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System Dynamics Models of Electrical Wind Power

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Abstract

This paper describes the gradual transformation of the spreadsheet model from the Wind Force 12 *report by the EWEA and Greenpeace -which assesses the world wind power potential by 2020- into system dynamics models of the same problem. First the (static) spreadsheet model is replicated in a system dynamics structure, which allows us to correct some errors crept into the spreadsheet model and the report. Second, this static model is turned into a first system dynamics model very close to the spirit and dynamics of the original* Wind Force 12 *model. Then, the unsatisfactory structures from this first system dynamics model are replaced by more appropriate structures in a second system dynamics model. Finally, the three resulting models with different degrees of complexity are compared and some conclusions are drawn.*

Key-words: Electrical Wind Power, Wind Force 12

Contents

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1 Introduction

The world wind power models and simulations presented in this paper came into being as a by-product of a system dynamics research project on the impact on the CO2-emissions of the re-regulation of the European and Belgian energy markets.

While consulting many sources on renewable energy sources, and especially on wind power potentials, it was noticed that most wind power projections fell short of reality, leading to regular upward revisions of projections and goals. That could be caused by the use of spreadsheet models which seem to miss the dynamics of the wind turbine industry expansion as well as from the underestimated growth rates of the wind turbine industry. One of the sources where this appears to be the case is the *Wind Force 12* report by the European Wind Energy Association and Greenpeace [1] which assesses the feasibility of reaching a penetration of 12% wind electricity of global electricity demand by 2020. That, and doubts about the consistency of the results obtained in the report caused us to remodel the (static) spreadsheet model in a stock/flow structure and to compare the simulation results with the data from the report. The doubts proved to be justified.

Since the dynamics of the problem are very obvious in the *Wind Force 12* report -in spite of the static spreadsheet model- and that the report is an interesting source of data (on e.g. wind turbine numbers, capacity and experience curve) to build or validate a highly aggregated, long-term system dynamics model of world wind power, the initial static model was gradually transformed into system dynamics models. Part of this transformation process will be shown step-by-step in the following sections and subsections.

First of all, a simple model is extracted from the report and explained in subsection 2.1[1]. Some of the shortcomings of and possible improvements to this simple model extracted from the *Wind Force 12* report are discussed in more detail in subsection 2.2. Then, this model is extended to become a -still simple- system dynamics model in subsections 3.1, 3.2 and 3.3. Some sensitivity analysis results of that model are presented in subsection 3.4. In section 4 a more elaborated version of the model is discussed. Some simulation results of the three models will be discussed and compared in section 5. Section 6 deals with the methodological and applied conclusions. Finally, the equations of all models can be found in the appendix.

All models are discussed in detail so as to render explicit all modelling choices and hypotheses and make the models understandable to all. The variables are written in *italic*.

[1]Working paper [4] descibes these and other models, sensitivity analyses and simulation results in much more detail. The working paper also extends the analysis to the European and Belgian levels which are after all the focus of the reseach project.

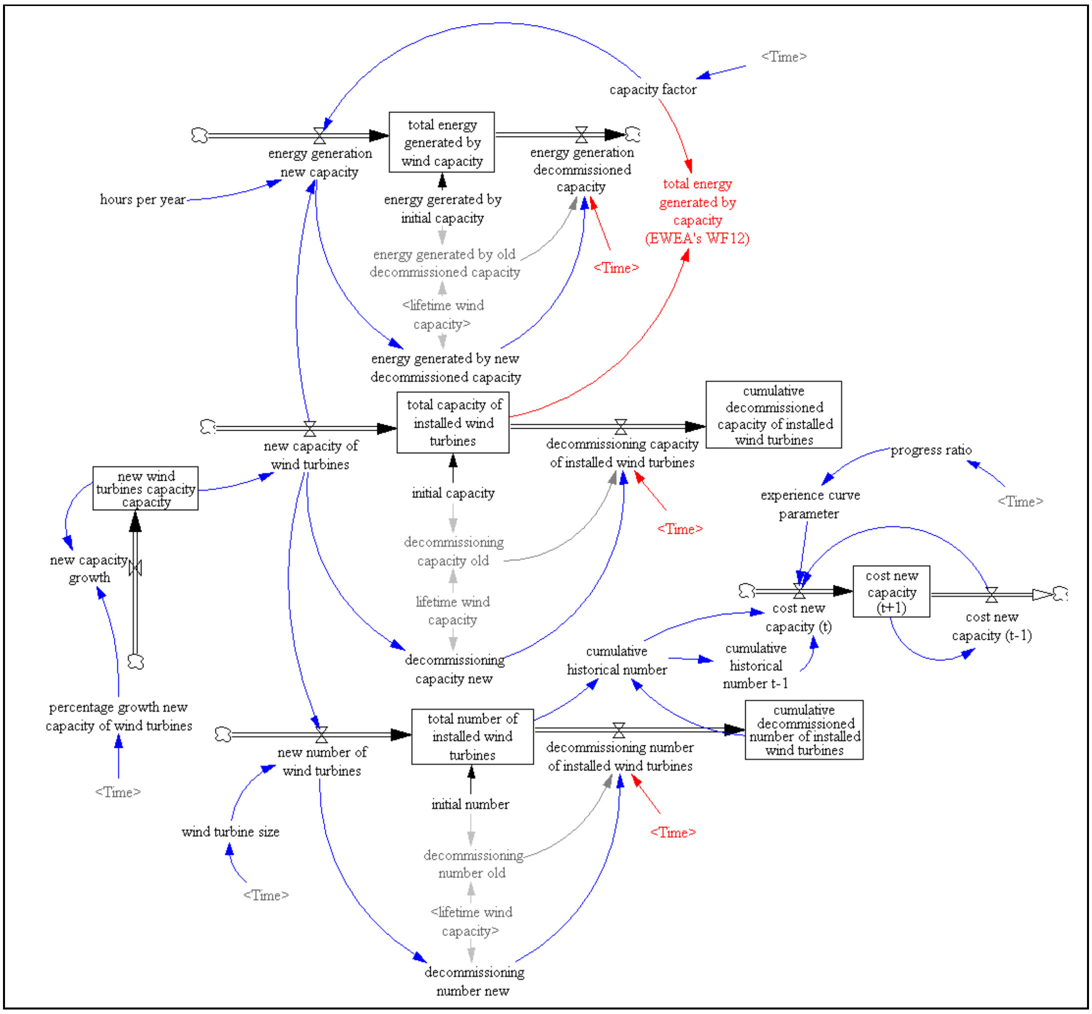

Figure 1: The stock/flow diagram of the initial model of part of the Wind Force 12 report.

2 A *Wind Force 12* replication model: the sd0WF12 model

2.1 The uncorrected sd0WF12 replication model

Figure 1 shows a stock/flow structure replicating exactly the logic and data from table 4-1 [p12], appendix table 1 [p46] and appendix table 3 [p48] of the *Wind Force 12* report[1] when using the Euler integration scheme with a time step of one year[2].

We will start the brief discussion of this (rather static) model with the variable *percentage growth new capacity of wind turbines* which is the exogenous driver of the growth of the stock variable *new wind turbine capacity capacity*[3] and therefore of the whole replication model. In the report, this wind turbine construction capacity increases from 2002 on with 25%[4], from 2008 on with 20%, from 2013 on with 15%, and from 2016 on with 10%, in 2020 with 4,36% and from 2021 on with 0%. Despite the shrinking percentages, the industry will not shrink[5]. The *new wind*

[2]This integration scheme matches the yearly changes in the spreadsheet approach. In sections 5 this model will be compared to other models using the Runge-Kutta 4 integration scheme, which will improve the results, but will lead to a deviation from the original spead sheet data. In order to correct the deviation, the initial value of the stock variable *new wind turbine capacity capacity* has been reset from 8500 (in 2002) to 7225.

[3]which represents the capacity of the wind turbine construction industry

[4]Although the report states on p4that '[. . .] the industry [. . .] is growing at a rate of almost 40% per year'.

[5]These 'hidden' positive and negative feedback loops will be looked at in two different ways in sections 3 and 4.

turbine capacity capacity will be commissioned every year through the flow variable *new capacity of wind turbines* in the installed capacity structure in figure 1. This commissioned capacity will be decommissioned after a *lifetime wind capacity* of 20 years.

In the *Wind Force 12* report, only the newly added wind turbines from 2004 on are decommissioned. This means that 75215 wind turbines are never decommissioned. To correct that error, the model structure in light-grey is added to simulate a linear decommissioning of capacity installed before 2004 on top of the decommissioning of newly installed capacity from 2004 on. The light-grey structure is not used to replicate the data from the report but to generate improved output.

Another error in the *Wind Force 12* report is replicated by the variable *total energy generated by capacity (EWEA's WF12)*. It replicates the way in which the EWEA report erroneously calculates the total wind electricity generated, namely as the *total capacity of installed wind turbines* times the *capacity factor*[6] at each moment in time for all wind turbines all around the world without taking into account the technology common in the year of installation. On top of that, this *capacity factor* changes abruptly and discontinuously from 25% to 28% in 2011 and from 28% to 30% in 2035 for all wind power installed.

The stock variable *total energy generated by capacity* calculates the same thing, but in a more correct way. Here, the flow variable *energy generation new capacity* consists of the multiplication of the *new capacity of wind turbines*, the *number of hours per year* (8760h) and the expected *capacity factor* at the time of installation. This amount of energy generated per year is then stored in the stock variable *total energy generated by capacity* during a *lifetime wind capacity* of 20 years. Thus, the stock variable *total energy generated by capacity* represents the total energy generated per year taking into account the installed capacity of wind turbines at that moment and the capacity factor at the time of their commissioning.

The similar bottommost structure in figure 1 counts the number of installed wind turbines. The *new number of wind turbines* consists of the *new capacity of wind turbines* divided by the average *wind turbine size* at the moment of commissioning. The sum of the *total number of installed wind turbines* and the *cumulative decommissioned number of installed wind turbines* is the *cumulative historical number* of wind turbines. The variables *cumulative historical number*, *cumulative historical number t-1* of the previous year and the *experience curve parameter* determine the production cost per kW of a new wind turbine according to the following experience curve formula used in the report:

$$C_t = C_{t-1}\Big(\frac{X_t}{X_{t-1}}\Big)^e$$

Where C_t stands for the production cost of a wind turbine per kW at moment t and X_t for the *cumulative historical number* of wind turbines ever built, and e for the *experience curve parameter* which is equal to $-log_2 progressratio$. The *progress ratio* used by the EWEA augments abruptly from 85% in the period 2001-2010 to 90% in the period 2011-2025 and jumps to 100% from 2026 on (see figure **??** for the resulting *cost new capacity (t)* as compared to the constant *progress ratios* of 90% and 85%). A *progress ratio* of 85% tells us that when the cumulative output X_t doubles, the production cost C_t decreases with the learning rate of (1-85%) or 15%. The *progress rate* of 100% from 2026 on means that learning leading to production cost decreases will have stopped completely. In the limit, this would also have happened with a constant *progress ratio*. The *initial cost* of new capacity in the report and the model is 879 €/kW in 2001. The stock variable *cost new capacity (t+1)* performs of course the technical function of memory.

2.2 Some corrections to the *Wind Force 12* model

As already mentioned in the previous section, some errors and weaknesses were discovered in the *Wind Force 12* report. These weaknesses and errors and possible corrections will be discussed in more detail and corrected in this section.

[6]The capacity factor is the fraction of the year the wind turbine would have to generate at nominal (maximum) power to generate the electricity generated intermittantly on average during the year.

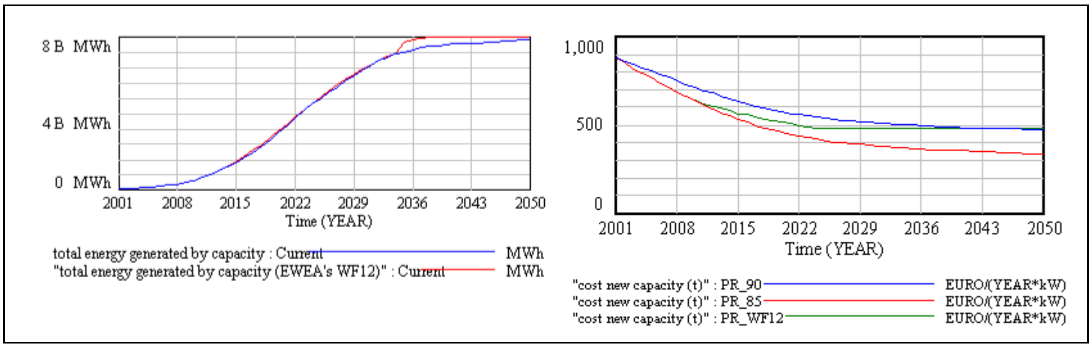

Figure 2: **Left-hand side:** *Total energy generated by capacity* as in the *Wind Force 12* report (red curve) and as calculated in the corrected model (blue curve). **Right-hand side:** The impact on the *cost of new capacity (t)*[€/kW] of the changing *progress ratio* of the *Wind Force 12* report compared to two constant *progress ratios* of 85% and 90%.

