technologies. Many of these CO_2-poor generation technologies already exist and are (almost) competitive, or are currently under development. Second, huge investments in new generation capacity are required –whether a transition to a CO_2-poor generation mix is pursued or not– and the sector has the necessary financial leverage. And third, it is argued that there are many advantages on other dimensions related to a more sustainable generation mix which are worth pursuing, such as improved health, lower imports of –and thus a lower external vulnerability to– imported hydrocarbons, more growth of innovating industries and more (local and high-tech) jobs. Higher efficiency, reduced demand and learning effects might even keep consumer electricity prices affordable. Thus, the European Energy Policy seems to promise good performance on all of these different dimensions –which were until recently assumed by many to be incompatible, even opposites. And there might even be 'free lunch' policies[1]. Whether such free lunches exist in the European electricity system has been explored with system dynamics models and will be discussed in this paper.

1.2 Characteristics of the European Electricity System

Electricity is a very peculiar service. It is an intermediate form of energy that is currently difficult and expensive to store on a large scale and needs to be generated from different other forms of energy to satisfy electricity demand at any moment. Most European electricity is currently generated in large centralised power plants and is transmitted and distributed through the national grids that are supposed to become ever more interconnected and to develop –in the long term– into a European electricity grid.

Most energy policies have in the past been made at the level of the member states, but the relevant policy level is also (believed to be) shifting to the European level. The European Energy Policy shows that the EU has strong policy-making ambitions in the energy/electricity domain.

There are many interactions and (delayed) feedback effects between and especially within these levels, which cause complex systems behaviour over time (e.g. cyclic behaviour or boom-and-bust behaviour), path dependence and lock-ins. The energy/electricity system and affected systems (such as the global climate system) are particularly characterised by the existence of important delays, and long average life- and response times. The average lifetime of European generation capacity amounts currently for example to about 20-50 years and learning and lock-in effects play on longer time scales, and other consequences[2] play on even longer time scales. The effects of the energy/electricity systems should therefore not only be analyzed in the short term and medium term, but in the long and very long term too (intergenerational time scales). The (past) inertia of the system does however not mean that it is not dynamic and that it could not drastically change in the future: such a drastic change is precisely what is envisaged by well-considered transition management. And the dynamic behaviour of the energy/electricity system is also multi-dimensional in nature, directly impacting the economic, social, environmental, technological and security of supply dimensions.

1.3 Consequences for Policy Analysis and Policy Design

An effective and efficient transition of the European electricity system towards a sustainable electricity system (with drastically reduced CO_2 emission, increased security of supply and economic growth and more jobs) requires the design and implementation of appropriate, timely, informed and justifiable policies and decisions. And for designing appropriate policies, a thorough understanding of the potential influence of the policies, characteristics of the system and the resulting multi-dimensional dynamics on multiple dimensions is needed.

The goal of the model discussed in this paper is precisely the generation of such understanding. Initially, the aim of this modeling endeavor was to explore the potential development of the *European wind power* sector over time. But in the end, the potential dynamic development of the entire European power sector had to be looked at because the developments of other generation technologies are major determinants of the development of wind power itself. The dynamic development –from the very short term to the very long term– of the entire European electricity sector will therefore be looked at in this paper, with a special focus on wind power.

[1]'Free lunch' policies are policies 'that improve some or most measures of performance without degrading others' (Forrester 1994, p251).

[2]such as the average atmospheric life-time of CO_2 which is estimated to be about 100-200 years, and is assumed to increase global temperatures for centuries and to raise ocean levels for millennia

In view of this, a system dynamics model is developed in this paper which is used to analyze the potential consequences of policies on multiple dimensions over time. The multi-dimensional simulation results are then explored and evaluated. These simulation results should not be seen as 'predictions', but rather as possible evolutions from which understanding might be derived which could be used to make more robust decisions.

1.4 Organization

In section 2, the structure of the system dynamics model will be discussed. The dynamics of the model will be explored in section 3 by means of a base case simulations, policy simulations, scenario analyses and (univariate and multivariate) sensitivity analyses. These multiple dimensional results are compared to other models and the literature. Finally, some conclusions, ex-post criticisms and directions for future research are discussed in section 4.

2 The Structure of the System Dynamics Model

2.1 Model Boundary and Influences Considered

The focus of the model discussed here is on the potential long-term dynamics of 9 electricity generation technologies[3]: gas-, coal-, nuclear-, wind-, biomass-, PV-, 'clean coal'-, hydro- and geothermal-based electricity generation technologies. The EU-25 policy level had been chosen at the time of its conception because it seemed to be the most relevant policy level for the future European electricity system. The focus on the high-level dynamic complexity of the competing technologies means that the model is highly aggregated: individual countries, companies, power plants, consumers, grids,... are not considered explicitly. The final time horizon of this model is the year 2100 –although most policies simulated are phased out before 2030– in order to analyze the long term dynamics of these short(er)-term policies. These aggregations, simplifications and modeling choices are acceptable only in view of the particular goal of exploring the general qualitative model behaviour in order to increase the understanding of the link between the structure and long-term qualitative time evolutionary behaviour of the simulated policies/structures, not of precise forecasts.

Endogenously modelled causal influences are among else: (i) the competition between these power generation technologies for supplying electricity; (ii) the competition between these power generation technologies for new generation capacity to be installed; (iii) the dynamic (endogenous) technological change of electricity generation technologies by means of experience curves; (iv) trade in CO_2 tradable emission certificates and tradable green certificates.

Causal structures assumed to be important but which are modelled only superficially (in a highly aggregated and simplified way) include: (i) the maximum potential wind power capacity; (ii) the societal value system and related to that, the public acceptance of wind power; (iii) siting and grid integration costs; (iv) the increasing need for backup generation and storage capacity with higher shares of variable wind power output in the total electricity system, decreasing the price and increasing the costs of wind energy; (v) the electricity demand and related to that demand side management and rational energy use; (vi) and the European import dependence and the potentially resulting energy system uncertainties and stresses.

Many other causal influences are thought to be important but are nevertheless modelled exogenously because their endogenous inclusion would require additional structures which would only draw the attention away from the issue of interest, namely the potential development of European wind power (and other power generation technologies) in order to decrease the contribution of the electricity sector to climate change. These exogenous influences are nevertheless varied in scenario and sensitivity analyses in order to assess their potential impact on the system dynamics model. Included exogenous variables are among else: (i) the general European economic development (which should actually be rendered partly endogenous); (ii) the evolution of the European energy

[3]See (Pruyt 2007b) for a detailed description of the model structure and multi-dimensional dynamics

intensity (which should actually be rendered partly endogenous); (iii) international fuel prices; (iv) the public acceptability of wind turbines and the ('greenness' of the) societal value system; (v) the degree of effective liberalization and competition; (vi) and the public support for nuclear power. Many related issues, influences and structures are not integrated in the model (see p28).

2.2 Feedback Loops – Feedback Loop Diagrams

The model contains many important feedback loops such as: positive *experience-cost* loops $\oplus$, a positive *wind power potential expansion* loop $\oplus$, negative *maximum potential* loops $\ominus$, positive *profitability* loops $\oplus$, positive *competition for generation* loops $\oplus$, negative *decommissioning* loops $\ominus$, negative *diminishing profitability* loops $\ominus$, positive *generation cost reduction* loops $\oplus$, a positive *capacity expansion of the wind power construction industry* loop $\oplus$, positive *new capacity required* loops $\oplus$, positive *experience improvement* loops $\oplus$, negative *backup and storage* loops $\ominus$, a negative *fuel import dependence* loop $\ominus$, negative *expected TGC and TEC cost* loops $\ominus$, a negative *demand elasticity* loop $\ominus$. These feedback loops are discussed in detail in section 1 of the appendix. The simplified stock-flow diagram in figure 1 (p5) also shows some important feedback loops for all generation technologies: the positive *experience-cost* loops and the positive *profitability* loops.

So, the model includes learning and experience effects, cost expectations, expectations of profitability of generation technologies potentially to be installed, effects of (dynamic) maximum potentials, effects of industrial expansion, competition effects between generation technologies and demand reductions, price-demand elasticity effects, intermittence effects (requiring sufficient backup or storage) and fuel import dependence effects.

2.3 Stocks and Flows – Stock-Flow Diagrams

The stock-flow diagrams of this model are displayed and discussed in detail in section 2 of the appendix. Figure 1 shows a 'summary' stock-flow diagram of some of the most important feedback loops for a generic *technology i*. The main stock variable for any particular technology is of course the *capacity installed* of that particular *technology i*.

3 Exploring the Dynamics

It takes a rather time and energy consuming iterative exploration process to build, test, simulate and interpret such dynamic models: many alternative structures and policies need to be modelled and simulated and many scenario analyses, uni-variate and multi-variate sensitivity analyses need to be performed. This issue is also very complex and there are too many uncertainties, assumptions and simplifications in order to use this model for point or trajectory predictions or to pay much attention to numerical sensitivity[4]. The general behaviour, behaviour mode and policy sensitivity are therefore of interest. The general behaviour of a structural base case scenario will be discussed in this subsection, followed by a discussion of the general behaviour of several policies, scenarios and sensitivity analyses.

3.1 Dynamics of the Base Case Scenario

Settings of the Base Case Scenario In the base case (BC) scenario[5], all *progress ratios* are equal to 85% except the *progress ratio of PV power capacity* which equals 75%. The *initial wind power capacity factor* is 1/3, the initial *capacity of the wind power construction industry* is 10GW, and the annual *maximum percentage growth wind power construction industry* is 30%. The *maximum wind power potential lookup* is displayed in figure 2a and the *siting and other investment*

[4]The work presented here was the immediate cause for the research on 'System Dynamics and Uncertainties' as presented in (Pruyt 2007a).

[5]The base case discussed here should be seen as a set of basic structural assumptions in order to better understand the link between model structure and model behaviour. It is *not* a 'Business As Usual' or reference scenario.

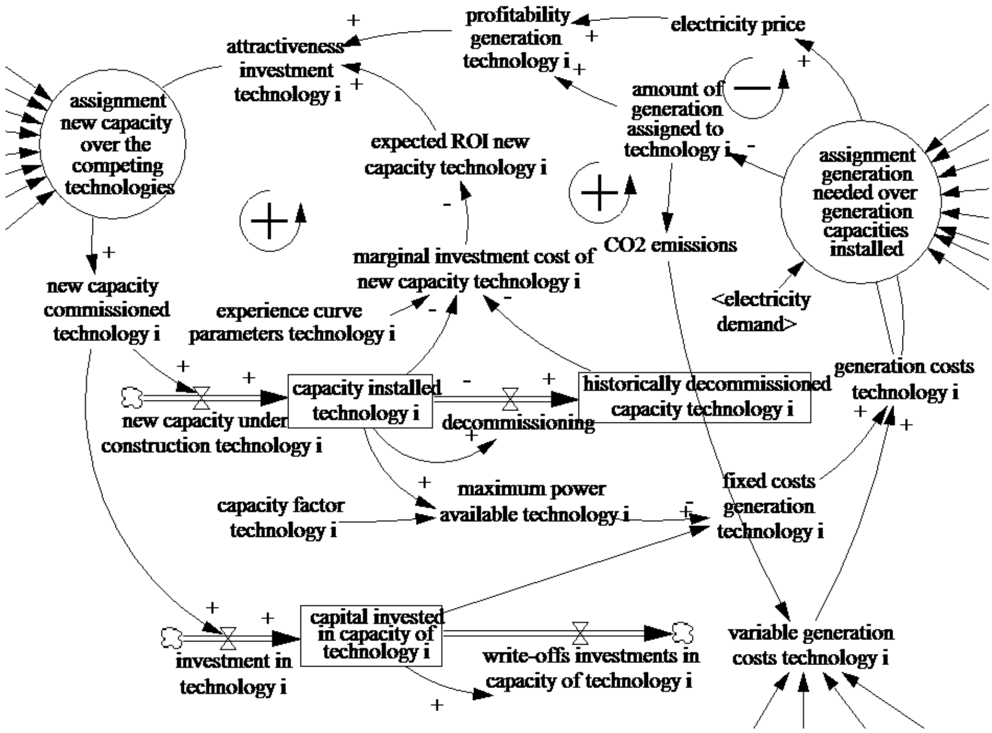


Figure 1: Summary stock-flow diagram of some of the most important feedback loops for a generic *technology i*

costs lookup in figure 2b. These lookup functions are nothing but guestimates and will therefore be subjected to sensitivity analyses.

The *initial marginal cost of wind power capacity 2006* is taken to be 900M€/GW, that of *gas capacity* 500M€/GW, of *coal capacity* 1100M€/GW, of *nuclear power capacity* 2000M€/GW, of *clean coal capacity* 5000M€/GW, and of *new PV power capacity* 6000M€/GW.