2.2.1 The decommissioning of initial capacity.

The first problem relates to the decommissioning of old capacity after a *lifetime wind capacity* of 20 years. In the report, decommissioning of capacity starts only in 2024, which means that the initial capacity and the capacity commissioned before 2004 are not decommissioned. All other things being equal (thus not corrected for other errors), we are talking about 75125 wind turbines with a total nominal power of 44025MW generating 96,41TWh per year assuming a capacity factor of 25% (as is being done before 2011), or 107,98TWh assuming a capacity factor of 28% (2011-2034), or 115,69TWh assuming a capacity factor of 30% (as is being done from 2035 on) (see also tabel 1). For comparison, the total Belgian electricity demand in 2003 was 85,50TWh.

If we are interested in the long-term dynamics of world wind power, these 44025MW should be decommissioned before 2024. Any decommissioning scheme is in that respect better than no scheme. Therefore we modelled in the corrected model a (simplistic) linear decommissioning of 1245MW per year until 2020[7], of 6800MW in 2021 (commissioned in 2001), of 8500MW in 2022 (commissioned in 2002) and of 10625MW in 2023 (commissioned in 2003). Other decommissioning schemes could be simulated as well.

2.2.2 The sudden capacity factor change for all wind turbines.

A second problem in the report is the sudden *capacity factor* change for all installed wind turbines. Indeed, in 2011 the capacity factor increases all of a sudden from 25% to 28% for the *total capacity of installed wind turbines*, and not only for those that are being commissioned at that moment, but also for all those that have already been installed before. In 2035 the *capacity factor* increases again all of a sudden from 28% to 30% for all these wind turbines which results in a rather marked and unrealistic discontinuity in terms of *total energy generated by capacity*(compare the red line in the left-hand side graph of figure 2 to the blue line). Structurally, it would be better to assume that all wind turbines commissioned from 2011 on have a theoretical *capacity factor* of 28%, and all wind turbines commissioned from 2035 on have a theoretical *capacity factor* of 30%. That would result in a less pronounced adjustment (the blue line in the left-hand side graph of figure 2).

All else being equal (thus not correcting the decommissioning of initial capacity) the difference amounts to 76TWh in 2020, and to 413TWh in 2040 (see tabel 1). Combined with the previous remark (the decommissioning of initial capacity), the simulated difference grows to 128TWh in 2020, to 164TWh in 2025, to 624TWh in 2035 and 510TWh in 2040.

Another problem with the *capacity factor* is that the direction of its evolution is not straightforward. Considering experience curve effects and endogenous technological development, it could

[7] $\frac{1}{lifetimewindcapacity}$ or $\frac{1}{20}^{th}$ of the initial capacity of 24900MW

Table 1: The difference between the *total energy generated by capacity* as in the *Wind Force 12* report and as calculated in the corrected model [TWh]

Year	2010	2020	2025	2030	2035	2040
Only correcting the decommissioning of initial capacity	25	58	108	108	115	116
Only correcting the *capacity factor*	0	76	68	25	398	413
Correcting the *capacity factor* **and** the decommissioning of initial capacity	25	128	164	122	624	510

indeed be expected that the 'technical' *capacity factor* of newly commissioned wind turbines increases. On the other hand, the site or location of the wind turbine influences the on-site *capacity factor* too. And it could be assumed that the best wind sites will be developed first and that the remaining new wind turbine sites will be characterised by less favorable wind condition, which, all else being equal, leads to a decreasing average 'on-site' *capacity factor*. Both evolutions will be modelled in the system dynamics models presented in sections 3 and 4 .

2.2.3 The increasing progress ratio of the experience curve.

Quite particular is the experience curve driven by the *cumulative historical* ***number*** of wind turbines instead of the cumulative historical **capacity**, which means among other things that the development of larger sized -instead of more smaller sized- turbines slows learning. The *progress ratio* assumed in the report starts at 85% until 2010. After that it rises suddenly to 90%. Beyond 2025, when 'development is approaching its saturation level', it goes *up*[8] abruptly to 100%.

One could wonder why the increasing *progress ratio* has been chosen, while experience curves with constant *progress ratios* also become constant in the limit. This results from the fact that the percentage decrease in costs only happens when doubling the cumulative capacity installed or produced or the number of wind turbines installed or produced or the quantity of electricity generated. The right-hand side of figure 2 shows the effect of the EWEA evolution of the *progress ratio*, and that of a *progress ratio* of 85% and one of 90%. The explanation[1, p30] given is rather confusing:

> The reason for this graduated assumption, particularly in the early years, is that the manufacturing industry has not so far gained the full benefits from series production, especially due to the rapid upscaling of products. Neither has the full potential of future design optimisations been utilised. Even so, the cost of wind turbine generators has still fallen significantly, and the industry is recognised as having entered the "commercialisation phase", as understood in learning curve theories.

But if the full benefits of series production are still to be reaped, how could the progress ratio go up instead of down? And why should costs stop decreasing after 2029?

Therefore we propose to use one single *progress ratio* in the corrected model, and not a combination of *progress ratios*. The advantage of using one single *progress ratio* is that this enables us to subject the *progress ratio* to sensitivity analysis (see subsection 3.4).

3 A simple system dynamics model of the same problem: the sd1WF12 model

In this section, the corrected model will be extended to become a simple system dynamics model, with more endogeneous change, an aggregated causal logic, feedback loops, delays and non-linear causality. This enables us to render hypotheses explicit and test them, to test the sensitivity of the model (and reality?) to parameter changes and to simulate different policies.

[8] instead of down as indicated in the report

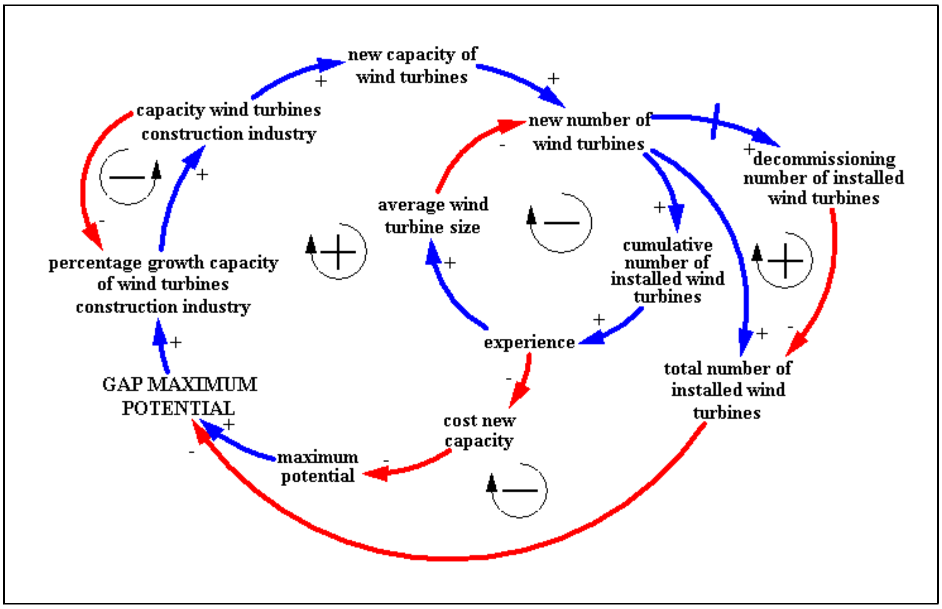

Figure 3: The core feedback loops in the causal loop diagram of the simple system dynamics model.

But the system dynamics model presented in this section is only a limited start. It will be developed further in section 4 to deal in a more appropriate way with world wind power. Reasons for the limited start are that such a model cannot be explained easily and most importantly that such a model cannot be compared directly to the *Wind Force 12* report to be validated.

3.1 The causal loop diagram of the sd1WF12 model

Starting from the previous model, several exogenous variables have been rendered endogenous in this simple system dynamics model (see the causal loop diagram in figure 3 and the stock/flow diagram in figure 5). The core structure consists of 5 basic feedback loops which will be briefly discussed now using the disaggregated feedback loops in figure 4, before we start exploring some details of the stock/flow diagram.

The decline in the percentage growth of the wind turbine industry is not fully exogenous but depends here on the capacity already installed by this same industry. More capacity installed on interesting wind turbine sites leads to a decrease in interesting wind turbine sites until finally the maximum potential area is occupied. This is represented by the topmost (negative) feedback loop in figure 4. Or in more detail: an increased *new number of wind turbines* increases the total number of installed wind turbines above what it would have been otherwise, which decreases in turn the *GAP MAXIMUM POTENTIAL*[9], which decreases the *percentage growth capacity of the wind turbines construction industry*. This in turn, leads to a **lower**[10] **increase** of the *capacity wind turbines construction industry* than what it otherwise would have been resulting in a lower increase of the *new number of wind turbines*. This feedback loop is a negative feedback loop because of the fact that an initial increase of the variable leads to a **lowered** increase.

The flow variable *decommissioning number of installed wind turbines* in the same topmost figure follows the increase of the *new number of wind turbines* with a delay and decreases the *total number of installed wind turbines*, which in the end results in a higher *new number of wind turbines* than what it would have been otherwise. Therefore, this feedback loop is a positive one.

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9 $\frac{totalnumberofinstalledwindturbines}{maximumpotential}$; For reasons of clarity, all newly introduced variables (in this model compared to the previous model) are writtten in capitals.

10 *Capacity wind turbines construction industry* is a stock variable.

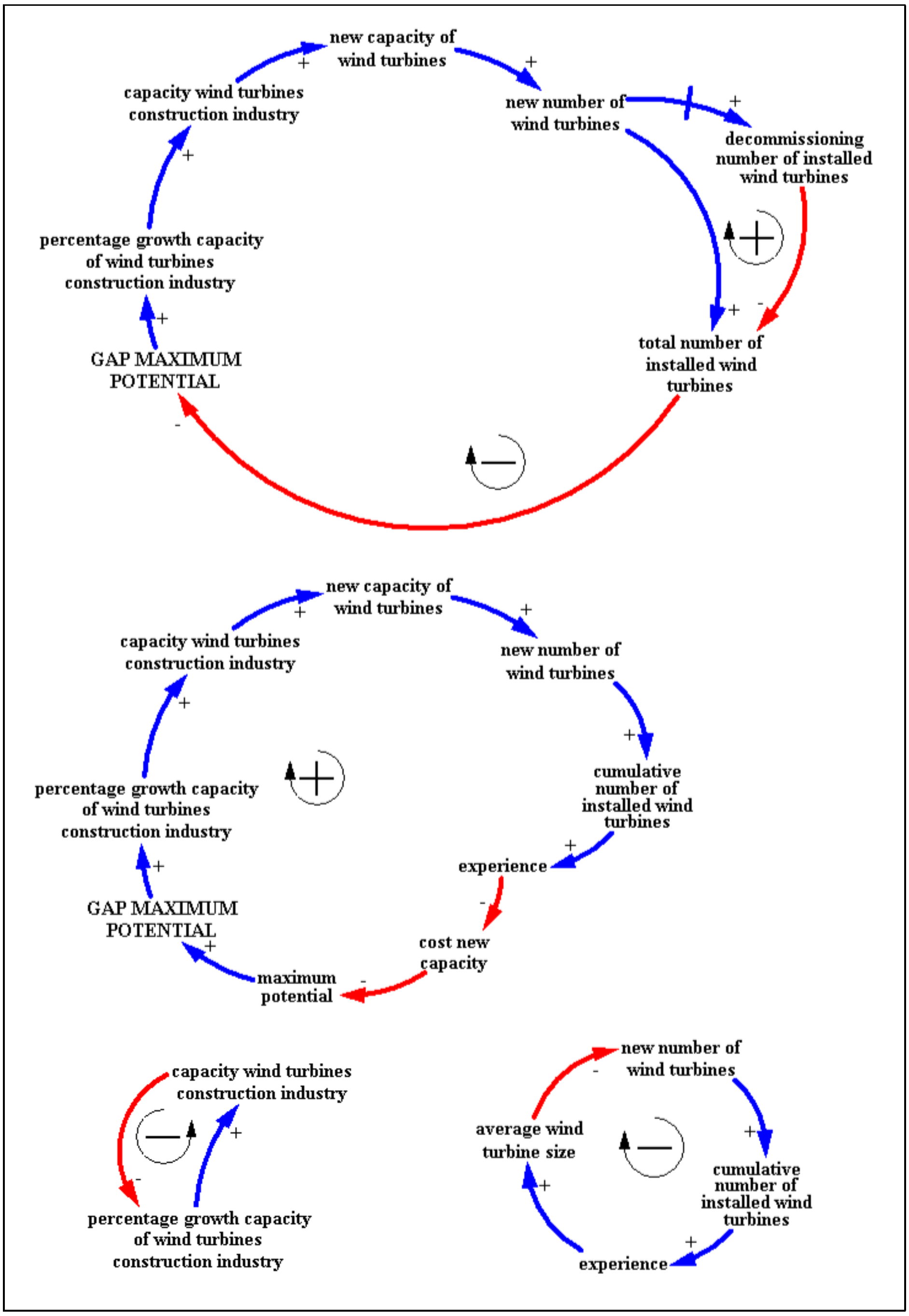

Figure 4: The disaggregated feedback loops of the simple system dynamics model.

However, both feedback loops are tightly coupled and unseparable.

The *experience* loop in the middle of figure 4 is a positive one because of the fact that more *experience* (better design, series production, et cetera) leads to lower costs (which makes more less-windy sites interesting enough for wind projects) to more wind turbines and still more *experience*. Or in more detail: starting from an increased *new number of wind turbines* we see an increasing total *cumulative number of* [ever] *installed wind turbines*, leading to more *experience* and a lower *cost* of *new capacity*, which increases the *maximum potential* and decreases the *GAP MAXIMUM POTENTIAL*. That in turn results in a higher *percentage growth of the capacity of the wind turbines construction industry* and thus in a higher *capacity* and *new number of wind turbines* than what it otherwise would have been.

The left bottommost feedback loop is an artificial negative loop curbing the *capacity of the wind turbines construction industry*. A less artificial structure will be proposed in section 4.

The right bottommost structure increases the *average wind turbine size* with increasing *experience*, leading to bigger but less *new [number of] wind turbines* than what would have been the case otherwise, which slows the increase of the *cumulative number of installed wind turbines* and *experience* and is therefore a negative feedback loop.

3.2 The stock/flow diagram of the sd1WF12 model

We will now discuss the stock/flow diagram (see figure 5) in detail. Here, the *cumulative historic number* of wind turbines installed or produced decreases the *cost of new capacity (t+1)*. The decrease of these *costs of new capacity*, increases the *MAXIMUM POTENTIAL* from the *INITIAL MAXIMUM POTENTIAL* of 907313[11] wind turbines with an assumed delay of 10 years[12] (delay caused by preparatory studies, slow change in public acceptance of wind turbines and even slower change in spatial planning policies). The *GAP MAXIMUM POTENTIAL*, which is the fraction of the *total number of installed wind turbines* over the *MAXIMUM POTENTIAL*, drives the variable *percentage growth new capacity of wind turbines*. When the *total number of installed wind turbines* is very low in proportion to the *MAXIMUM POTENTIAL* and the fraction is consequently near 0, the percentage growth new capacity of wind turbines is 25% just as in the *Wind Force 12* report. Higher fractions however result in continuously decreasing growth percentages of the wind turbine construction industry. Since the variable *percentage growth new capacity of wind turbines* is now linked to the *GAP MAXIMUM POTENTIAL*, instead of to the variable *Time*, the causal link has to be made accordingly. As a first approximation we will make abstraction from the fact that the *MAXIMUM POTENTIAL* increases with the experience gained. Therefore the *total number of installed wind turbines* in table 2 has been divided by the *INITIAL MAXIMUM POTENTIAL*. So if for example this fraction reaches 15,13% then the *percentage growth new capacity of wind turbines* becomes 20%.

Table 2: First approximation of the causal link between *MAXIMUM POTENTIAL* and *percentage growth new capacity of wind turbines.*

(1)*Growth Ratio*[WindForce12]	25%	20%	15%	10%	0%
(2)*total number of installed wind turbines*	56000	137274	301369	473209	907313
(3)*INITIAL MAXIMUM POTENTIAL*	907313	907313	907313	907313	907313
(2)/(3) *GAP MAXIMUM POTENTIAL*	0,0617	0,1513	0,3322	0,5216	1

Since the *MAXIMUM POTENTIAL* starts to diverge after the delay of 10 years (see the left-

[11] This is a modelling choice. It is equal to the number of wind turbines in 2020 from when the *percentage growth new capacity of wind turbines* becomes 0% in the report

[12] For now, this is an unchecked assumption which will be the subject of a sensitivity analysis.

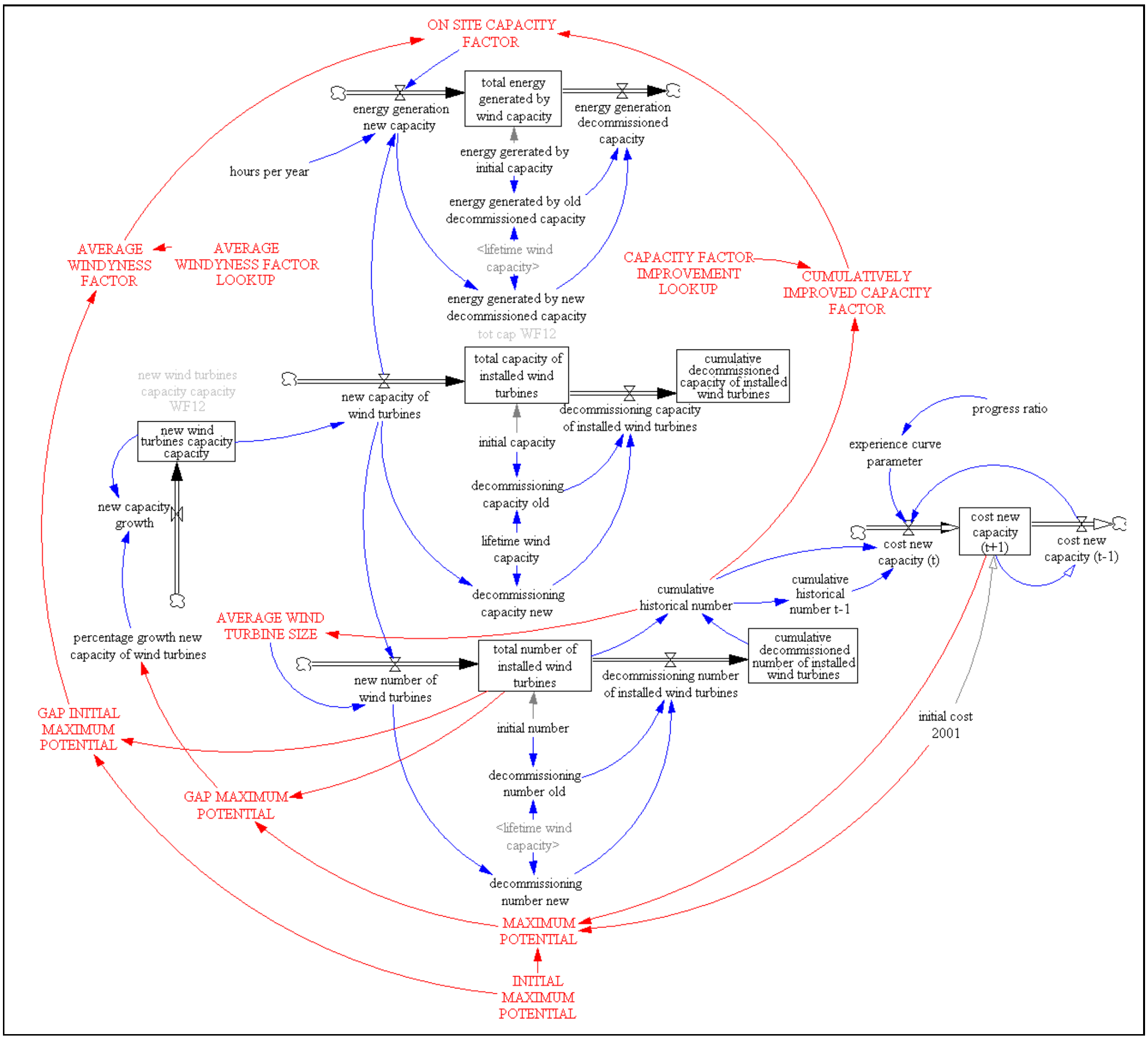

Figure 5: The stock/flow diagram of the sd1WF12 system dynamics model deducted from the *Wind Force 12* report. All structures in red are either new or adapted in comparison with the static sd0WF12 model.

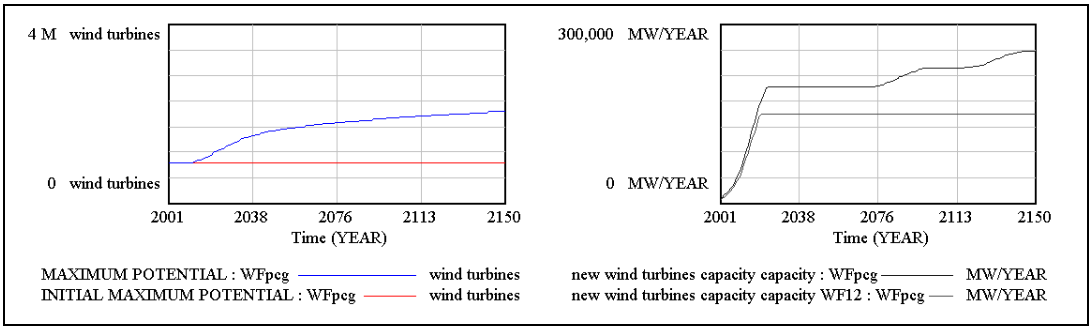

Figure 6: **Left-hand side:** The dynamic difference between the static *INITIAL MAXIMUM POTENTIAL* and the dynamic *MAXIMUM POTENTIAL*. **Right-hand side:** The difference between the same static and dynamic growth percentages in terms of annual capacity of the wind turbine construction industry.

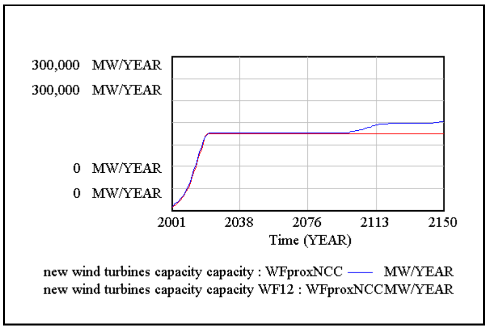

Figure 7: The good fit between the WFproxNCC scenario and the data from the *Wind Force 12* report.

hand side graph in figure 6) from the *INITIAL MAXIMUM POTENTIAL*, the fraction *GAP MAXIMUM POTENTIAL* decreases and the percentage growth will be higher leading to a higher *new wind turbines capacity capacity* -the capacity of the wind turbine construction industry (see the right-hand side graph in figure 6).

This divergence could be eliminated by using a static *INITIAL MAXIMUM POTENTIAL* as is done in the previous model or a static *ABSOLUTE MAXIMUM POTENTIAL* instead of a dynamic *MAXIMUM POTENTIAL* variable. That implies however, that we discard the interesting concept of an increasing maximum potential with decreasing costs and cumulative installed capacity. Another option -one where we do not lose the dynamic concept- would be to adjust the static percentages downward in order to obtain dynamic percentages that give rise to the same dynamics. The adapted values of scenario `WFproxNCC`[13] in table 3 give a good fit as can be seen in figure 7.