The lifetimes of these technologies are taken to be 20 years for *wind power*, *PV* and *geothermal* power generation technologies, 30 years for *gas*, *coal*, *clean coal* and *biomass* power generation technologies, and 40 years for *nuclear* and *hydro* power generation technologies.

The *initial average fuel cost of gas* based generation is taken to be 15419€/GWh, and of *coal* based generation 6665€/GWh. The *additional fuel cost clean coal* on top of the fuel cost of coal based generation is 10%, but there are no *additional carbon capturing and storing costs.* Later on, *additional carbon capturing and storing costs* will be added and subjected to sensitivity analyses. The *average fuel cost of biomass* is 80% of the normal cost if there is no biomass compared to its maximum potential, 150% the normal biomass fuel cost if the biomass capacity reaches its maximum potential, and even 500% the normal fuel cost if the capacity seriously overshoots the maximum potential. Normal fuel costs are incurred here when 50% of the maximum potential is reached. The *average nuclear fuel cost* is initially taken to be €2000/GWh, but there is an additional *future nuclear waste storage costs* of €1000/GWh. All market technologies also incur *other variable costs* of €8000/GWh.

The *initial specific CO_2 emissions of gas* based generation amount to 400tCO_2/GWh, the *initial specific CO_2 emissions of coal* based generation to 800tCO_2/GWh, and there is a *percentage CO_2 emissions of clean coal* of 10% of conventional coal emissions.

In the base case, the *GDP growth EU trend* is taken to be 3% per year (without a randomiser), the *electricity intensity of the EU growth* is taken to be 63% and there is a *price elasticity* of the electricity demand of 15%. There is no *annual percentage decrease of the electricity demand by forced DSM and REU.* The *electricity price* structure used here is equal to 1/3 the *apriori*

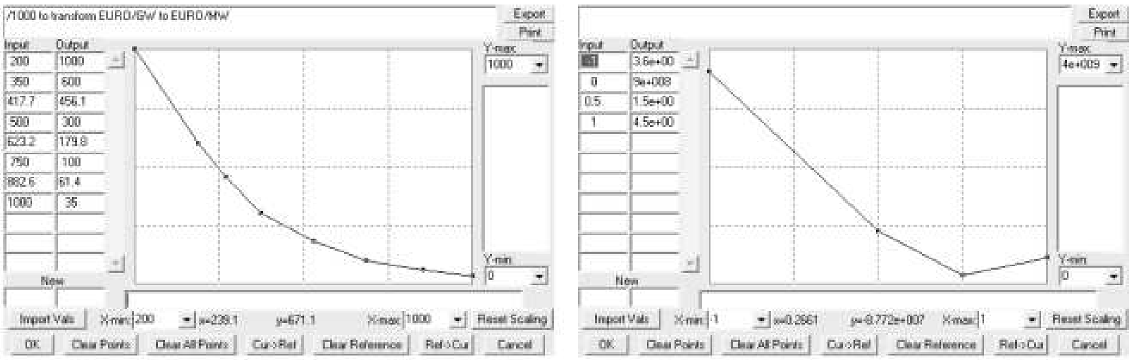


Figure 2: The *maximum wind power potential lookup* (left) and the *siting and other investment costs lookup* (right)

electricity market price plus 1/3 the *aposteriori electricity market price* plus 1/3 the *aposteriori electricity market price of the previous period.* And there is a general electricity price *markup* of maximum 5% in case of shortages.

There is no *real hydrogen or storage breakthrough* –hence no *additional growth rate electricity demand by hydrogen breakthrough* and no storage capacity for intermittent generation– and no *initial investment in clean coal capacity.* The *maximum biomass power capacity potential* is 500GW, the *initial maximum potential PV capacity* 1000GW, and the *maximum potential hydro capacity* 262.88GW. In the base case, there are no *wind power capacity investment subsidies*, no *initial investment in clean coal capacity*, no *percentage TGCs required*, the *TAX/TEC price* is €0/tCO_2, there is no *public support for new nuclear power* and the *greenness of the societal value system* is neutral, hence not specifically favouring wind power.

In the base run of the base case there is no *additional decommissioning nuclear capacity* or accelerated nuclear phase-out, and there is no renewed *public support for new nuclear power.*

The description above makes clear that the base case is actually an extreme scenario in that it does not contain many climate change policies to be expected or currently implemented. At most, it could be seen as a reference run of what would happen without any climate change policies, which is given the current context quite unrealistic. The base case is therefore not to be seen as a 'Business As Usual' (BAU) scenario. The moderate climate change scenario discussed on page 7 is currently more like a BAU scenario for the EU-25. This base case is therefore not really useful for policy relevant questions. But it *is* useful for assessing the overall dynamics of the model, and for assessing the influence of the policy measures. And even if the base case would be an adequate BAU run, then it should still be kept in mind that the model is nothing but a micro theory or an ensemble of structural assumptions. Many of these 'assumptions' will be varied in this and following subsections.

Simulation of the Base Case Scenario It should be kept in mind that the dynamics discussed in this and the following paragraphs are *not* projections, predictions, forecasts or foresights. They are first of all simulations to increase the understanding of the structure and the dynamics of the model during the iterative modelling process. This is one of the reasons why general time evolutionary dynamics are generated in the rest of this section instead of any (precise) numerical outcomes: the dynamics of the simulations will mainly be discussed by means of figures displaying the evolution of key variables over time.

The BC *electricity demand* increases steadily. The normal electricity supply –the *amount of electricity potentially generated*– periodically falls short of demand in the second half of the century, but the *absolute maximal potential electricity generation* allows to cover the electricity demand at all times, even in tight times. This is not necessarily so in case of strongly fluctuating demand.

The *total CO_2 emissions* from electricity generation continue to increase to about the sixfold of current emissions. The reason for this increase is to be found in the increasing electricity demand/supply combined with (more or less) constant *specific CO_2 emissions of electricity generated* resulting from the combined influence of a decreasing fraction of CO_2-poor generation technologies, an increasing fraction of gas based generation and decreasing specific CO_2 emissions of coal and gas based generation due to efficiency gains and learning and experience effects.

The fraction of CO_2-poor electricity generation decreases from 50% to about 20% (because of the continuously decreasing nuclear generation), whereas the fraction of coal remains rather stable, the fraction of gas-based electricity generation continuously increases, and the fraction of renewables increases until the middle of the century after which it slightly decreases.

Initially, the increase of the renewable generation fraction is mostly attributable to the rapid increase of the biomass fraction among else due to a high *premature conversion of coal to biomass capacity*. From 2022 on, the increase of the renewable fraction could be attributed mainly to the increasingly important fraction of PV electricity generation. The decreasing renewable fraction after 2050 could be explained by the maximum potentials reached of several of these renewable power options, whereas other potentials remain untapped in the absence of policies, for instance that of wind power (because of the intermittence requirement and the high amounts of PV capacity).

The enormous capacity installed of the PV type leads to less then 15% of generation because of its particular low –but dynamically increasing– capacity factor. Decisions about capacities to be installed are very important because they determine for a very long time, what technologies will be used for generation purposes and what technologies will be further invested in due to learning effect dynamics. The enormous capacity installed of the PV type additionally leads directly to lower wind power capacity.

The *annual investments* suggest decennial investment cycles which might in reality be even more pronounced because of the real-world commissioning and decommissioning of large fixed (discontinuous) amounts of generation capacity.

3.2 Policy Analyses

Three sets of climate change policies will now be introduced. These three base policy sets are compared with the base run of the BC, mainly by means of figures showing the evolution of important variables over time for the BC and the 3 climate change policy sets.

Description of the 3 Policies: The three climate change policies discussed here are actually sets of diverse policies assumed to be applied to the entire EU-25. The base POL1 policy set is a set of moderate climate change policies. The base POL2 policy set is a set of medium to strong climate change policies. And the base POL3 policy set is a set of very strong climate change policies. Many more policy sets could be simulated with this model, but only these three –and several variants– will be discussed here.

- In the base POL1 policy set –a set of moderate climate change policies– there is
  - no *annual percentage decrease electricity demand by forced DSM and REU*,
  - no accelerated/*additional decommissioning of nuclear capacity* as currently foreseen by many European countries,
  - no renewed political/*public support for new nuclear power*,
  - no *initial investment in clean coal capacity*,
  - a rising *greenness of the societal value system*, rising from 0% in 2006 to 10% in 2020 and remaining 10% thereafter,
  - a *public support for wind generation* of 10% above neutral (1.1 in the model),
  - a *wind power capacity investment subsidy* of 10% until the year 2020 after which it drops to 0%,

  - a TGCs system with a *percentage of TGCs required* increasing linearly from 0% in 2005 to 10% in 2020 dropping to 0% afterwards, a *minimum TGC price* rising from €0/TGC in 2005 to €10/TGC in 2020, and a *maximum TGC price* rising from €10/TGC to €50/TGC in 2020,
  - and a deterministic *TAX/TEC* system increasing linearly from €0/tCO_2 in 2005 to €50/tCO_2 in 2100.

- In the base POL2 policy set –a set of medium to strong climate change policies– there is
  - an *annual percentage decrease of the electricity demand by forced DSM and REU* of 1% per year from the year 2006 until the year 2012, as foreseen in a recently proposed European directive,
  - no accelerated/*additional decommissioning of nuclear capacity*,
  - no renewed political/*public support for new nuclear power*,
  - a rising *greenness of the societal value system*, rising from 0% in 2006 to 10% in 2020 to 30% in 2050 and 50% in 2100,
  - a *public support for wind generation* of 10% above neutral,
  - a *wind power capacity investment subsidy* of 20% until 2030 and 0% afterwards,
  - an *initial investment in clean coal capacity* of 2GW/y in the years 2010 and 2011,
  - a TGCs system with a *percentage of TGCs required* increasing linearly from 0% in 2005 to 20% in 2020 and 0% afterwards, a *minimum TGC price* increasing linearly from €0/GWh in 2006 to €20/GWh in 2020, and a *maximum TGC price* increasing linearly from €20/GWh in 2006 to €50/GWh in 2020,
  - and a *TAX/TEC* increasing linearly from €0/tCO_2 in 2006 to €100/tCO_2 in 2100.

- In the base POL3 policy set –a set of very strong climate change policies– there is
  - an *annual percentage decrease of the electricity demand by forced DSM and REU* of 1% per year –not only until 2012 as foreseen in the recently proposed European directive– but until the year 2030,
  - no accelerated/*additional decommissioning nuclear capacity*,
  - no renewed *public support for new nuclear power*,
  - a rising *greenness of the societal value system*, rising from 0% in 2006 to 10% in 2020 to 30% in 2050 and to 50% in 2100,
  - a *public support for wind generation* of 10% above neutral,
  - a *wind power capacity investment subsidy* of 20% until 2030 and 0% afterwards,
  - an *initial investment in clean coal capacity* of 4GW/y in the years 2010 and 2011,
  - a TGCs system with a *percentage of TGCs required* increasing linearly from 0% in 2005 to 20% in 2020 and 50% by 2030 and afterwards, with a *minimum TGC price* increasing linearly from €0/GWh in 2005 to €20/GWh in 2020 and afterwards, and a *maximum TGC price* increasing linearly from €20/GWh in 2005 to €50/GWh in 2020 and afterwards,
  - and a *TAX/TEC* increasing linearly from €0/tCO_2 in 2006 to €200/tCO_2 in 2100.