Table 3: *GAP MAXIMUM POTENTIAL* to *percentage growth new capacity of wind turbines* [percentage]

GAP MAXIMUM POTENTIAL	0.06	0.15	0.30	0.5	0.75	2
percentage growth new capacity of wind turbines[`WFproxNCC`]	25%	20%	15%	9%	0%	0%

In the `WFproxNCC` simulation, no growth of the *new wind turbines capacity capacity* will occur

[13]WFproxNCC stands for the scenario ap**prox**imating the **n**ew wind turbine **c**apacity **c**apacity variable of the *Wind Force 12* report.

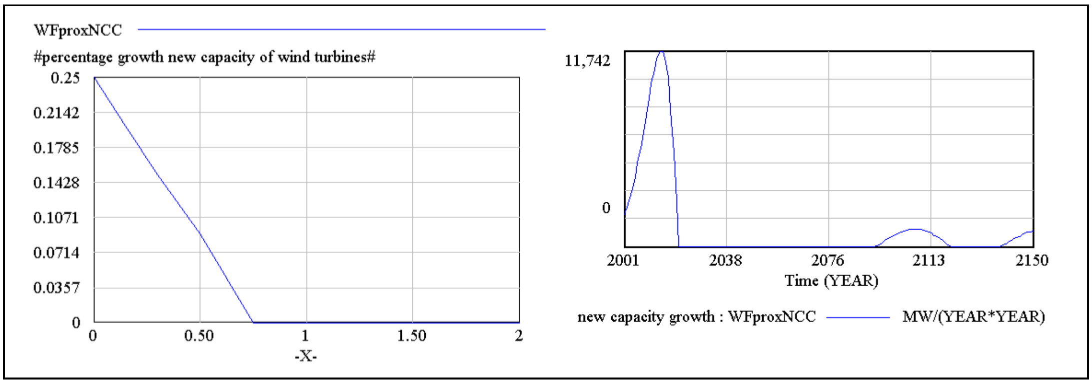

Figure 8: **Left-hand side:** The *percentage growth new capacity of wind turbines* lookup. **Right-hand side:** The resulting annual *new capacity growth.*

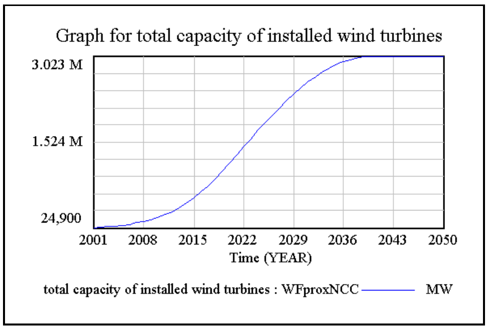

Figure 9: The *total capacity of installed wind turbines.*

above 75% of the increasing *MAXIMUM POTENTIAL* as shown in table 3 and the left-hand side graph in figure 8. This results in a *new capacity growth* as shown in the right-hand side graph of figure 8. However, the decreasing positive growth percentages will not decrease but only stabilise the *new wind turbines capacity capacity* -the capacity of the wind turbine construction industry- and the annually commissioned *new capacity of wind turbines* just as in the report.

In section 3.4, the possibility of a decreasing wind turbine industry will be looked at. The delay of 20 years (*lifetime of wind turbines*) between the increase of the *new capacity of wind turbines* and the increase of the *decommissioning capacity of installed wind turbines* generates the S-shaped evolution of the stock variable *total capacity of installed wind turbines* (figure 9).

For reasons of comparability with the *Wind Force 12* report, the *new capacity of wind turbines* divided by the *AVERAGE WIND TURBINE SIZE* gives the *new number of wind turbines.* Because the *AVERAGE WIND TURBINE SIZE* increases with the *cumulative historic number* of wind turbines and the *new capacity of wind turbines* stabilises after 2025, the *new number of wind turbines* increases and then decreases. This in turn generates the S-shaped growth followed by a slow decrease of the *total number of installed wind turbines* in the left-hand side graph of figure 10 and the accelerating and then linear increase of the *cumulative historic number* of wind turbines in the right-hand side graph.

The *cumulative historic number* of wind turbines also drives the technological improvement of the capacity factor (*CUMULATIVELY IMPROVED CAPACITY FACTOR*) which is assumed (following the *Wind Force 12* report) to reach 25% at a *cumulative historic number* of wind turbines of 56000, 28% at a *cumulative historic number* of wind turbines of 258338 and 30% at a *cumulative historic number* of wind turbines of 2282313[14] as defined in the *CAPACITY FACTOR IMPROVEMENT LOOKUP*. This *CUMULATIVELY IMPROVED CAPACITY FACTOR* times

[14] and 32% at a *cumulative historic number* of wind turbines of 20000000, assumed for very long term simulations.

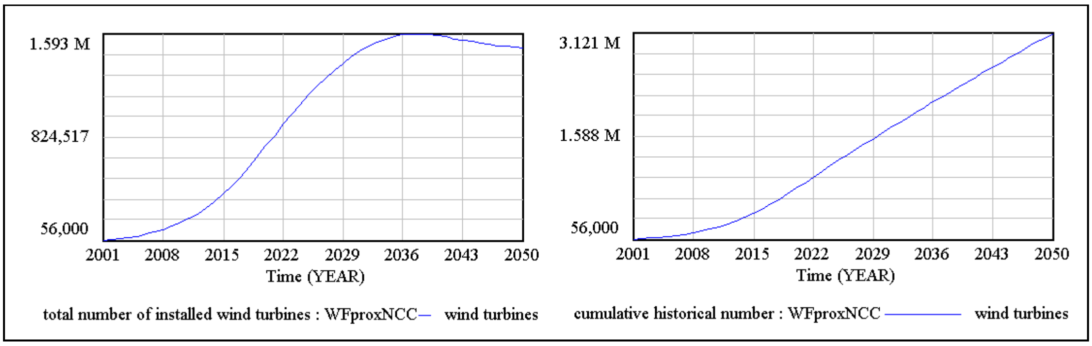

Figure 10: **Left-hand side:** The *total number of installed wind turbines.* **Right-hand side:** The *cumulative historical number* of wind turbines.

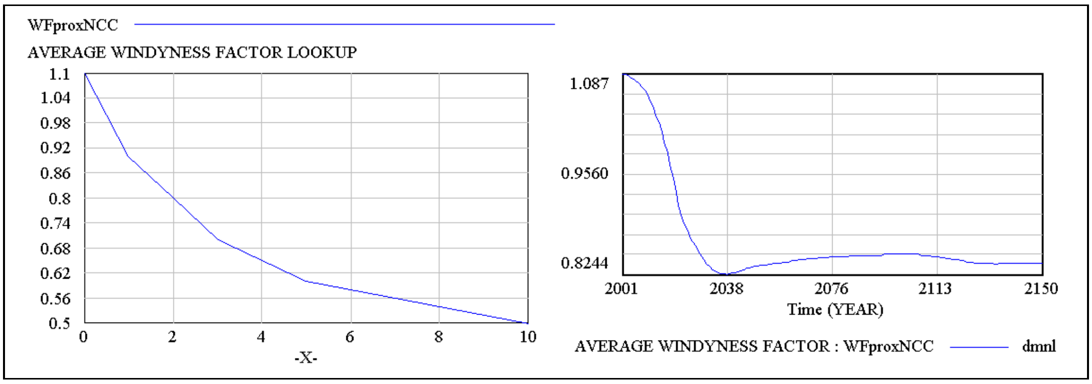

Figure 11: **Left-hand side:**The *AVERAGE WINDYNESS FACTOR LOOKUP***Right-hand side:** The resulting *AVERAGE WINDYNESS FACTOR*

the *AVERAGE WINDYNESS FACTOR* gives the *ON SITE CAPACITY FACTOR*, which feeds into the *energy generation new capacity.* The *AVERAGE WINDYNESS FACTOR* expresses that all the best wind sites will be developed first (see figure 11). When the variable *GAP INITIAL MAXIMUM POTENTIAL* -which is the fraction of the *total number of installed wind turbines* over the *INITIAL MAXIMUM POTENTIAL*- is 0, the *AVERAGE WINDYNESS FACTOR* is 1.1 and decreases with higher fractions as depicted. It means that the best wind sites generate an on-site capacity factor which is 10% above normal at half the *INITIAL MAXIMUM POTENTIAL*, that the on-site capacity factor falls 10% under normal at the *INITIAL MAXIMUM POTENTIAL*, to 20% under normal at double the *INITIAL MAXIMUM POTENTIAL* and to 30% under normal at triple the *INITIAL MAXIMUM POTENTIAL.* This is just an assumption and is only made to sketch the idea. It does not change the dynamics of the system dynamics model[15]. These small structural changes result in a dynamic behaviour similar to the one in the *Wind Force 12* report, validated by many experts from the industry. This might create some confidence in this model as well. The advantage of the system dynamics model is that now the hypotheses and parameters can be subjected to sensitivity testing and different policies could be tested.

[15]In the following more-elaborated model (see section 4) where the (site-specific) *capacity factor* influences the *profitability* (via the (expected) *electricity generated*), the endogenous *capacity factor* influences all other variables too.

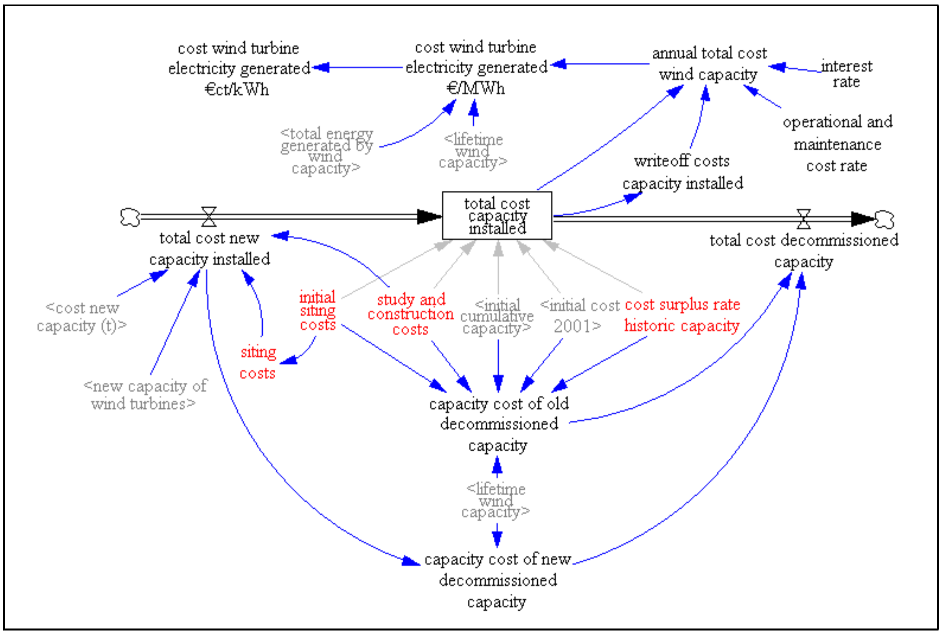

Figure 12: The additional stock/flow structure to calculate the private production costs per kWh wind power generated.

3.3 Adding calculation modules for the electricity generation costs, jobs created and CO2 emissions avoided

In this subsection, three small modules are added to the system dynamics model to calculate directly the costs per kWh of the wind turbine electricity generated, the (direct and indirect) jobs created by the wind turbine industry and the CO2 emissions avoided by the generation of wind power instead of electricity generated with other technologies. In this model, these calculation modules will not lead to dynamic changes in the rest of the model. In section 4 two of the three modules -those on the CO2 emissions avoided and the price per kWh- will feed back to the main model. That will lead to a more sofisticated system dynamics model.

3.3.1 Electricity generation costs

In this module (see figure 12), the stock variable *total cost capacity installed* keeps track of the total costs of the installed capacity. To account for the more expensive historical capacity, the *initial cost 2001* could be multiplied with a *cost surplus rate historic capacity*, making the capacity installed before 2001 on average more expensive. Besides that, *study and construction costs* and *siting costs* are added to the model. In this simple system dynamics model, both additional costs will remain 0. In the dynamic model presented in section 4, the *study and construction costs* will remain 0 while the *siting costs* will rise with the capacity installed, since the best and cheapest sites will be used first.

Just like in the former similar structures, the currently installed as well as the newly commissioned *total cost new capacity installed* will be decommissioned after the *lifetime wind capacity* of 20 years.

Annually the *operational and maintenance costs* amount to 3% of the *total cost capacity installed*, the interest costs amounts to the *interest rate* of 10% times the *total cost capacity installed*, and the *writeoff costs capacity installed* equal the fraction of *total cost capacity installed* over the *lifetime wind capacity*[16].