Comparison with the Base Case Figure 3 (p9) shows that the *electricity demand* differs strongly between the BC, POL1, POL2 and POL3 policy sets. The reason for this marked difference is that DSM and REU play an increasingly important role in these respective climate change policies. The differences in *electricity demand* and the differences in *specific CO_2 emissions of the electricity generated* (see figure 5 (p10)) account for the very different evolution of the CO_2

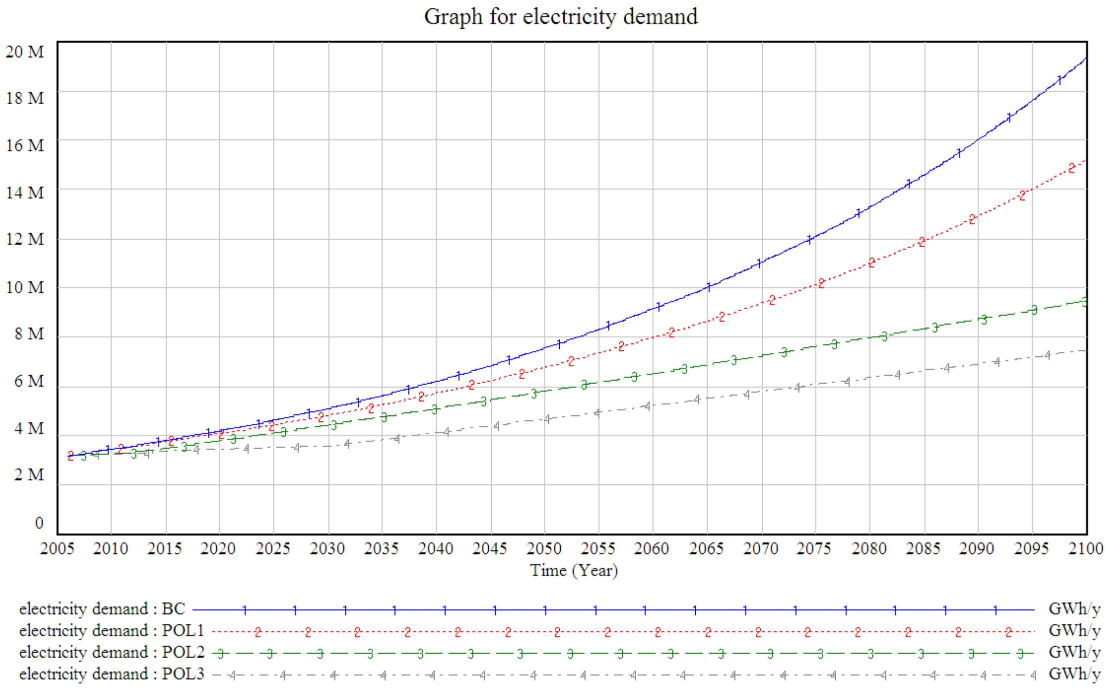


Figure 3: The *electricity demand* in case of the BC, POL1, POL2 and POL3 policies

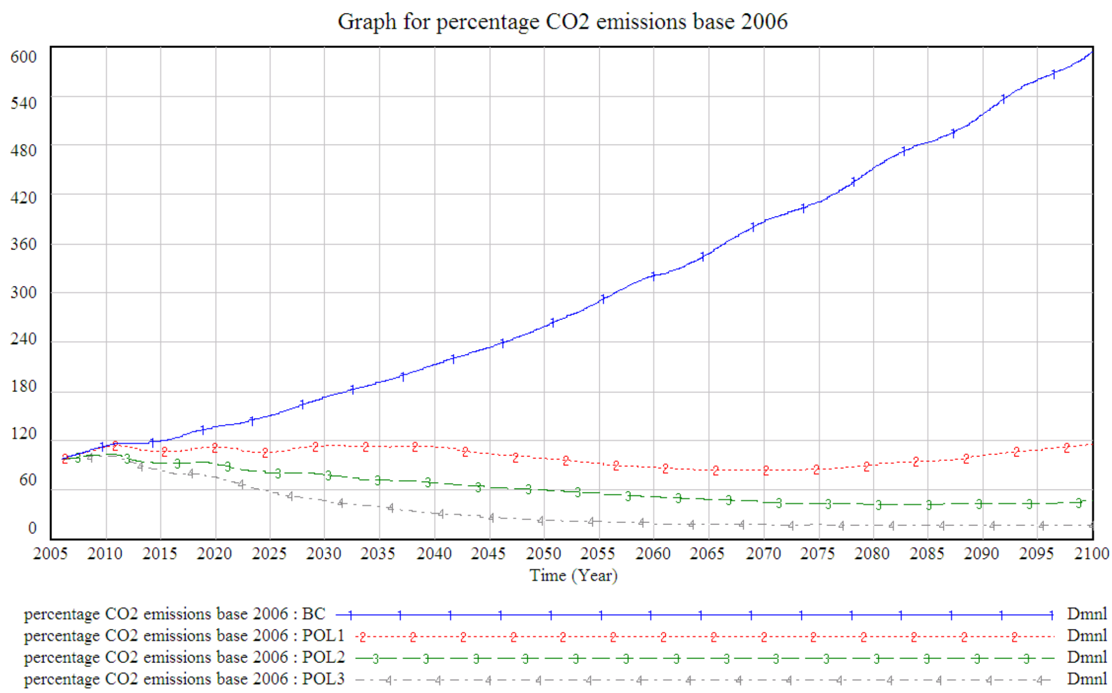


Figure 4: The *percentage CO_2 emissions* in function of the base year 2006 in case of the BC, POL1, POL2 and POL3 policies

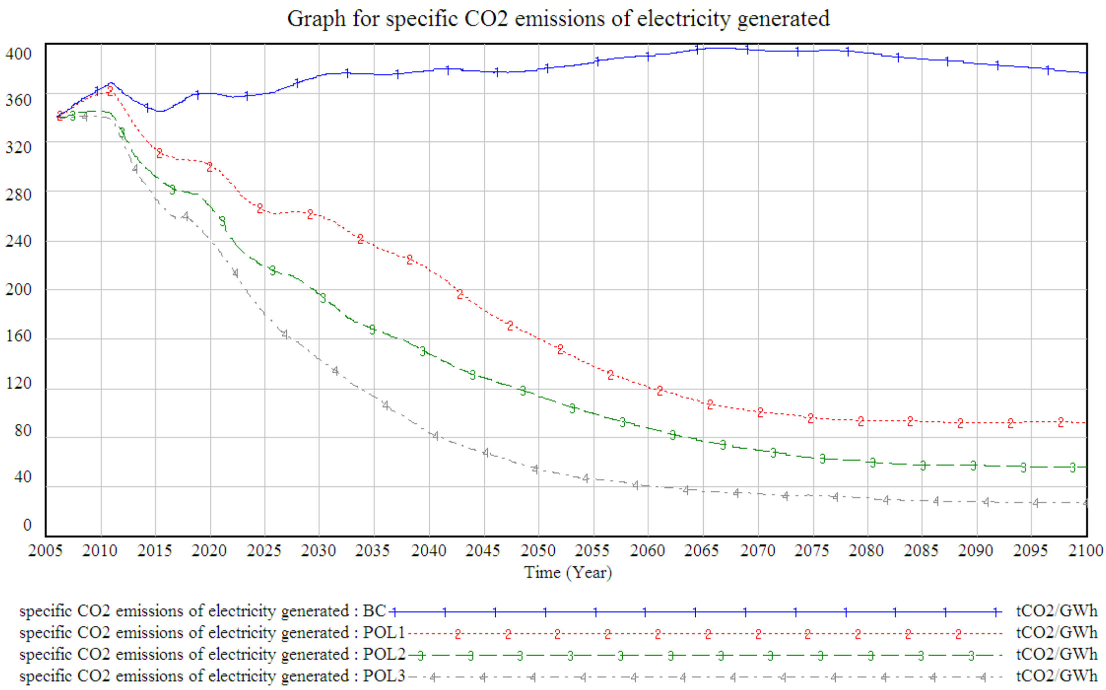


Figure 5: The *specific CO_2 emissions of electricity generated* in case of the BC, POL1, POL2 and POL3 policies

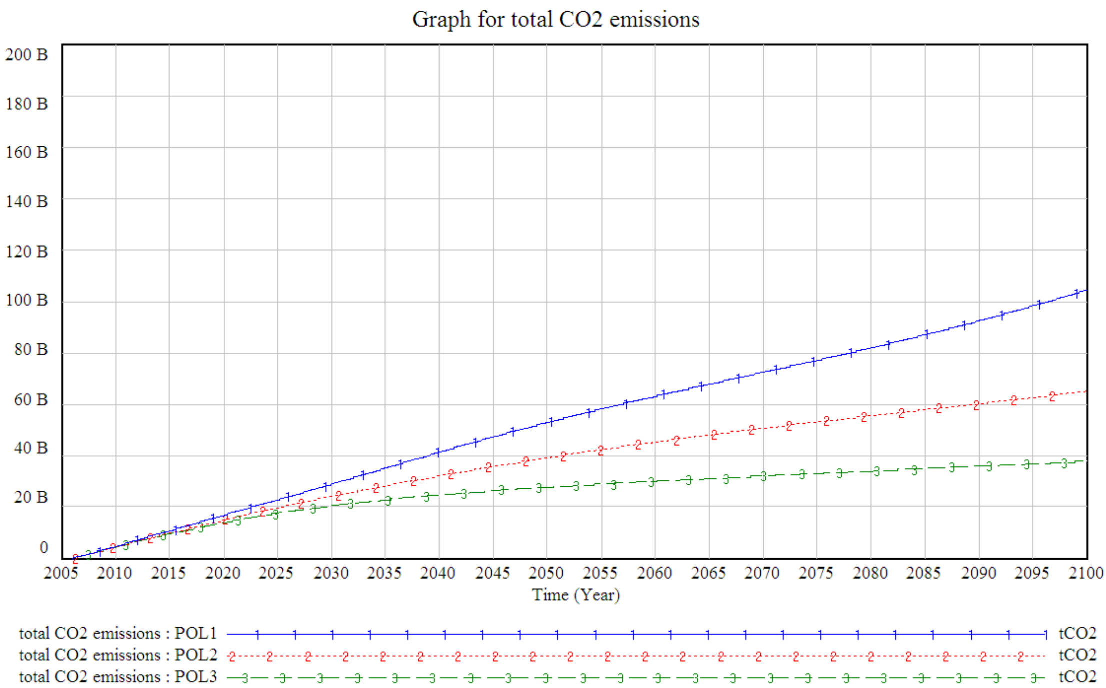


Figure 6: The *total **cumulative** CO_2 emissions of electricity generated* in case of the BC, POL1, POL2 and POL3 policies

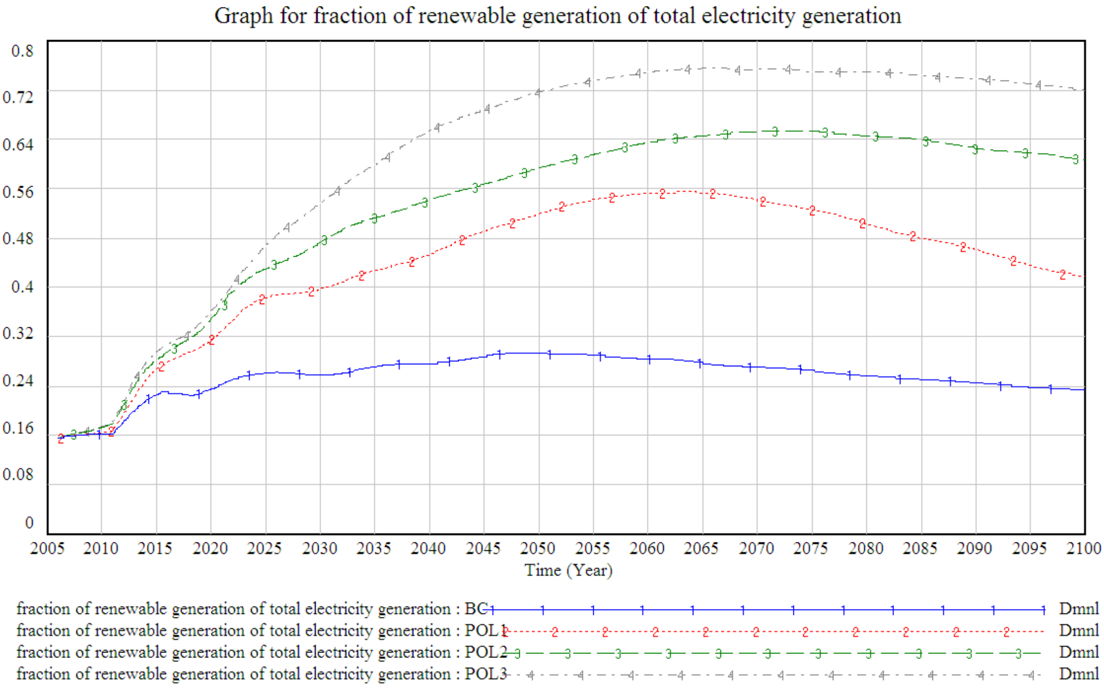


Figure 7: The *fraction of renewable generation of total electricity generation* in case of the BC, POL1, POL2 and POL3 policies

emissions (see figure 4 (p9)). The BC results in an exponential increase of the annual CO_2 emissions to about 6 times the 2006 emissions in 2100. The moderate climate change policy (POL1) leads –after an initial increase followed by a decrease and again an increase– to emissions of about 16% above year-2006 emissions. The medium climate change policy (POL2) leads to gradually decreasing CO_2 emissions to less than half the 2006 emissions. And the very strong climate change policy (POL3) results in a more rapid decrease of CO_2 emissions to less than a fifth of 2006 annual emissions.

However, the annual emissions are not as important as the cumulative CO_2 emissions displayed in figure 6 (p10) for POL1, POL2 and POL3. There it could be seen that these different paths make a huge difference in terms of behaviour of the accumulated emissions which eventually partially make up the atmospheric concentration.

The decreasing average specific CO_2 emissions per GWh generated of the three climate change policies are the result of the increasing fractions of renewable generation (see figure 7 (p11)) –most notably biomass generation (see figure 8 (p12))– and CO_2-poor generation in general (see figure 9 (p12)) –including clean coal generation (see figure 10 (p13))–, and the decreasing fraction of gas and especially coal based generation (see figure 11 (p13)).

Wind power generation makes up –at least in the base runs of the BC, POL1, POL2 and POL3– only a relatively small fraction of the renewables and total generation because of a low capacity factor and low capacity installed. The peak is mainly caused by TECs and TGCs schemes and direct investment subsidies and the subsequent decrease is mainly caused by an overshoot of the capacity installed above the dynamic maximum potential, the negative impact of a high fraction of intermittent capacity –caused by the increasing PV capacity installed– on the further development of wind power capacity, and the development of other CO_2 poor generation technologies.

It is interesting to see that the non-subsidised BC wind power capacity installed –in absolute terms– increases above that of heavily subsidised POL3 by the year 2045 and reaches about the same levels of capacities installed of the POL2 and POL1 policy sets. The underlying reason is

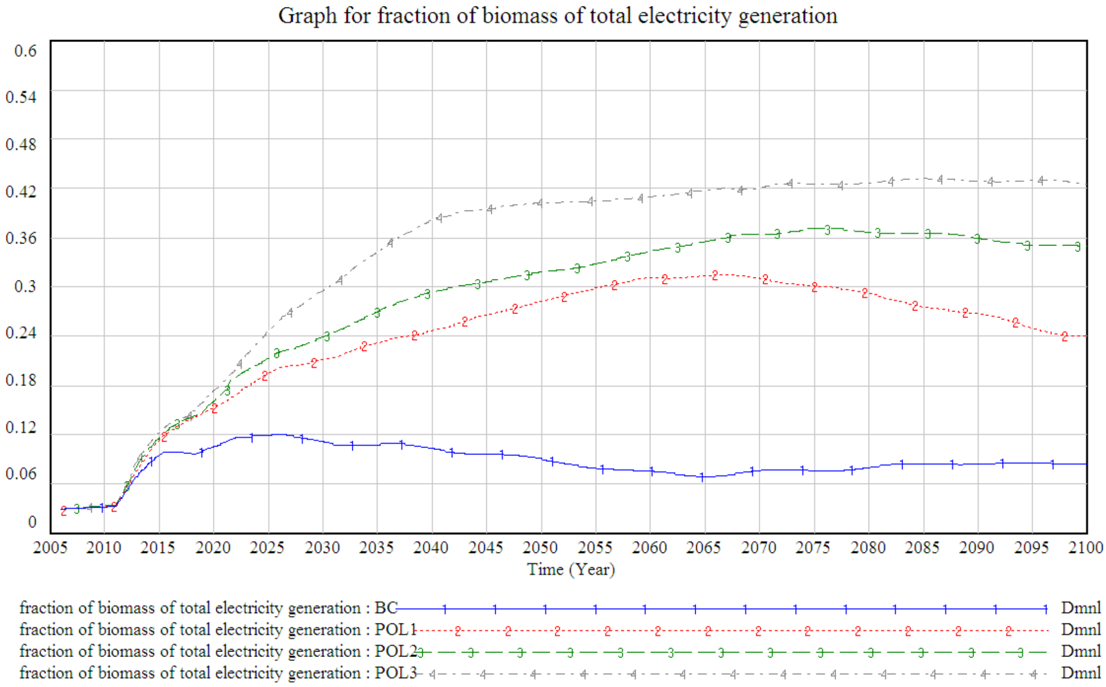


Figure 8: The *fraction of biomass generation of total generation* in case of the BC, POL1, POL2 and POL3 policies

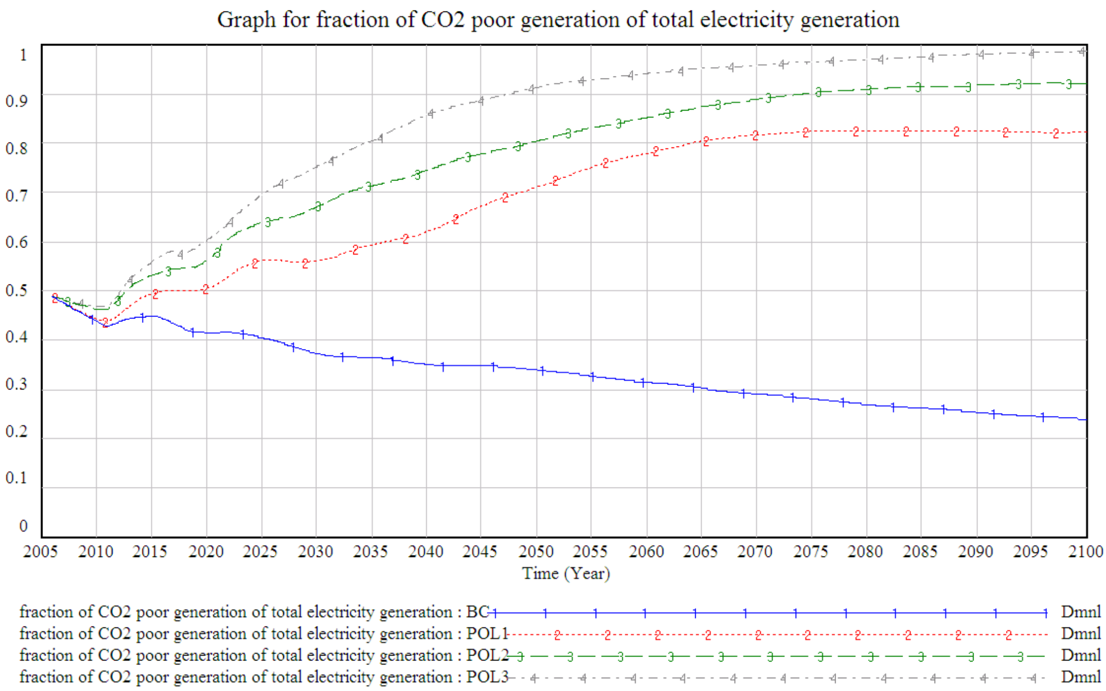


Figure 9: The *fraction of CO_2 poor generation of total electricity generation* in case of the BC, POL1, POL2 and POL3 policies

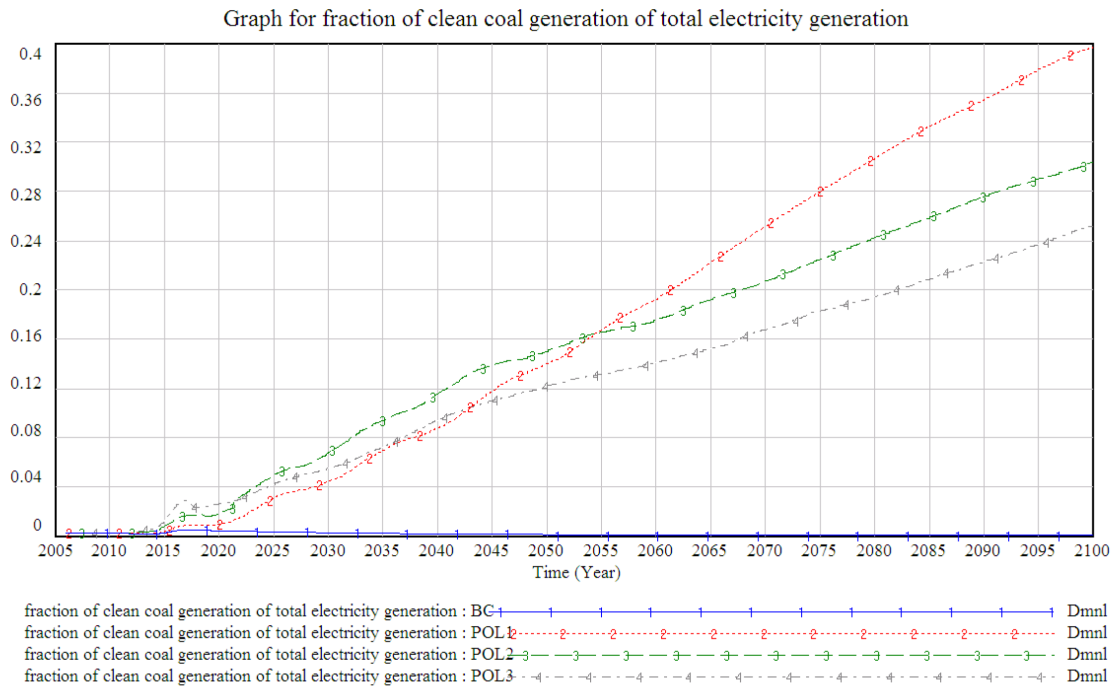


Figure 10: The *fraction of clean coal generation of total electricity generation* in case of the BC, POL1, POL2 and POL3 policies

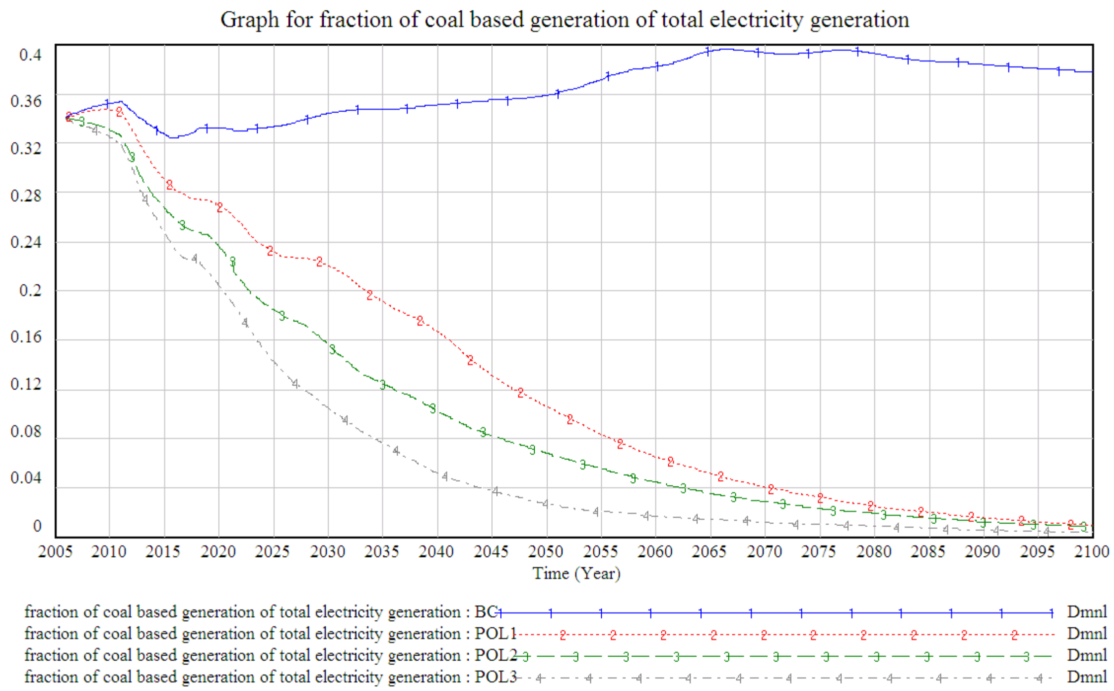


Figure 11: The *fraction of coal generation of total electricity generation* in case of the BC, POL1, POL2 and POL3 policies

the more substantial growth and total installed capacity.

The cumulative private investments from the year 2006 on are displayed enormous and still lead to potential generation shortages if the capacities are only used for generation within their normal capacity factor limits. These generation shortages slightly impact the electricity price: the BC leads to slightly decreasing electricity prices, that the POL1 climate change policy set leads to slightly increasing electricity prices, and that the POL2 and POL3 sets lead in the end to almost doubling and tripling electricity prices. Three main reasons for this are (i) the choice for (initially) more expensive generation technologies than would have been the case without climate change policies, (ii) the additional price paid for TGCs, CO_2 TECs and taxes on remaining CO_2 emitting generation, and (iii) the omission of external costs or potential climate change related costs.

3.3 Scenario/Policy Analyses

Gas Price Scenarios: Two gas price scenarios –a high and a low gas price scenario[6]– are –by means of the *average fuel cost gas as percentage of initial fuel cost lookup*– applied to the BC, POL1, POL2 and POL3 policy sets. In the high gas price scenario, the gas fuel cost expressed in percent of the initial fuel cost grows linearly from 100% in 2005 to 150% in 2020 to 180% in 2050 and to 200% in 2100. In the low gas price scenario, the gas fuel cost expressed in percent of the initial fuel cost decreases from 100% in 2005 to 70% in 2050 and to 50% in 2100.