[16] annual total cost wind capacity = total cost capacity installed * (interest rate + operational and maintenance cost rate) + writeoff costs capacity installed

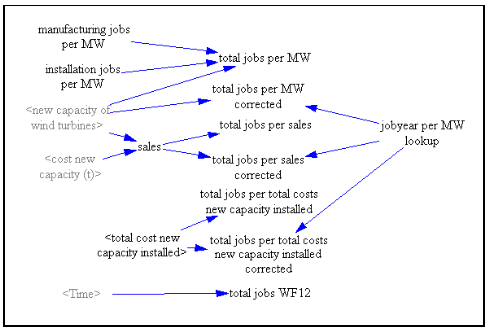

Figure 13: The additional stock/flow structure to calculate several evolutions of the man-year jobs created.

Table 4: The decreasing number of jobs per MW (*jobyear per MW lookup*).

1998	2005	2010	2015	2020
22	14.7	12.2	10.9	9.8

The *cost wind turbine electricity generated* in [€/MWh] is then calculated as the *annual total cost wind capacity* divided by the *total energy generated by wind capacity*.

In section 4 the cost of new wind turbines electricity generated will influence the *expected profitability* of the investments in wind turbine capacity and thus the investment decision. Such a natural investment decision process will then replace this artificial construction used here. That construction is more natural because in reality '[f]or investors, it is [...] the cost of electricity that determines the economic attractiveness of a wind park'[3, p5].

3.3.2 Jobs created

In the jobs module, six ways to calculate the *total* (direct and indirect) *jobs* created are compared to the data on future jobs created from the *Wind Force 12* report (*total jobs WF12*), all starting from the information[1, p36] that

> 17 man-years are created for every MW of wind energy manufactured and 5 job-years for the installation of every MW. With the average price per kW of installed wind power at $1000 in 1998, these employment figures can then be related to monetary value, showing that 22 job-years (17+5) are created by every $1 million in sales.

The *total jobs per MW* is simply the initial 22 jobs per MW times the *new capacity of wind turbines*. The *total jobs per MW corrected* is the *new capacity of wind turbines* times the lookup *jobyear per MW lookup* which borrows the decreasing number of jobs per MW (see table 4) from the *Wind Force 12* report [1, p37].

The *total jobs per sales* is calculated as 22 jobs per € 1 million of sales times the yearly *sales* of wind turbines (*new capacity of wind turbines* times the *cost of new capacity (t)*). The *total jobs per sales corrected* is the *sales* times the corrected *jobyear per MW lookup* (see table 4). The *total jobs per total costs new capacity installed* does not only take the sales into account, but the full *total cost new capacity installed* which includes the *siting costs*, the *study and construction costs* and the *cost new capacity* times the *new capacity of wind turbines*. The *total jobs per total costs new capacity installed corrected* is the *total jobs per total costs new capacity installed* but not times the 22 jobs per € 1 million total costs, but times the corrected number of jobs (see table 4).

The reason why these six job variables are being calculated is twofold: first, the lack of information in the *Wind Force 12* report concerning these jobs does not allow to replicate the data, and second, the choice in the report is based on an uncertain assumption. Since we are not interested in a point estimate or one prophecising trajectory, these six variables -all based on the

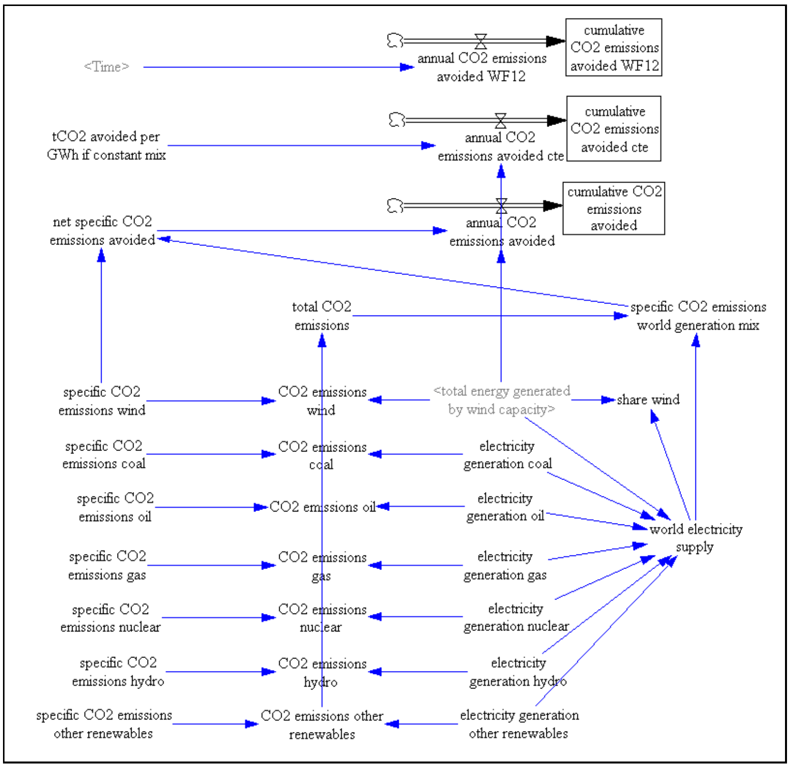

Figure 14: The additional stock/flow structure to calculate the avoided CO2 emissions.

same number of jobs created per MW installed in 1998- provides us with a broader view (see the righ-hand side graph in figure 17) than the one modelling choice offered by the report.

3.3.3 CO2 emissions avoided

The quantity of CO2 emissions avoided depends on the CO2 emissions of the electricity generation mix it is substituting for. The *Wind Force 12* report assumes a mix with a constant average value of 600tCO2/GWh to 2020. But the higher the wind energy percentage in the total mix, ceteris paribus, the lower the emissions per GWh of the mix, the new wind turbines are substituting for. Therefore, it seems to be better to take the specific emissions of the substituted generation mix into account.

In this model, coal technologies are assumed to emit directly and indirectly between 751-962tCO/GWh, gas technologies between 400-428tCO/GWh, oil technologies 726tCO2/GWh, nuclear technologies 7tCO/GWh, wind turbines between 9-28tCO2/GWh[17], hydro between 8 and 15tCO2/GWh and biomass[18] between 55-540tCO/GWh (see table 5). These values come from the *Wind Force 12* report [1] and from D'haeseleer [5]. Table 5 also lists the assumed shares of the different technologies at different moments in the world electricity supply taken from the IEA's World Energy Outlook 2000[2, p356] to calculate the mix and its specific emissions.

Figure 14 illustrates the structure of the CO2 calculation module. The sum of the *specific CO2 emissions* of the different technologies multiplied by the electricity generated with these technologies, gives the annual *total CO2 emissions*. The *world electricity supply* is simply the sum of the *electricity generation* with the different technologies. The *total CO2 emissions* divided

[17] The CO2-emissions payback of the manufature, installation and servicing of a wind turbine is 3 to 6 months[1, p].

[18] The generation of the item *Other Renewables* from the WEO2000 [2, p356] is assumed to be generated completely by *biomass*. Thus, biomass is probably overrated. On the other hand, the specific emission of 100tCO2/GWh has been applied here.

Table 5: Assumptions in the system dynamics model concerning CO2-emissions and generation by other technologies.

Technology	CO2-emissions per GWh [tCO2/GWh]	basecase spec. CO2 [tCO/GWh]	generation in 2001 [TWh]	generation in 2010 [TWh]	generation in 2020 [TWh]
gas	400-428	400	5992	4698	7745
coal	751-962	800	1331	7467	9763
oil	726	726	2940	1442	1498
nuclear	7	7	2471	2647	2369
hydro	8-15	8	2804	3341	3904
biomass	55-540	100	268	395	603

by the *total CO2 emissions* gives the sought-after *specific CO2 emissions world generation mix*. Subtracting the *specific CO2 emissions wind* from the latter variable, gives the variable *net specific CO2 emissions avoided*. Multiplying this variable by the *total energy generated by wind capacity* gives the flow variable *annual CO2 emissions avoided* and the stock variable *cumulative CO2 emissions avoided* from 2001 on. This flow and stock structure is compared to the two structures above it in figure 14, where the annual CO2 emissions are calculated with a fixed *tCO2 avoided per GWh if constant mix* of 600t/GWh as in the *Wind Force 12* report times the electricity generated as in the model, and with the data from the *Wind Force 12* report (*annual CO2 emissions avoided WF12* and *cumulative CO2 emissions avoided WF12*).

3.4 Sensitivity analysis of the sd1WF12 model

3.4.1 The growth rates of the wind turbine construction industry

The *total number* and *capacity of installed wind turbines* seem to be very sensitive to the *Wind Force 12* assumption about the percentage growth of the wind energy industry as reworked and applied in the system dynamics model. To illustrate this, the five topmost scenarios of table 6 are simulated over 150 years[19].

Table 6: Several scenarios for lookup variable *percentage growth new capacity of wind turbines*.

GAP MAXIMUM POTENTIAL	0 (0.06)	0.15	0.30	0.5	0.75	1	2
`BC2150`	0.25	0.20	0.15	0.10	0.05	0	0
`WFproxNCC`	0.25	0.20	0.15	0.09	0.00	0.00	0.00
`PG-0.1`	0.25	0.20	0.15	0.10	0.05	0.00	-0.1
`PG-0.1-0.2`	0.25	0.20	0.15	0.10	0.05	-0.1	-0.2
`PG0.03-0.05-0.1`	0.25	0.20	0.15	0.10	0.03	-0.05	-0.1
`WFproxNCC_neg_perc`	0.25	0.20	0.15	0.09	0.00	0.00	-0.1

In the `BC2150` (see table 6) and `WFpcg` (see table 2) scenarios, the static growth percentages have been applied in the dynamic context. `WFproxNCC` mimics the behavior of the *Wind Force 12* report in a dynamic context. And the `PG-0.1`, `PG-0.1-0.2` and `PG0.03-0.05-0.1` scenarios represent with varying degrees a wind turbine construction industry that could grow as well as decline. The growing-and-declining industry together with the endogenous growth of the *MAXIMUM POTENTIAL* of the number of wind turbines due to the decreasing *cost of new capacity* with the *cumulative historical number* of wind turbines produced or installed, results in oscillatory behavior (see figure 15).

In the case of a possibly shrinking industry, an overshoot of the industry is compensated by a following temporary decline. Since a never-declining wind turbine construction industry is

[19]...in order to show the very long term behavior, not to prophecise or forecast

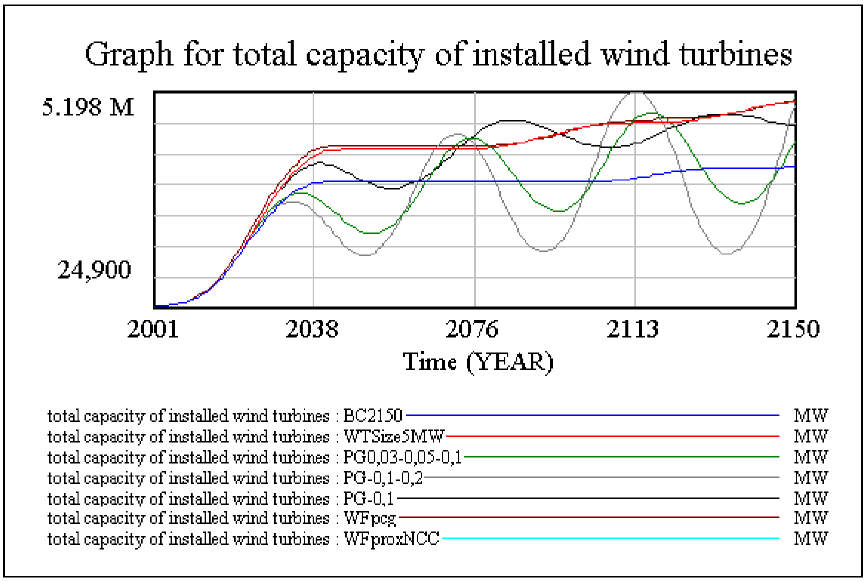

Figure 15: The behavior of the *total capacity of installed wind turbines* depending on the hypotheses about the growth dynamics of the wind turbine construction industry.