These gas price scenarios most heavily impact the BC simulations because they are characterised by a higher electricity demand and a higher fraction of gas based electricity generation than the other policy sets.

The total cumulative investment costs are much lower in case of low gas prices because of the low marginal investment cost of new gas capacity. The total cumulative private investments are about €10^{12} lower (on a total amount of about €8 billion) in the low gas price scenario of the BC simulations than in the high gas price scenario. This leads to lower electricity prices and consequently more electricity demand in case of low gas prices which leads to almost 2000GW more cumulative new capacity installed in case of low gas prices.

The impact of these gas price scenarios on the fraction of CO_2 poor electricity generation is also more pronounced in the BC and the POL1 set, which leads to a marked difference in total cumulative CO_2 emissions. It is interesting to see in the BC runs that both the lower and –especially– the higher gas price scenarios lead to lower total cumulative CO_2 emissions than the normal price scenario. In the low gas price scenario, gas-based generation substitutes coal-based generation and therefore leads to lower specific emissions than in the normal price scenario. And in the high gas price scenario, this is due to the much lower fraction of gas-based generation, the higher fraction of clean coal based generation, the lower demand, and the higher renewable fraction –foremost due to the increased biomass based generation and to a lesser extent wind power generation. The fractions and absolute values of wind power capacity are only impacted in the BC simulations in the second half of the century. A possible reason for this is the need for flexible generation and/or storage capacity to compensate for the intermittent character of wind power. This will be explored in the following paragraph.

Nevertheless could it be concluded that the higher and lower gas prices lead in this model to different technology development and investment paths and hence to a different generation mix. This also means that the gas price could (potentially) be used for policy-making purposes.

Real Hydrogen or Storage Breakthrough Scenarios: The base BC, POL1, POL2 and POL3 policy sets are not characterised by a real breakthrough of hydrogen or cheap electricity storage technology. The impact of such a hydrogen (or storage) breakthrough in the year 2020 will be looked at in this paragraph. First, a breakthrough *without* an additional increase of the electricity demand and then a breakthrough *with* an additional growth of the electricity demand

[6]Fluctuating gas prices have also been simulated and lead to intermediate results.

by the hydrogen breakthrough –for example caused by the gradual switch from fossil fuels to hydrogen by road transport– is looked at.

Without additional growth of the electricity demand, the model shows a strong impact of a *real hydrogen or storage breakthrough* in 2020 on the penetration of wind power from that year on. The main reason for this is of course that a higher fraction of intermittent electricity capacity requires either backup generation capacity or significant cheap storage capacity. In the model, new intermittent capacity is disfavoured and flexible non-intermittent generation is favoured with increasing fractions of intermittent capacity before a real hydrogen or storage breakthrough. But this constraint ceases to exist once cheap hydrogen or a mass-storage technology becomes available. Massive storage could from then on form a buffer between the intermittent supply and variable demand.

This scenario leads to a substantial increase of the fraction of wind generation: on average about a quarter higher in 2030, about twice as high in 2050 and even higher in 2100. The same goes for the *fraction of wind power capacity installed of total capacity installed* depicted in figure. In the case of a cheap *real hydrogen or storage breakthrough*, more wind power capacity is installed in the long to very long term *without* stringent climate change policies. The reason for this is that electricity demand is much higher in such cases which means more absolute capacity additions and hence more sales.

There is only a small impact on the *fraction of CO_2 poor generation*, the *specific CO_2 emissions* and the annual *total CO_2 emissions*. The cumulative impact on *total cumulative CO_2 emissions* –which is what matters in case of CO_2 emissions– is small, but not negligible.

The impact on the *fraction of renewable generation of total electricity generation* is slightly bigger, between about 5 and 10%. This is caused by a substantial increase of the fraction of wind power and a decrease of the fractions of gas, biomass, coal (only in the BC) and especially of clean coal.

It also leads to marginally higher *total cumulative private investments* and a slightly higher *total cumulative new capacity installed* since wind power requires more capacity to be installed because of the lower capacity factor. So, the breakthrough of cheap storage or hydrogen technology *without* any additional demand leads –at least in this model– to a shift in technology.

But *with* an additional annual increase of the electricity demand increasing from 0% in 2020 to 2% in 2030 and remaining 2% until 2050 after which the additional annual increase of the electricity demand falls to 0%, does this scenario lead to slightly different specific CO_2 emissions, but also to a strongly increased electricity demand such that the CO_2 emissions of the European electricity sector increase –while at the same time most likely decreasing in other sectors such as the road transport sector– to such an extent as to undo the CO_2 mitigating efforts of the policies. It also leads to substantially higher amounts of *cumulative new capacity installed* and of *cumulative private investments*.

Furthermore, this scenario initially leads to higher fractions of wind power capacity and wind power generation, subsequently turning into fluctuating fractions, which combined with the significantly increased demand lead to much more wind power capacity installed –balancing on the limit of maximum potential. The other fractions therefore also change. Most notable among these changes are the significant increases of the fractions of gas generation and of clean coal generation, and the significant decrease of the fraction of biomass generation. This leads –contrary to the same scenario *without* additional demand– to significantly *lower* fractions of CO_2-poor and renewable generation. Balancing at the limit of the dynamically increasing maximum potentials also leads to slightly fluctuating electricity prices and to higher generation shortages.

The general conclusion of this hydrogen scenario analysis is that wind power capacity development is extremely sensitive to a real breakthrough of hydrogen (or storage) technology, especially when this leads to an increase of the electricity demand, at least *if* intermittence is punished.

GDP Scenarios: The influence of the GDP growth will be looked at in this paragraph. In the base runs, the *GDP growth* amounts to 3%. Here, two additional scenarios per policy set are compared to these base runs, more precisely one with a high *GDP growth* of 4.5% and one with a low *GDP growth* of 1.5%. The model also allows the assessment of the impact of fluctuating and random electricity demand increases, which are not explored here.

The *electricity demand* differs significantly between these scenarios. The CO_2 emissions expressed as a percentage of 2006 emissions therefore also differ substantially and, in spite of the smaller difference in specific CO_2 emissions per GWh. The same goes for the *total cumulative new capacity installed* and the *total cumulative private investments*.

These scenarios actually lead to bigger differences in the *fractions of renewable generation* than the *fractions of CO_2-poor generation* (the growth of the GDP is actually –per policy set– inversely proportional to the fraction of renewables), because of the major impact on the fraction of clean coal.

The growth also has an enormous influence on the absolute amount of wind power capacity installed and a smaller influence in relative terms. These simulations are again characterised by intermittence penalties and the lack of a *storage or hydrogen breakthrough* which partly explains the overshoot and subsequent depression (boom and bust) of relative wind power capacity and wind power generation in most runs.

The GDP growth also significantly influences the fractions of gas-based generation. The growth does not have a significant influence on the fraction of coal based generation because all scenarios applied to the policies (except for the BC policy set) lead to a substantial decrease of the fraction of coal based generation.

It could be said that higher GDP growth initially leads –at least in the case of POL1, POL2 and POL3– to higher fractions of biomass until the maximum potential is reached and the fractions of biomass decrease.

In the GDP scenarios, the electricity price decreases slightly in the BC policy case, increases slightly in the POL1 case, doubles in the POL2 case and triples in the POL3 case as it did in the base policy runs. Prices in the various scenarios diverge only slightly. The lower the modelled growth rates of GDP are, the lower the electricity prices in the model are.

The scenarios discussed here do not include a decoupling of the growth of the GDP and the growth of the electricity demand by means of a decreasing *electricity intensity of the EU growth*. Without such decoupling of the growth of the electricity demand from the economic growth, it could be concluded that the growth of the GDP has a major impact on many dimensions, also on the wind power capacity installed.

Combined Policies/Scenarios: Many other scenarios/policies and combined scenarios/policies might be simulated as well. Cross-impact assessment might also be used to assess the sudden/discontinuous occurrence of events –such as the outbreak of a major international conflict or a sudden political interference– or sudden (r)evolutions. This also helps to assess the in/sensitivity to such events and hence the robustness. The sudden addition of politically forced new nuclear capacity will be looked at later. Space precludes a full discussion of such additional analyses here.

3.4 Univariate Sensitivity Analyses

Sensitivity Related to the Maximum Wind Power Potential: The sensitivity related to the maximum wind power potential could be tested by changing the *maximum wind power potential lookup* function, or by changing the –specifically for such sensitivity analyses added– *maximum wind power potential lookup factor* (which is 1 in the base runs), thus changing the *gap wind power potential*[7] function.

A doubling of the *maximum wind power potential* –without any hydrogen breakthrough– leads to a higher absolute amount of wind power capacity installed and higher fractions of wind capacity installed and generated. It also leads to somewhat higher fractions of renewables and CO_2 poor generation. But it only leads to *slightly lower* fractions of gas, coal, biomass, and clean coal

[7](maximum wind power potential lookup factor * maximum wind power potential lookup - wind power capacity installed) / (maximum wind power potential lookup factor * maximum wind power potential lookup)

based generation, and to slightly lower relative, total and cumulative total CO_2 emissions. So without a hydrogen breakthrough there is not much change except for the higher amounts of wind power capacity and generation. A reason for this might be the fact that, here, wind power is still constrained by the backup generation or storage capacity required.

But if a hydrogen breakthrough (or another evolution removing the backup generation or storage capacity constraint) takes place, then a doubling of the *maximum wind power potential* substantially increases the wind power capacity installed, increases the fractions of CO_2 poor and renewable generation, decreases the fractions of gas based generation, of clean coal generation and of biomass generation. It also substantially decreases the percentage and cumulative emissions to such an extent that other emission paths (and thus atmospheric concentrations) are actually reached. More wind power capacity also means more cumulative investments and more cumulative new capacity installed.

Another potential source of sensitivity related to the maximum wind power potential are the *siting and other investment costs*. The sensitivity of the model to changes in this variable is explored by means of the specially added variable *siting and other investment costs lookup factor* which is 1 in the base runs. Two variants per policy set are simulated here, doubling and halving these *siting and other investment costs*. This only has a small influence on the wind power capacity installed and the fraction of wind power generated, and almost no influence on the other variables in the model. Completely other siting costs functions might however have a bigger impact but were not tested here.

Sensitivity Related to the Maximum Biomass Potential: In previous analyses, the absolute *maximum biomass power capacity potential* was taken to be 500GW which might actually be too high for the EU-25. The question explored here is whether lower maximum potentials would lead to very different dynamics.

If biomass is only used for electricity generation, then Ericsson and Nilsson (2006) assess the potential EU-25 biomass supply –using a resource-focussed approach– to lie between 4.1 and 17.2 EJ/y –compared with the biomass target of 5.6 EJ/y of the 1997 EC White Paper on Renewables– which comes down to a maximum power potential of about 76GW to 318GW knowing that 1EJ = 1/3.6 10^6GWh and assuming an efficiency of 35% and capacity factor of 60%. Parikka (2004) estimates –based on other studies– the European biomass potential to amount to 8.9 EJ/y –or 164GW assuming an efficiency of 35% and capacity factor of 60%. And the European Energy Agency (2005, p2) estimates (preliminarily) that 'the potential of *environmentally-compatible* primary biomass for producing energy could increase from about 180 Mtoe in 2010 to about 300 Mtoe in 2030', equivalent[8] to a maximum EU25 biomass power capacity potential of 159GW in 2010 to 265GW in 2030. Given this information, it seems reasonable to explore absolute *maximum biomass power capacity potentials* of 160GW and 280GW.

The biomass capacity installed in the POL1, POL2 and POL3 policy sets grows –in a slightly oscillatory fashion– to reach the maximum potential after 2025 and 2050. The BC policy set is influenced but does not reach the maximum potential at all. The cumulative total CO_2 emissions between 2006 and 2100 significantly increase with the lower biomass potentials. The difference between the base POL1 run and the 160GW POL1 scenario run even amounts to about 20GtCO_2 or more than 15% of the total cumulative emissions. This increase is mostly due to a decreasing fraction of biomass based generation, an increasing fraction of gas based generation, slightly higher coal based generation, much higher clean coal based generation and a somewhat higher fraction of wind power generation. And such an increased fraction of wind power generation requires a considerable additional amount of wind power capacity to be installed. The rest of the variables in the model (electricity price, cumulative investments, et cetera) only change slightly. So it could be concluded that the model outputs of the CO_2 emissions and wind power capacity installed are actually rather sensitive to the maximum biomass potential.