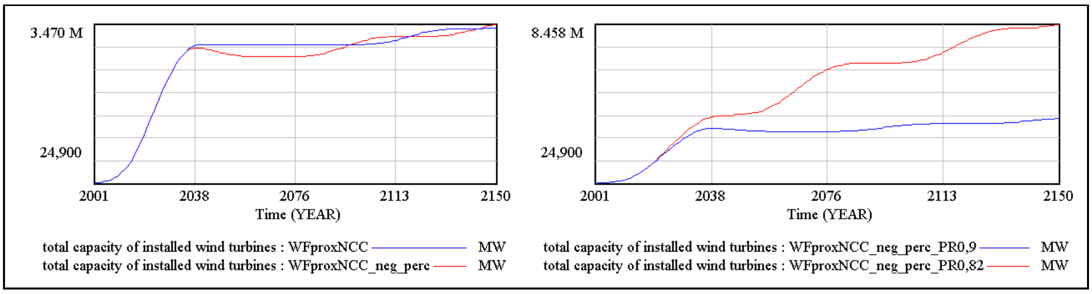

Figure 16: **Left-hand side:** The fluctuation of the *total capacity of installed wind turbines* in the *WFproxNCC neg perc* scenario around that in case of the non-negative growth scenario *WFproxNCC*. **Right-hand side:** The evolution of the total installed capacity in case of progress ratios of 0.82 and 0.90.

not realistic and huge oscillations seem unrealistic too, the `WFproxNCC` and `PG-0.1` scenarios are blended to form the `WFproxNCC_neg_perc` scenario (see table 6) which shows a small oscillation around the `WFproxNCC` scenario (left-hand side graph in figure 16).

3.4.2 The progress ratio and the experience curve

The second variable that we will subject to a sensitivity analysis is the *progress ratio*. Integrated models with endogenous technological progress are often quite sensitive to variations in the *progress ratio*. This leads some authors to conclude that 'uncertainties in the progress ratio seriously affect the robustness [sic] of this kind of macro-economic models'[3, p8]. But ideally, all models should be sensitive to considerable production cost drops, so all models should be sensitive to a variation in the *progress ratio*. The decreased 'robustness of the models' does not say anything about the quality of the models. It only indicates that the real-world decrease in production costs with cumulative production should be monitored carefully and that the models should be adapted accordingly.

Many definitions of experience curves exist, all resulting in different values of the *progress ratio*. Mostly, experience curves for wind energy are expressed under the following three forms:

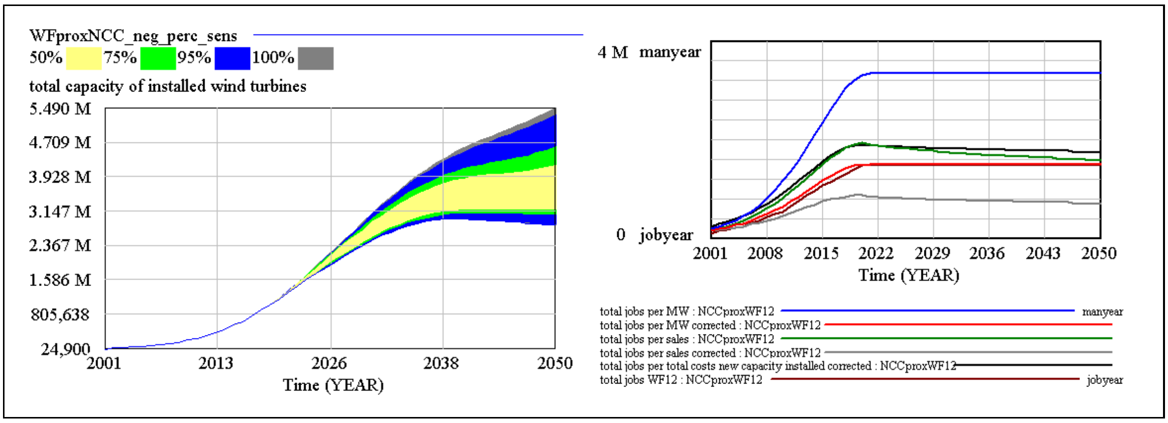

Figure 17: **Left-hand side:** Sensitivity analysis of a progress ratio between 0.77 and 0.90 **Right-hand side:** Six definitions of jobs created

PR_I: price of capacity (€/kW) in function of cumulative capacity installed or produced (kW),

PR_{II}: price of electricity (€/kWh) in function of cumulative number of kWh generated (kWh),

PR_{III}: price of electricity (€/kWh) in function of cumulative capacity installed or produced (kW).

The *progress ratio* from the *Wind Force 12* report (the price of capacity in funcion of the cumulative ***number*** of wind turbines) is not very common. Junginger et al. [3, p8] calculate the *Wind Force 12 progress ratio* in terms of these more prevailing definitions as $PR_I = 90.5\%$, $PR_{II} = 94\%$, $PR_{III} = 90.5\%$. These values are rather high, which means that the learning rate is low.

Furthermore they show that:

> global progress ratios for wind farms may lie between 77% and 85% (with an average of 81%), which is significantly more optimistic than progress ratios applied in most current scenario studies and integrated assessment models

This is indeed more optimistic than the increasing progress ratio used in the *Wind Force 12* report. They suggest to use an uncertainty interval between 77% and 85%. Here we have widened the interval to include a pessimistic 90%[20]. The right-hand side graph of figure 16 shows the `WFproxNCC_neg_perc` scenario for *progress ratio*s of 0.90 and 0.82 until 2150. The left-hand side graph in figure 17 shows the impact of a randomly distributed *progress ratio* between 0.77 and 0.90 until 2050 [21].

So, in this model too, the sensitivity to changes in the progress ratio is important but only in the long term (after 2022). And all simulations in this sensitivity analysis (with the specific scenario) are more optimistic than the *Wind Force 12* hypothesis.

The sensitivity to changes in the *delay* between the investment cost decrease and the increase of the maximum potential, the *initial cost*, the *average wind turbine size*, the *capacity factor* (both the *capacity factor improvement lookup* and *average windyness factor lookup*), the specific CO2 emissions of the world mix (both the *specific CO2 emissions* and the *electricity generated* with the different technologies, the costs (*siting costs*, *study and construction costs*, *cost surplus rate historic capacity*, and *operational and maintenance cost rate* and *interest rate*) is described in detail in the working paper [4].

Finally, the number of jobs created in the right-hand side graph in figure 17 depends of course on the definition and formula and on the scenarios used.

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[20] close to the one of the *Wind Force 12* report

[21] $progessratio(PRsens1) = RANDOM - UNIFORM[0,77;0,90]$

4 A more elaborated system dynamics model of world wind power: the sd2WF12 model

4.1 The causal loop diagram of the sd2WF12 model

It is clear that the dynamics of the development of world wind power depend on many fysical, technological, (world-)economic, socio-cultural and institutional developments and dimensions[22]. Deducted from the static *Wind Force 12* report, the previous model already showed some dynamics such as the positive experience curve feedback loop, the negative maximum potential feedback loop, the positive lower-costs-more-potential feedback loop and the feedback loop reproducing the negative growth of the wind turbine construction industry. The latter three could however be improved by the introduction of variables such as the *expected profitability* as shown in this section (see figure 18 for the causal loop diagram), driving us however further away from the initial starting point -the *Wind Force 12* report[23].

In this model:

- a higher *new number of wind turbines* increases the siting costs, reducing the *expected profitability* and thus the *new number of wind turbines* (see the negative feedback loop in figure 19);
- the red dotted structure could (if switched on) drastically reduce the output of the wind turbine construction industry -the variable *new capacity of wind turbines*- in case of negative *expected profitability*. This represents a possible short term reaction of the industry to demand cycles;
- a higher *new number of wind turbines* decreases the site specific *onsite capacity factor* reducing the *expected profitability* and thus the *new number of wind turbines* (see the negative feedback loop in figure 20);
- a higher *new number of wind turbines* increases the *experience*, reducing the *cost of new capacity* which increases the *maximum potential* which in turn decreases the *siting costs*, leading to an increased *expected profitability* and thus an increased *new number of wind turbines* (see one of the two positive feedback loops in figure 21)
- a higher *new number of wind turbines* increases again the *experience*, reducing the *cost of new capacity* which also reduces the expected costs and thus increases directly the *expected profitability* which leads to an increased *new number of wind turbines* (see the second positive feedback loop in figure 21);
- more *experience* leads to a higher *onsite capacity factor* (technological improvement) and thus to a higher *expected profitability* and a higher growth rate of the wind turbine construction industry and thus to more *new [number of] wind turbines* and more *experience* (see the postive feedback loop in figure 22);

[22] New wind turbine areas need to be places with high average wind speed fit for wind turbines with huge blade diameters (since the energy generated is proportional to v^3 and D^2), need good grid connections on a stable grid, should not jeopardise the stability of the grid (since wind energy is intermittent and practically non-storable) should preferably not hinder or interfere with other activities (visual or aerodynamic and mechanical noise effects interfere with living, electromagnetic effects interfere with communication systems) or nature (bird safety).

[23] The dynamics included in the model are however limited by the scope of this paper. The working paper [4], deals amongst other things with the (i) increasing grid integration and grid investment costs and need for backup generation and storage capacity with higher shares of intermittent wind power in the total electricity system, decreasing the price and increasing the costs of wind energy (negative feedback loop); (ii) limited land area disposable for wind power projects (negative feedback loop); (iii) greening of the value system leading to higher acceptability of wind turbine projects, more favorable ruling and favorable spatial planning policies, decreasing delays and increasing the potential leading to an even greener value system (positive feedback loop). And other integrated models available by the author also treat the interaction with the other generation technologies.

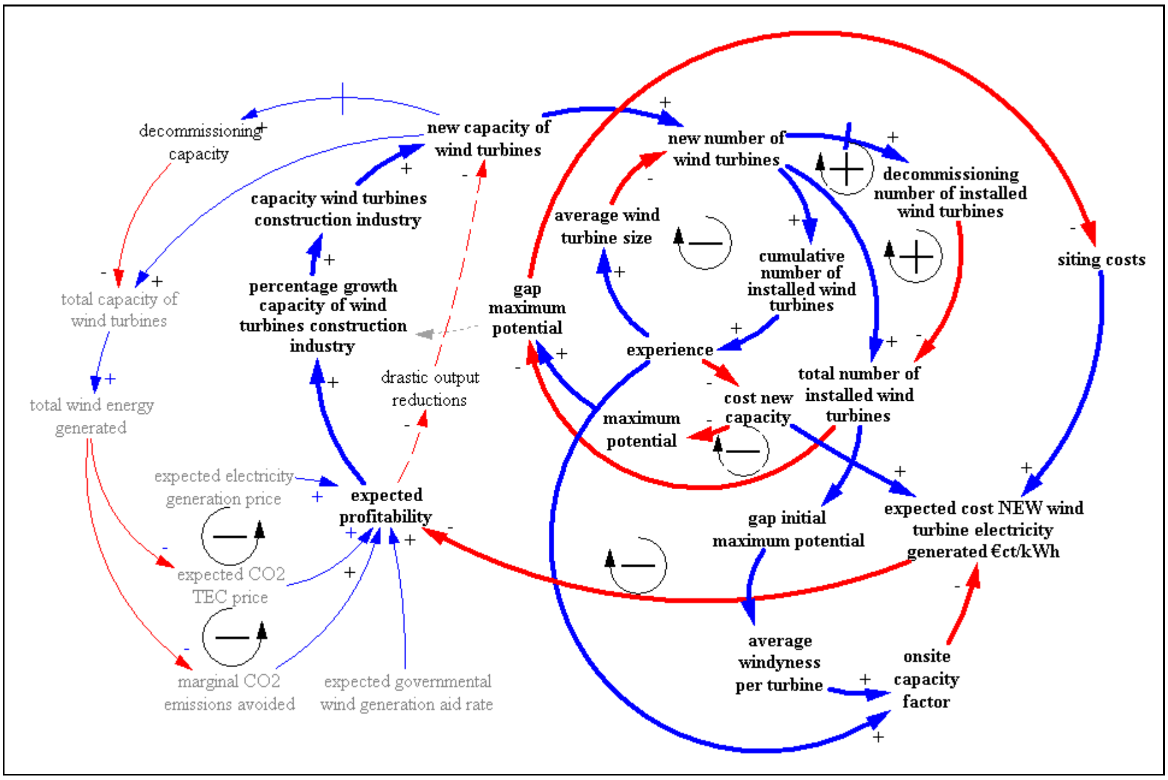

Figure 18: A causal loop diagram of the core feedback loops of the more elaborated sd2WF12 model. All negative causal links are marked in red, all positive causal links are marked in blue. The dotted light-grey link has been replaced by the *expected profitability* construct. The left-hand structure (not in bold) is only active in case of CO2 trade or taxes. The red dotted structure could introduce a drastic output reduction in case of negative expected profitability.