[8] converting Mtoe to GWh by multiplying by $1/(8.6 * 10^{-5})$ and assuming an efficiency of 35% and a capacity factor of 60%

Sensitivity Related to the Maximum PV Potential: The *maximum potential PV capacity* in this model is a dynamic maximum PV potential, although there is no truly endogenous dynamic link between the PV module and the rest of model. This maximum potential is in the limit almost double the initially provided *initial maximum potential PV capacity*. The 'correct' value of this *initial maximum potential PV capacity* is really uncertain because the ultimate maximum potential depends on many uncertain and unknown factors: the space ultimately available for PV panels, the relative price of the PV modules, potential technological (r)evolutions (Thin-Film Solar Cells), EU-25 support, the dynamics of other generation technologies, et cetera. It is therefore necessary to explore the sensitivity related to this *initial maximum potential PV capacity*. In the base runs, its value was taken to be 1000GW.

Here, a ten times lower value (100GW) and a two times higher value (2000GW) are first of all simulated. This has of course a very serious influence on the *PV power capacity installed* and the *fraction of PV of total electricity generation*. But in this particular form of the model, it also has a very important influence on the *wind power capacity installed* and the *fraction of wind power generation*, on the *fraction of gas based generation*, on the *fraction of clean coal generation*, and a somewhat weaker influence on the fractions of CO_2 poor generation and renewable generation –more wind but less PV generation and vice versa– and a weaker influence on the *fraction of coal based generation*. This also means that there is a small influence on the *(cumulative) CO_2 emissions*.

The *total cumulative private investments* are consequently much lower because the marginal investment cost of PV power is relatively high, and the *total cumulative new capacity installed* is also much lower because the capacity factor of PV power is relatively low which means that much more capacity is required to satisfy the electricity demand.

Two influences might at first sight seem surprising: (i) the very strong influence of the *initial maximum potential PV capacity* on the absolute amount *wind power capacity installed*, and (ii) the negative influence of the *(initial maximum potential) PV capacity* on the CO_2 emissions (less PV, less CO_2 emissions). Both influences are the result of two modelling choices (and their combination) in the model. First of all, PV power generation is considered to be distributed/decentralised 'must-run' generation. And second, it is directly linked to wind power capacity by the requirement that –unless there is a hydrogen breakthrough– there is a maximum *percentage of intermittent capacity*. Now, this influence (corresponding to my initial mental model) is rather strong in this model whereas it might actually even be very weak in the real world. It might therefore be considered to weaken this requirement or keep the requirement but uncouple wind power and PV power.

Sensitivity Related to the Clean Coal Power Costs: Many of the previously discussed simulation runs –especially those of the POL3 policy set– show enormous increases of clean coal power capacity and generation. This effect might however be due to the determinist assumptions used in these runs. Until now, the model included no *additional carbon capturing and storing costs*, *additional fuel cost clean coal* of only 10% above the *average fuel cost of coal* based generation, a *percentage of CO_2 emissions* of 10% of coal emissions, and an *initial marginal cost of clean coal capacity 2006* of €5/W, falling very rapidly after taking-off given the progress ratio of 0.85 and the assumed *cumulative historic clean coal capacity* of only 1GW. These assumptions –and the possible effects on other variables and the model as a whole– will be further explored here.

Anno 2006, potential clean coal power and carbon capturing and storing (CCS) are still characterised by many (fundamental) uncertainties and unknowns and are therefore to be accessed with broad uncertainty ranges and different assumptions and estimates. These additional costs are not certain and different estimates and ranges are advanced by different researchers and parties. Sensitivity analyses therefore seem to be quite necessary. The model sensitivity related to clean coal power costs could be dealt with in different ways:

- Sensitivity related to *additional carbon capturing and storing costs*:

  Additional costs of CO_2 *capturing* in power plants are estimated to amount to some US$30-50/t$CO_2$ (Moomaw, Moreira, Blok, et al. 2001, p250), 18-70 US$/t$CO_2$ (AMPERE Commission 2000, D154), or 15-75 US\$/tCO_2 (IPCC 2005). But these 'capturing *and storing* costs' also depend on the storing costs which depend on the potential economic application of the storing of these captured CO_2 emissions. The total costs might even become 0 or negative in case of using the CO_2 emissions for *enhanced oil recovery* or *enhanced coal bed methane recovery*.

Until now, these *additional carbon capturing and storing costs* in the model amount to €0/tCO_2. Here, amounts of €30/tCO_2 and €60/tCO_2 will be tested.

These costs per tCO_2 captured need to be transformed to coal based electricity generation costs in order to be used in the model. Estimated additional carbon capturing and storing costs per tCO_2 of €30/tCO_2 in case of carbon based generation with a CO_2-intensity of about 800tCO_2/GWh gives *additional carbon capturing and storing costs* of about €24000/GWh and about €48000/GWh for a cost of about €60/tCO_2.

With the *additional carbon capturing and storing costs* of €24000/GWh– clean coal power does not take off in the POL1 policy set compared to the very successful take-off without these additional costs, that clean coal power takes off very late (after 2070) in the POL2 policy set and that it takes off with much lower fractions in case of the POL3 policy set. POL1 and POL2 lead –*with* this additional cost– to higher fractions of gas, biomass and wind (and of renewables in general), to lower fractions of CO_2 poor generation, to much higher annual emissions and cumulative emissions, to somewhat higher prices (about €5000/GWh higher), to lower *total cumulative private investments* but higher amounts of *total cumulative new capacity installed* (more gas).

These evolutions are strengthened in case of *additional carbon capturing and storing costs* of €48000/GWh. Then only POL3 takes off but very slowly and only really in the second half of the century round about the time POL2 would take off in case of *additional carbon capturing and storing costs* of €24000/GWh and POL1 in case of *additional carbon capturing and storing costs* of €12000/GWh.

- Sensitivity related to the *additional fuel cost clean coal*:

  Carbon capturing also requires extra energy. These extra energy requirements are estimated to lie between 15 and 21% (International Energy Agency 2003, p415-420) or between 14 and 25% (IPCC 2005) for IGCC plants and up to 40% for other coal fired plants. These initial extra fuel needs in the model were initially taken to be 10%. An *additional fuel cost* of 40% somewhat slows the penetration of clean coal power. It also slightly influences the amount of wind power capacity installed, the total and cumulative CO_2 emissions and other variables in the model, but does not lead to fundamental behavioural changes.

- Sensitivity related to the learning curve parameters – the *cumulative historic clean coal capacity*, the *progress ratio of clean coal power capacity* and the *initial marginal cost of clean coal capacity*:

  These three interrelated parameters strongly influence the development of clean coal power in the model. The impact of changing the *cumulative historic capacity* of clean coal from 0GW (or actually 1GW what it was until now) to[9] 10GW or to[10] 50GW, each time about halving the fraction of clean coal power. And halving the fraction of clean coal power also seriously impacts –especially in the POL1 and POL2 runs– the fraction of gas (which it is substituted by the relative and cumulative CO_2 emissions and to a lesser extent the wind power capacity installed and the electricity prices. The underlying reason for the halving of the fraction of clean coal power is the less radical decrease of the marginal investment cost of clean coal capacity. Now, a less radical decrease of the marginal investment costs might actually seem reasonable given the maturity of existing coal technologies.

[9] POL1sensCCShistcap10, POL2sensCCShistcap10 and POL3sensCCShistcap10
[10] POL1sensCCShistcap50, POL2sensCCShistcap50 and POL3sensCCShistcap50

Until now, the *initial marginal cost of clean coal capacity* was set to €5/W, which is rather high when compared to estimates in the literature (International Energy Agency 2003, p415-420). A lower *initial marginal cost of clean coal capacity* of about €3/W might be more appropriate in combination with the *cumulative historic capacity* of 10GW and the progress rate of 0.85. This leads –depending on the evolution– to prices for new clean coal capacity of about double the investment cost of conventional coal power by the year 2015 and of about the same investment cost (as current conventional investment costs) by the year 2060, and it also leads to about the same behaviours as discussed before –although the numerical values slightly differ– with one important exception: these values lead *also* in the BC to a take-off of clean coal power. The underlying reason is of course the specific capacity assignment structure combined with the less prohibitive initial marginal investment costs.

But it is not really important which precise values are selected here because (i) their analyses lead to increased understanding and (ii) these variables are *so* uncertain that they need to be treated as uncertain too. One way to do that is to subject them to multivariate sensitivity analyses as is done on page 21 and following pages.

- Sensitivity related to the breakthrough of *clean coal power*:

  Related to the previous sensitivity analysis, is the analysis of the consequences of a clean coal non-occurrence. This could be simulated by assigning a prohibitively high *initial marginal cost* to clean coal capacity and removing the initial amounts supported by governments. Another interesting analysis would be the exclusion of clean coal power from the TECs scheme.

Sensitivity Related to the Flexibility Premium: The model is behaviourally sensitive to different flexibility premia for the flexible gas-based electricity generation: gas-based electricity generation is not particularly attractive without flexibility premium (BCflexgas00) –because without this premium, it is more expensive than coal-based generation. With a flexibility premium of 10% and without higher gas prices, it is relatively more interesting than coal-based generation until about 2040 after which coal-based generation becomes more interesting. With a flexibility premium of 20% and without higher gas prices, it is always more interesting than coal generation. But higher gas prices (rising to 150% of the BC gas price between 2020 and 2080) undo the additional advantage caused by the flexibility premia of 10% or 20%. The flexibility premia do not only impact gas and coal-based generation, but also the wind power capacity installed and wind power electricity generated, and the emissions of CO_2. They also point at the importance of (expected) prices and additional characteristics such as flexibility.

Sensitivity Related to the Pricing Structure: The model contains many 'simplistic' structures among which the electricity pricing structure, the generation assignment structure, the new capacity assignment structure, the electricity and environmental markets structures, et cetera. All of these structures are open to criticisms and could –if needed– be further tested, elaborated and improved. A sensible extension of the model would be the addition of feedback loop structures to render the TECs and TGCs schemes and prices truly endogenous.

The simplistic electricity pricing structure used here is equal to 1/3 the *apriori electricity market price* plus 1/3 the *aposteriori electricity market price* plus 1/3 the *aposteriori electricity market price of the previous period.* An alternative electricity pricing structure has been thoroughly tested: 0 * *apriori electricity market price* + 1 * *aposteriori electricity market price* + 0 * *aposteriori electricity market price of the previous period.* Almost all simulations described above have been simulated with this alternative structure too. The structure is even more simplistic, but less robust, and leads to many slightly different numerical outcomes, but not to very different general behaviours, and some additional insights. These results are not presented here given the lack of space.

Other Possible Sensitivity Analyses and Alternative Structures: Many other structures and values are and could be subjected to such univariate sensitivity analyses. Many of them will now be explored all together.

3.5 Multivariate Sensitivity Analyses

The system dynamics model discussed here contains many (sometimes fundamentally) uncertain assumptions (structures, functions and values) and simplifications. Until now, the assumptions have been changed, simulated and explored one at a time in order to thoroughly understand the link between these separate assumptions and their resulting time evolutionary behaviours. Now, a different approach will be followed to grasp the possible joint implications of these uncertain values, variables and structures.

Here, multivariate sensitivity analyses (or Monte-Carlo analyses) will be performed, simulating the model 2000 times, randomly selecting values for the uncertain assumptions from uncertainty distributions hypothesised to underly the uncertain phenomena. Multivariate sensitivity analysis (MSA) is useful here in at least four respects. It could be used to:

- assess the general behaviour of the policy sets (in the particular model) when subjected at the same time to many uncertain assumptions;
- compare the resulting behaviour with the behaviours of the separate simulation runs discussed before and to learn from this comparison;
- assess the sensitivity of the model to these changing assumptions;
- assess the sensitivity and robustness of the particular policy sets in *this* model.

The probability ranges/distributions assumed: The following distributions/ranges are assumed in the multivariate sensitivity analyses discussed here:

- Initial maximum potentials:
  - maximum biomass power capacity potential = RANDOM UNIFORM(75,200)
  - initial maximum potential PV capacity = RANDOM UNIFORM(100,2000)
  - maximum wind power potential lookup factor = RANDOM UNIFORM(0.8,2)
  - maximum potential hydro capacity = RANDOM UNIFORM(200, 300)
- Initial marginal investment costs:
  - initial marginal cost of clean coal capacity 2006 = RANDOM UNIFORM(1.5 10^9,4 10^9)
  - initial marginal cost of coal capacity 2006 = RANDOM UNIFORM(0.9 10^9,1.3 10^9)
  - initial marginal cost of gas capacity 2006 = RANDOM UNIFORM(0.4 10^9,0.6 10^9)
  - initial marginal cost of wind power capacity 2006 = RANDOM UNIFORM(0.7 10^9,1.1 10^9)
  - initial marginal cost of nuclear power capacity 2006 = RANDOM UNIFORM(1.5 10^9, 2.5 10^9)
  - initial marginal cost of biomass capacity 2006 = RANDOM UNIFORM(10^9, 2.5 10^9)
- Initial average fuel costs:
  - initial average fuel cost biomass = RANDOM UNIFORM(12000,18000)
  - initial average fuel cost coal = RANDOM UNIFORM(5000,9000)
  - initial average fuel cost gas = RANDOM UNIFORM(12000,20000)
  - percentage CO_2 emissions clean coal = RANDOM UNIFORM(0.08,0.2)

- Progress ratios:
  - progress ratio of clean coal power capacity = RANDOM UNIFORM(0.8,0.9)
  - progress ratio of biomass power capacity = RANDOM UNIFORM(0.8,0.9)
  - progress ratio of coal power capacity = RANDOM UNIFORM(0.80,0.95)
  - progress ratio of gas power capacity = RANDOM UNIFORM(0.8,0.9)
  - progress ratio of PV power capacity = RANDOM UNIFORM(0.7,0.9)
  - progress ratio of wind power capacity = RANDOM UNIFORM(0.8,0.9)
- Other costs:
  - additional carbon capturing and storing costs = RANDOM TRIANGULAR(0,48000,0,24000,48000)
  - additional fuel cost clean coal = RANDOM UNIFORM(0.1,0.5)
  - siting and other investment costs lookup factor = RANDOM UNIFORM(0.5,2)
  - maximal additional siting costs = RANDOM UNIFORM(0.1 10^9,1.3 10^9)
- Other parameters and events:
  - initial decommissioned clean coal power capacity = RANDOM UNIFORM(1,50)
  - public support wind generation = RANDOM UNIFORM(0.9,1.2)
  - additional percentage coal use clean coal generation = RANDOM UNIFORM(0.1,0.4)
  - flexibility premium = RANDOM UNIFORM(1,1.2)
  - year real hydrogen or storage breakthrough = RANDOM UNIFORM(2015,2106)
  - percentage CO_2 emissions clean coal = RANDOM UNIFORM(0.08,0.2)
  - electricity intensity EU growth = RANDOM UNIFORM(0.6, 0.66)
  - additional growth rate electricity demand by hydrogen breakthrough constant = RANDOM UNIFORM(0, 0.01)

The premature conversion of idle coal capacity to new biomass capacity of 10% of the coal capacity idle for over 2 years in a row, kick-starting biomass generation capacity and generation has been abandoned in this MSA: so there is no *premature conversion of idle coal capacity to biomass capacity*. This leads of course to lower fractions of biomass generation, but also to higher fractions of gas based and clean coal based generation, to lower fractions of CO_2-poor and renewable generation, and to higher annual and cumulative CO_2 emissions. But the wind power capacity installed and annual wind power generation only differ slightly from the high biomass cases. The results of these analyses will be discussed in the following subsection as part of the multidimensional evaluation of several policy sets.

3.6 Multidimensional Evaluation of Policy Sets

The goal of this multi-dimensional evaluation is to increase the understanding about the possible multi-dimensional impacts of strategies, the influence of different preference sets and the sensitivity of policy choices, not necessarily to determine the best or most appropriate strategy.

The continuous behaviour of the strategies were first of all qualitatively explored on several dimensions in order to learn from the qualitative behaviour and to eliminate unacceptable strategies. After that, a subset of criteria and specific moments in time was chosen, and an MCDA method (the PROMETHEE I–GAIA method) was applied to the remaining strategies in order to gain some understanding about the impact of evaluations on criteria and preferences, and their interaction. This formal multiple criteria decision analysis analysis and the results are not discussed in this paper.

3.6.1 Dimensions, Aspects and Criteria

There are many important dimensions when dealing with the interrelated issue of climate change and sustainable electricity systems such as the environmental dimension (ENV), the social-cultural dimension (SOC), the economic dimension (ECO), the technological-technical dimension (TECH) and the security-reliability of supply dimension (SEC).

There are also important criteria within these dimensions –many of them represented by variables in the system dynamics model– that could be looked at. The following seven specific criteria/proxies will be focussed on here: (1) f_1: *percentage CO_2 emissions base 2006* [%] (ENV); (2) f_2: *fraction of CO_2 poor generation of total generation* [%] (ENV/TECH); (3) f_3: *fraction of renewable generation of total generation* [%] (ENV/TECH); (4) f_4: *fraction of gas based generation of total generation* [%] (proxy for SEC); (5) f_5: *electricity price* [€/GWh] (SOC/ECO); (6) f_6: *total private cumulative investment cost 2006–...* [€] (ECO); (7) f_7: *wind power capacity installed* [GW] (ECO/TECH/SECTORAL).

3.6.2 Strategies

Many strategies could be simulated with the model. The multi-dimensional evaluation phase is illustrated by means of seven relatively simple strategies, all based on the policy sets discussed before.

The strategies are subjected to the multidimensional sensitivity analysis discussed in subsection 3.5 which is characterised by low biomass capacity and no premature conversion of coal to biomass based generation capacity and which leads to results similar to those found in the literature. The *initial wind power capacity installed* is taken to be 40.504GW and the *initial new wind power capacity under construction* 6.183GW/y. The reason for using these very precise numbers is that the results will most probably be interpreted by some in a numerical sense, no matter how many warnings against such interpretations.

Strategy S_0 is simply the BC policy set, strategy S_1 the POL1 policy set, S_2 the POL2 policy set and S_3 the POL3 policy set, all subjected to these new (initial) conditions. Strategy S_4 corresponds to the POL2 with a sudden *new politically forced new nuclear capacity* commissioning of 20GW in 2015, 50GW in 2020, 50GW in 2030, and 50GW in 2050. Strategy S_5 corresponds to POL3 but without clean coal. And strategy S_6 corresponds to POL3 with wind subsidies of 30% until 2050 and a real hydrogen breakthrough between 2015 and 2025.

3.6.3 Multi-dimensional MSA Dynamics

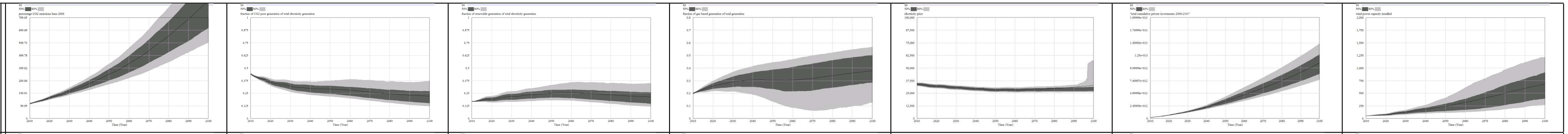
The resulting evolutions of the IQRs (Inter Quartile Ranges) and 80% IPRs (Inter Percentile Ranges) of the strategies on these criteria are displayed in table 1 (p24). The table contains an enormous amount of conflicting information that would be lost in aggregated form or without proper analysis and that is difficult to be used for decision-making without additional information. Examples of such conflicts are (i) performance conflicts of a strategy on different dimensions (for example $f_1(S_0)$ versus $f_5(S_0)$), (ii) performance conflicts of a strategy on different moments in time (for example $f_7(S_6)$), or (iii) performance and evolution conflicts of a strategy on a dimension and moment in time due to uncertainty (for example $f_4(S_5)$ on any moment between 2030 and 2075).

The criteria are also to be interpreted in different ways. Some criteria give an indication of the absolute performance of strategies on a criterion (f_1) whereas other criteria might be used to evaluate the relative performance of different strategies on a criterion (f_6). And some criteria provide information about the absolute performance of a strategy on a criterion but hide the relative performance of a strategy on a criterion ($f_7(S_6)$ suggests the absolute amount of wind power capacity installed in case of S_6 but does not indicate that the wind power fraction IQR of S_6 tops round 29-41% in 2053). The graphs also give an indication of the in/sensitivity or robustness of the strategies in the model.

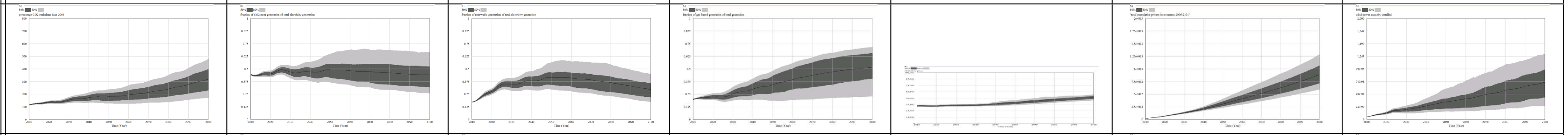
Many qualitative conclusions might be reached based on this table, for example (i) that no strategy is unambiguously good or bad on all criteria at any moment in time, (ii) that S_0 is

	f_1: percentage CO_2 emissions base 2006 [800%] (min)	f_2 : fraction of CO_2 poor generation [100%] (max)	f_3: fraction renewable generation [100%] (max)	f_4: fraction gas based generation [100%] (min)	f_5: electricity price [€200000/GWh] (min)	f_6: total cumulative private investments 2006- [10^{13} €] (min)	f_7: wind power capacity installed [4000GW] (max)

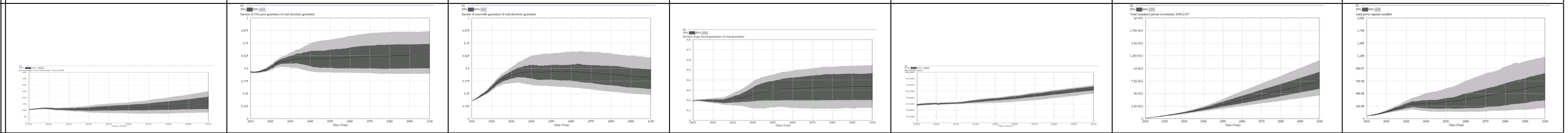
S_0



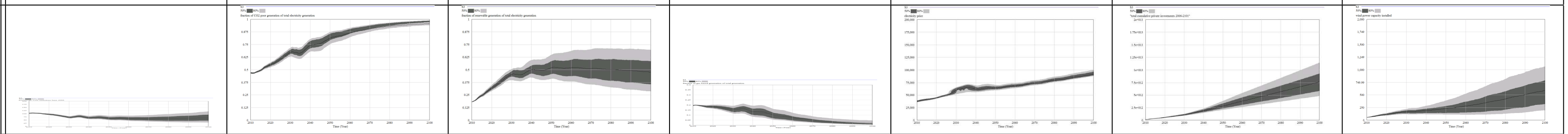
S_1



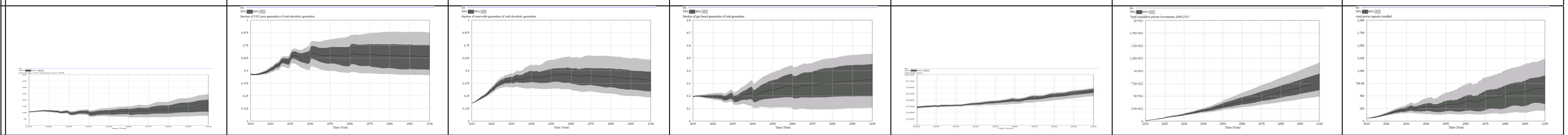
S_2



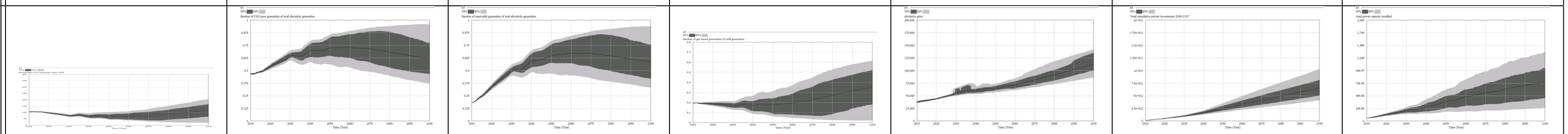
S_3



S_4



S_5



S_6

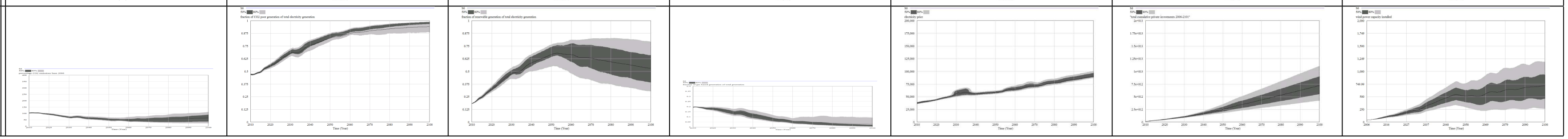


Table 1: Qualitative evaluation of the time evolutionary dynamics of six strategies on seven criteria: the dark grey area contains 50% of the simulation runs, the light grey area 80%, and the black line represents the median simulation run (readers are referred to the electronic version to zoom in on individual figures and (median) lines)

extremely bad on f_1 (the percentage CO_2 emissions) and several other criteria, (iii) that S_3 and S_6 are good on all criteria considered except the direct electricity price, (iv) that S_3 and S_6 show that the fraction of gas based generation needs to be reduced in order to effectively reduce CO_2 emissions. Such a table could then be used to eliminate unacceptable strategies.