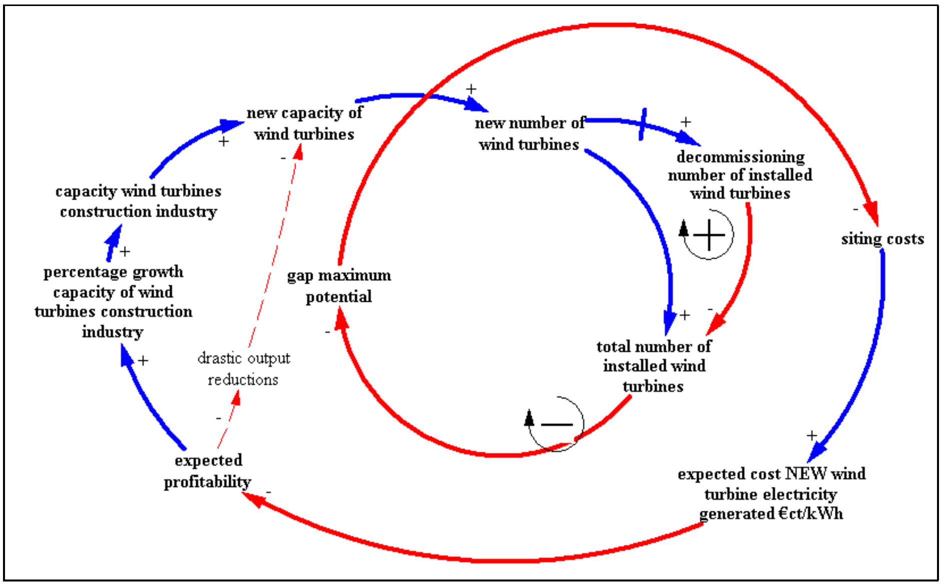

Figure 19: Siting costs reduce the expected profitability and thus the new capacity additions. All negative causal links are marked in red.

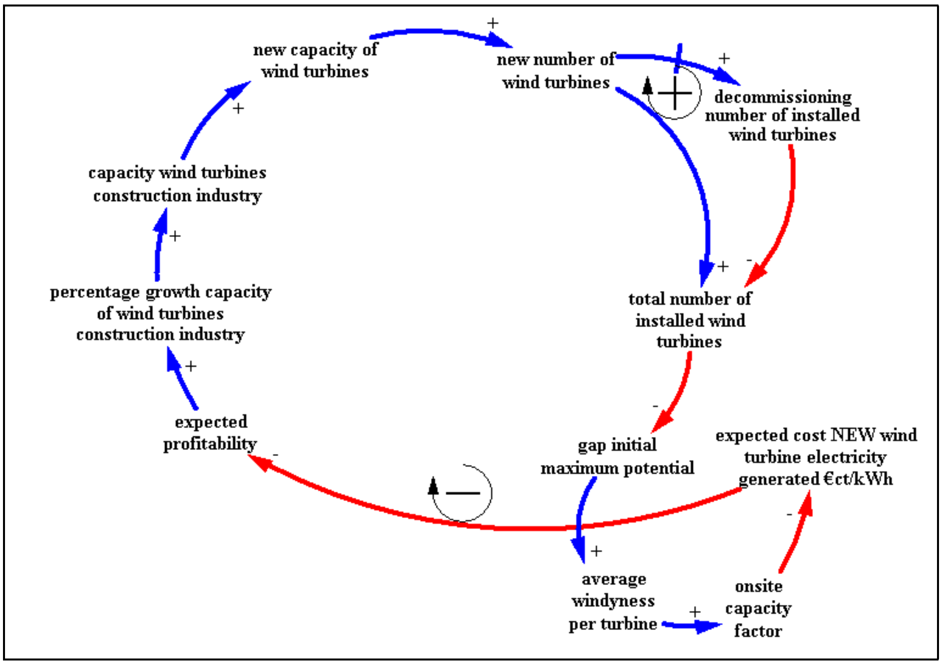

Figure 20: Less favorable wind sites will increase costs and cap the capacity too.

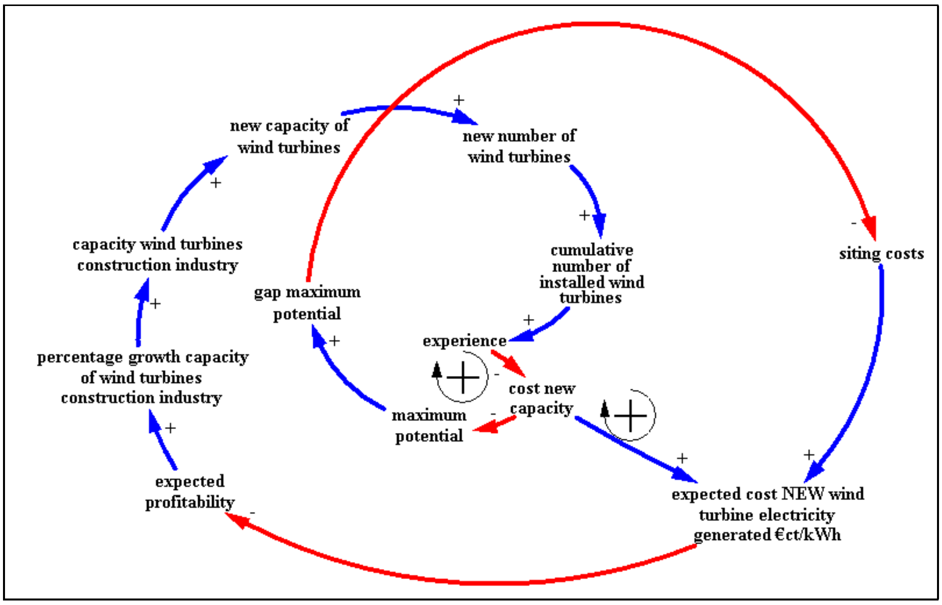

Figure 21: Siting costs and new capacity costs: two positive feedback loops accellerating the substitution by wind power.

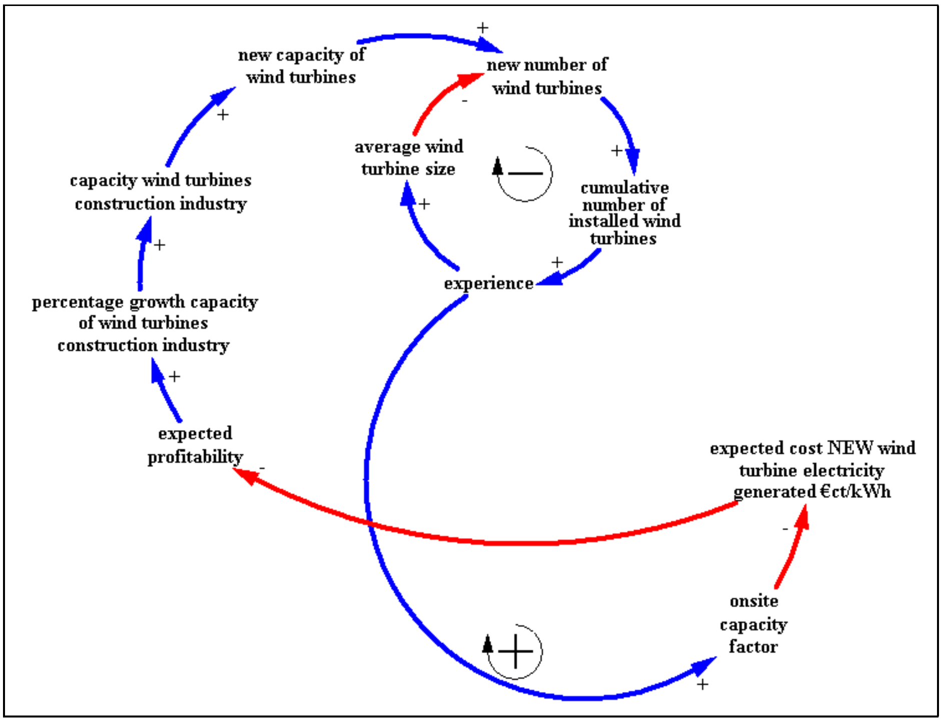

Figure 22: A positive feedback loop dealing with the increasing technological *capacity factor* with increased *experience* and a negative feedback loop slowing *experience* via an increased *average wind turbine size*.

- more *new wind turbines*[24] will lead to more *experience*, a bigger *average wind turbine size*, and thus, ceteris paribus, to less *new wind turbines* than if the size would have remained the same, just like in the previous model (see the negative feedback loop in figure 22);
- the *expected profitability* is also influenced by the *expected CO2 TEC price* and *marginal CO2 emissions avoided* in case of a CO2 emission trade system or CO2 taxes, and by the *expected governmental wind generation aid rate* in case of governmental support (see the negative feedback loops in figure 23) and of course by the market price (*expected electricity generation price*).

4.2 The stock/flow diagram of the sd2WF12 model

Since the model described in this section builds on the previous model, only the differences -which are marked in red in the stock/flow diagram (see figures 24 and 25)- are explicitly treated. The job and avoided CO2 calculation modules remain exactly the same (see figures 13 and 14).

The new variable *marginal annual cost NEW wind capacity* in the bottommost right-hand part of figure 24, calculates roughly the annual costs of a new (marginal) wind turbine of 1MW[25]. This *marginal annual cost NEW wind capacity* divided by the *marginal annual generation NEW wind capacity* of a new marginal 1MW turbine gives the *expected cost NEW wind turbine electricity generated* in *€/MWh* and *€ct/kWh* which plays an important role in the *expected profitability* variable[26]. Here the *expected profitability* of a marginal investment in wind turbines is roughly

[24] Again, the experience curve working on the **number** of turbines installed will be used for reasons of comparability with the other models and the *Wind Force 12* report.

[25] marginal annual cost NEW wind capacity = (cost new capacity (t) + additional siting costs + additional study and construction costs) * 1000 * (interest rate + operational and maintenance cost rate + 1/lifetime wind capacity)

[26] expected profitability = ((expected electricity generation price €ct/kWh - expected cost NEW wind turbine electricity generated €ct/kWh * (1 - governmental wind turbine electricity aid rate)) * hours per year * on site

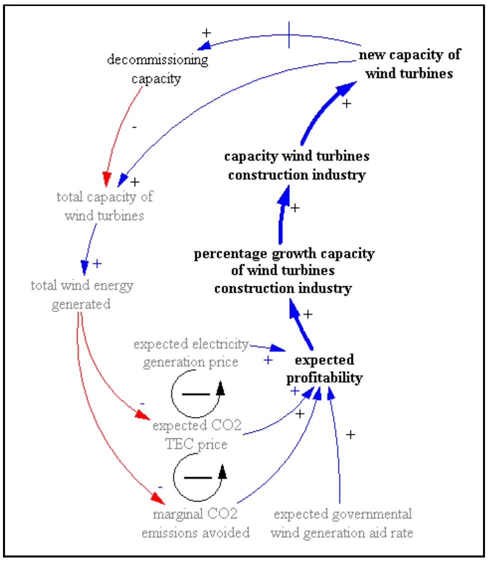

Figure 23: In case of CO2 taxes or trading, the increased wind capacity reduces TEC prices and the specific emissions of the mix.

estimated as the lifetime profits from the sales of the electricity generated and emission certificates sold divided by the capacity cost. In the base run the *switch CO2 trade and tax* is turned off, whereas the *expected electricity generation price €/kWh* is 6€ct/kWh, and the *governmental wind turbine electricity aid rate* is 15% until 2010. In case of emission trading or emission taxes, the feedback loops shown in figure 23 are activated, since the *net specific CO2 emissions avoided* are partly determined by the stock variable *total energy generated by wind capacity* and thus the total installed capacity and the *expected CO2 TEC price* by the *share* of *wind* energy.