The long term evolutions on criteria f_1 and f_2 indicate whether the CO_2 emissions and CO_2 poor fractions are heading in the right direction: S_3, S_5, S_6 are heading in the right direction, S_2 and S_4 not really, and S_0 and S_1 absolutely not. Strategies S_0 and S_1 might therefore be rejected on ethical (intergenerational) grounds. The S_2 and S_4 policy sets might on the other hand be strengthened and redirected after 2030 and might therefore not necessarily be rejected. Doing this for other criteria and time scales increases the understanding and allows to reject other strategies too. The price criterion might also lead to the elimination of other strategies. This exercise necessarily needs to be performed by the parties involved: just handing over conclusions is less effective. Such tables could then be used as very powerful tools for exploration, critical reflection and dialogue. They could also set the stage for more formal/quantitative analyses which are not discussed here.

4 Some Conclusions, Ex-post Criticisms and Venues for Future Research

4.1 Conclusions

Even without the possible extensions, valuable lessons for climate change policy-making could be learned from this model, for example that:

- The different long-term climate change policy sets differently impact the dynamics of the specific emissions of the power mix and the electricity demand, and therefore the CO_2 emissions. If a one-time policy set is chosen among the POL1, POL2 and POL3 policy sets taking their MSA distributions into account, then only POL3 leads –generally speaking– to significantly reduced annual CO_2 emissions and convergent cumulative CO_2 emissions.
- The CO_2 emissions are
  - only temporarily sensitive to abrupt nuclear phase-outs, but are sensitive to abrupt governmental nuclear initiatives,
  - sensitive to high gas prices in case of moderate climate change policies,
  - slightly dependent on a hydrogen/storage breakthrough,
  - very dependent on a hydrogen/storage breakthrough accompanied by an increased electricity demand,
  - very sensitive to variations in the GDP growth rate,
  - sensitive to the initial maximum wind power potential assumption in case of a hydrogen breakthrough.

Valuable lessons for boosting wind power capacity installed could be learned from this model –this could be done for other generation technologies too, but is not explicitly done here– for example that:

- The successful (very) long term development of wind power strongly depends on several related policies and/or evolutions, such as strong green/CO_2-poor investment/generation policies, a successful breakthrough of cheap hydrogen/storage technologies, the low potential and little success of other –especially of other CO_2-poor and/or intermittent– generation technologies, (expected) long term fossil fuel prices, continuously increasing electricity demand, and so on.

- In this model, the wind power capacity installed (and consequently the wind power generated) seems to be
  - marginally sensitive to varying siting costs,
  - slightly sensitive to high gas prices without a hydrogen/storage breakthrough,
  - very (behaviourally) sensitive to a hydrogen/storage breakthrough (with and without additional demand),
  - sensitive to varying maximum wind power and other renewable potentials,
  - very sensitive to varying GDP growth rates,
  - sensitive to a doubling of the maximum wind power potential *without* a hydrogen/storage breakthrough, and very sensitive to a doubling of the maximum wind power potential *with* a hydrogen/storage breakthrough,
  - sensitive to very sensitive to variations in the maximum potentials of other maximum renewable potentials,
  - very sensitive –but only in the long run and in case of POL1 and POL2– to variations in carbon capturing and storing costs,
  - and extremely sensitive to the in/activation of the structural intermittence assumption binding wind and PV power.
- A sustained and large-scale wind power breakthrough therefore requires a breakthrough by 2020 of a cheap storage/hydrogen technology and/or backup generation technology and/or other technologies –and thus much research into these related technologies– to solve the intermittence/variability problem.
- A temporarily subsidised wind power boom might –without such a storage/hydrogen technology breakthrough– end in an overshoot and subsequent collapse of EU-25 wind power. Long term perspectives, policies, goal setting and focussed research are therefore necessary.
- Wind power might face a bright future in the EU-25 if such a breakthrough occurs or if PV power and wind power are not linked in terms of their intermittence. However, most simulation runs do not lead to very high fractions of wind power generation.
- Projections of wind power capacity installed vary strongly: comparing the IQRs of POL1, POL2 and POL3, it could be said that POL3 is best in terms of wind power capacity installed by 2010, that POL2 is best between 2020 and 2030, and POL1 seems to be best afterwards, mainly caused by the higher electricity demand.
- Policies to boost wind power capacity installed do not necessarily lead to significant long-term decreases of CO_2 emissions, and vice versa. The absolute amount of wind power capacity installed is –in the long term– lower in case of strong climate change policies which means that less stringent climate change policies might in the long term be more interesting for the wind power industry. The goal of maximising wind power penetration is therefore not necessarily the same as that of reducing CO_2 emissions and concentrations. Persistent growth of electricity demand might for example help the development of renewables in absolute terms, but is detrimental in terms of CO_2 emissions.
- One should be careful with policies to boost one type of technology –in casu wind power– which might seem attractive from a financial point of view, because '[...] adding technologies to the portfolio will increase the need for learning investments, and if the added technologies compete for the same learning opportunities, they will delay break-even and reduce the present value of the portfolio. An efficient portfolio must balance allocation of learning opportunities against the need to diversify energy supply and to spread technology risk' (International Energy Agency 2000, p83).

Some of the many possible lessons to be learned from this model concerning fossil fuel based generation are that:

- gas might substitute for coal, and as such slow the introduction of renewables over time,
- the further evolution of gas based electricity generation is very (behaviourally) sensitive to the (expected) gas market price,
- (expectations of future) gas prices strongly influence the development of the future generation mix;
- and clean coal generation might become –in case of sufficient start-up investments, relatively low costs and inclusion in the TECs schemes– a very strong competitor to renewable technologies.

Some conclusions related to the needed investment costs are that:

- cumulative investment cost might be significantly higher than suggested in the literature and slightly higher than industrial forecasts. The IQRs of the three policy sets suggest that the cumulative investments in new generation capacity from 2006 on might amount to €100-200 billion in 2010, €500-750 in 2020, and €1000-1500 in 2030, which is slightly higher than industrial forecasts,
- the amounts of investments needed are lower in case of more sustainable electricity systems with lower electricity demands;
- investments in electricity infrastructure are necessarily cyclic (even with continuous capacity additions which is *not even* the case in reality),
- the cumulative investments are very sensitive to GDP growth and –in case of moderate climate change policies– rather sensitive to (high) gas prices,
- the choice of generation technologies to invest in is extremely important because it determines which technologies will (most likely) be used for future generation and which technologies will become ever cheaper and therefore ever more competitive.

And some –among many– other possible conclusions are that:

- electricity prices are proportional to the stringency of the climate change policy simulated if climate change damage and adaptation costs and other external costs are not included as in this particular form of the model,
- electricity prices are –when taking the whole picture (possible material and fuel price rises, climate change damage costs, needed investment costs, potential excess demand, et cetera) into account– not likely to decrease much –in spite of the efficiency gains and technological development– in the medium, long and very long term,
- apparently insignificant decisions/events might lead to very different evolutions over time. However, the fundamental direction of these markets is not a question left to be answered by 'the market' alone. Models –such as the ones discussed in this paper– might help to make decisions based on a better understanding of the possible consequences of such insignificant decisions/events,
- there are 'free lunches' if gradual (but rather drastic) electricity demand reductions also take place.

A particular structural form of a system dynamics model has been discussed here, followed by a general discussion of the simulated behaviour in case of several parameter sets and in case of two sets of parameter distributions to test the model behaviour and model (in)sensitivity/robustness. The system dynamics model necessarily contains many simplifications such as the treatment of nuclear power generation as must-run generation, the lack of competition between PV and other generation technologies, the aggregation of all wind power technologies or all hydro technologies, et cetera.

Some possibly interesting extensions and improvements that could be explored extending this model are among else:

- 'economy-energy-environment-climate change' loops for real long-term policy and integrated cost analyses, for example the necessary feedback loops to render the TECs and TGCs schemes truly endogenous;
- the interaction with other energy markets, such as the heating market, the mobility market, or the gas market;
- structures to explore revolutionary technological breakthroughs and/or accelerated technological evolution by means of temporary steeper learning curves;
- additional modules/structures dealing with other technologies for example oil based generation, fuel cells, CHP, et cetera, or more detailed (sub)technologies/technological differentiations such as onshore and offshore wind power instead of just wind power;
- subscripts dealing with the EU-25 member states in order to explore the issues of the EU-25 'energy islands' and their interconnections;
- detailed structures replacing really simplified structures such as the simplistic siting cost structure used here;
- new endogenous structures to deal with social and institutional aspects related to wind power penetration, such as the *expected public support for wind generation*, more or less favourable ruling and favourable spatial planning policies, increasing/decreasing delays, et cetera;
- detailed structures to deal separately with the EU-25 and the world component of learning curve effects;
- more elaborated structures to differentiate between expectations and 'real' evolutions.

4.2 Ex-post Criticisms and Venues for Future Research

Different system dynamics models or extensions of this system dynamics model should/could be developed to explore these related or other issues. The potentially important influences not implicitly and explicitly modelled matter because of the fact that these omissions are among the most important modelling assumptions made.

Potentially interesting related issues, influences, structures and aspects not dealt with here are for example: (i) the degree of competition between energy companies, their bounded rational behaviour and strategic gaming; (ii) the precise structures of these energy companies, their possible mergers and consolidations; (iii) regional and national boundaries and borders (although still very important) and detailed country-specific electricity trading and support structures; (iv) aspects of financing; (v) the broader/world demographic evolution, the broader energy domain, economy, climate change; (vi) international fuel supply, demand and availability; (vii) technical aspects of electricity grids; (viii) the distinction between peak load and base load; (ix) specific (sub)technologies such as CHP, et cetera.

The purpose of the model was the exploration of the development of electricity generation technologies –more specifically wind power generation technologies– in order to increase the understanding of its multi-dimensional dynamic complexity. Given the focus on analysing the competition between developing technologies, one might say the primary decomposition has been along the lines of technology-centered subsystems. Aspects of the issue explicitly dealt with were therefore the dynamic complexity aspect and the multi-dimensionality aspect, and to some extent the uncertainty aspect related to uncertain parameters and exogenous variables. Important aspects of this issue that were not dealt with include among else (i) the multi-actor aspect (divergent interests, views, goals, emotions of the many stakeholders and actors involved), (ii) the multi-level aspect (the many policy/physical/... levels, boundaries,...) (iii) the uncertainty aspect in its full depth and width, (iv) the network aspects (both in terms of physical networks such as electricity grids, as in terms of actor, technology, energy or financial networks), (v) the geographical aspect, et cetera.

The ex-post use of conceptual frameworks (Pruyt and Thissen 2007) helped to put the model and results into perspective too. Using a conceptual level framework, it could first of all be argued that it would have been better to model also at the level of the individual member states since that is currently the relevant level of policy-making. Second, it could be used to explore the included and omitted exogenous variables (inputs for this model) and output variables (inputs for other systems or models) which make up the interface with other (sub)systems and (sub)models. The influence of all exogenous variables should be thoroughly explored. This exploration in the case of the system dynamics model shows that some higher-level and lower-level systems should actually also be modelled because they deliver crucial dynamic inputs to this model that are not readily available in the literature or as outputs of other models.

Third, interactions with other related subsystems are not explored because of the fact that the necessary models are not compatible (in terms of purpose, time scales used, etc.) with the system dynamics model under consideration. Examples of omissions because of method-misfit are detailed grid-models. This leads to the implicit assumption that there is only one perfect grid, or multiple grids with perfect interconnections and infinite capacity. The influence of limited, constrained and marginally interconnected grids should therefore be assessed and –if important– be included in some way in the system dynamics model. The outcomes will then most probably be worse than suggested by the current model. This also shows that methods and models used determine what could actually be explored and what possible outcomes could be. And policy recommendations are in turn biased by the methods and models used through these outcomes.

Fourth, combining the aforementioned System-of-Systems hierarchy level view with the horizontal energy sector view (as in (Agusdinata 2006)) shows that the model boundary is rather narrow: only the competition between these 9 generation technologies is really endogenously modelled. Many other influences are nevertheless modelled semi-endogenously such as technological surprises, world fuel prices and availabilities, regional and local policies, and even the societal value system. But still, it shows the necessarily limited exploration of plausible influences such as the influence of currently unknown emerging technologies which are of course fundamentally uncertain.

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