The *expected profitability* influences the *new capacity of wind turbines* to be installed by the wind turbine construction industry in two ways: First, the *expected profitability* drives the *new capacity of wind turbines* indirectly by means of the growth of the wind turbine construction industry *new wind turbines capacity capacity* through the lookup variable *percentage growth new capacity of wind turbines* (see figure 26). These initial values imply that the industry will not shrink, that with an approximated profits over cost ratio of 25%, the industry will grow 10% et cetera. Secondly, the output of the industry *new capacity of wind turbines* could be directly limited in case of negative *expected profitability* via the *drastic output reductions* variable (see figure 27). In the base case, *drastic output reductions* of 50% of the output of the construction industry are subtracted (see figure 27 for the difference between *drastic output reductions* of 0%, 50% and 100%).

In the second view of the stock/flow diagram (see figure 25), only the lookup variable *additional siting costs* changes, but in a very important way. It will cap the total capacity and number of wind turbines via the decreased *expected profitability*. In the basecase (see the right-hand graph of figure 26), the *additional siting costs* are €0 per kW at a *gap maximum potential* of 0 and will increase to €150 at 0.7, to €700 at 1.4, to €1400 at 2 and to €2800 at 3.

capacity factor * lifetime wind capacity / 100 + net specific CO2 emissions avoided * expected CO2 TEC price * switch CO2 trade and tax * hours per year * on site capacity factor * lifetime wind capacity / 1000000)/ cost new capacity (t). The division by 100 converts €ct to €, and the division by 1000000 converts GW into kW.

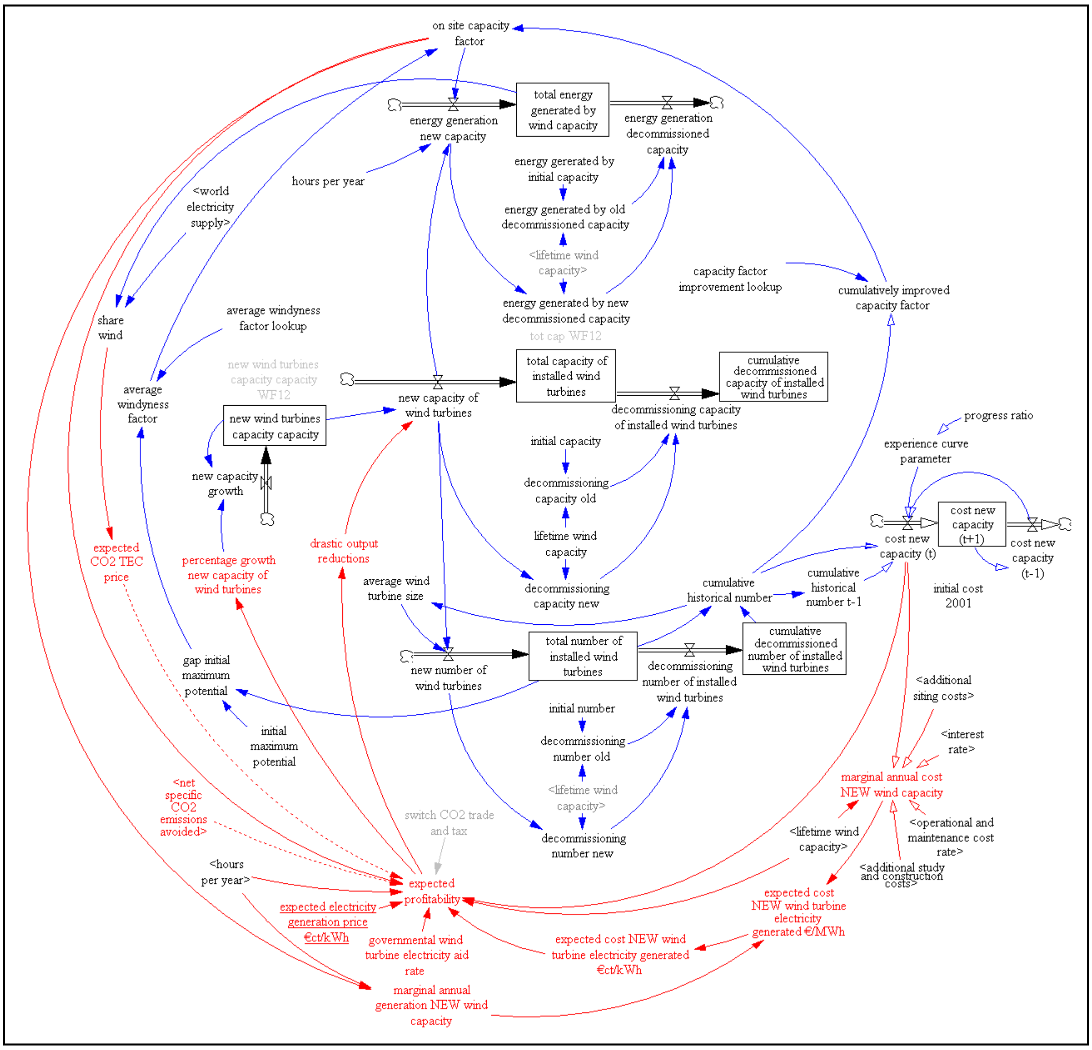

Figure 24: The first view of the stock/flow diagram of the sd2WF12 model, with the changed and newly added structures in red.

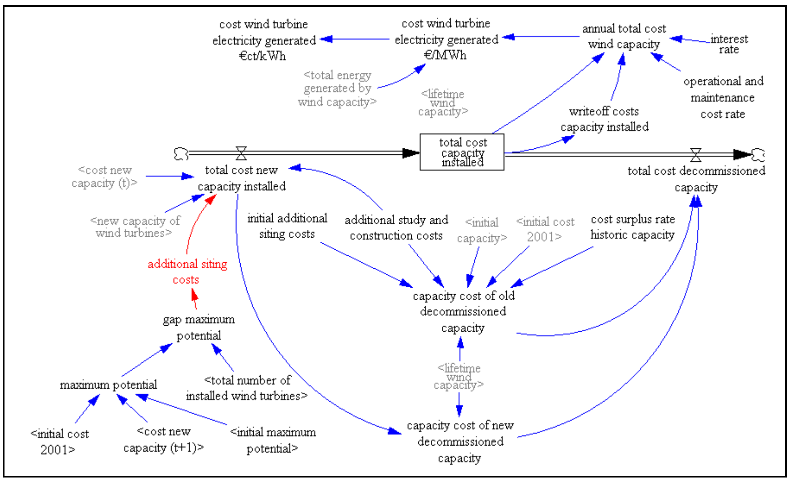

Figure 25: The second view of the stock/flow diagram of the sd2WF12 model, with the changed and newly added structures in red.

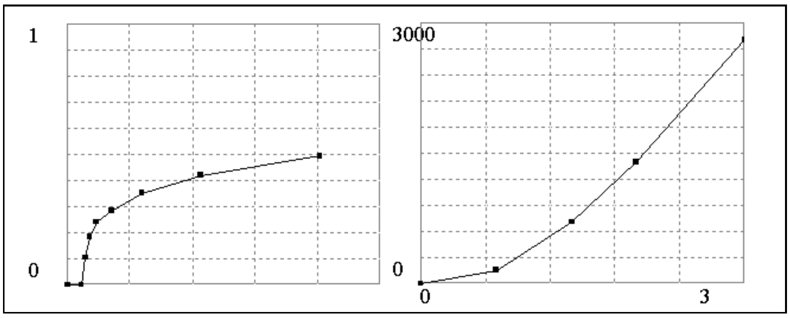

Figure 26: **Left-hand side:** The initial values of the lookup variable *percentage growth new capacity of wind turbines*: (-1;0), (0;0), (0.25;0.1), (0.5;0.18), (1;0.24), (2;0.28), (4;0.35), (8;0.42), (16;0.49). Further on, other (also negative growth) values will be tested too. **Right-hand side:** The basecase values of the lookup function in the variable *percentage growth new capacity of wind turbines*: (0;0),(0.7;150),(1.4;700),(2;1400),(3;2800).

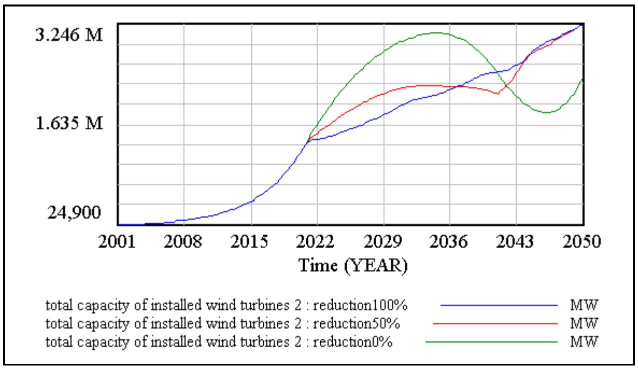

Figure 27: *Drastic output reductions* of 0%, %50 and 100% give rise to three very different evolutions of the *total capacity of installed wind turbines*.

4.3 Some simulation results of the sd2WF12 model

Since this model is centered around the *expected profitability*, it is very sensitive to the market price and the expected generation costs such as the *siting costs*[27].

In the left-hand graph of figure 28 we see that the *governmental wind turbine electricity aid rate* of 15% influences the roughly calculated *expected profitability* and pulls the *percentage growth new capacity of wind turbines* and consequently the *new capacity growth* up until 2010. After the drop in *expected profitability* due to the removal of the governmental support, the *expected profitability* increases, then declines because of rising *siting costs*. When the *expected profitability* becomes negative, the *new capacity growth* stops in the **basecase** scenario where no decline of the industry is possible. The resulting *total capacity of installed wind turbines* is depicted in the right-hand side of figure 28. In case of a possible decline as in scenario **neg-0,1** (with a decline up to 10% in case of an *expected profitability* of -1) the stock variable *total capacity of installed wind turbines* oscillates around the basecase scenario variable. The characteristic pattern of the *new capacity of wind turbines* is caused by the industry decline and the 50% drastic output reductions. Figure 29 shows the *total number of wind turbines* and the increasing *maximum potential*.

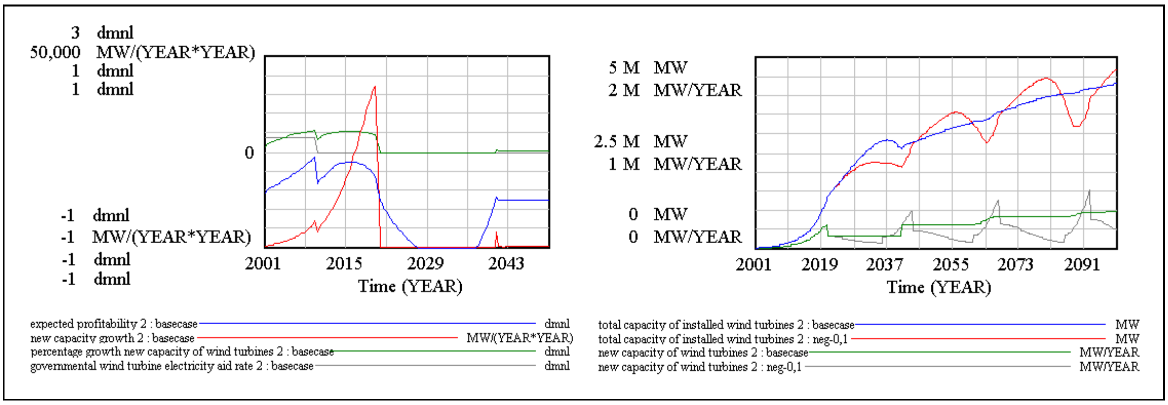

Figure 28: The *expected profitability*, *new capacity growth*, *new capacity of wind turbines* and the *total capacity of installed wind turbines* in the basecase and neg-0,1 scenarios of the sd2WF12 model.

5 Comparison of the models

Some basecase simulation results of the three models presented in the previous sections will be briefly compared[28] in this section. In the left-hand side graph of figure 30, the stock variables *total capacity of installed wind turbines* of the three models are compared. In the sd0WF12 model, this total capacity will increase and then remain constant at 3044000MW like in the report. In the sd1WF12 model, the total capacity increases, stagnates and then increases again after the wind turbine costs have decreased and the maximum potential has increased. The sd2WF12 model causes the total capacity to rise to almost 3044000MW, then to decline and finally to rise above it. These evolutions are directly caused by the *new capacity of wind turbines* variable depicted in the righ-hand side of the same figure.

Figure 31 shows the different evolutions of the *cost wind turbine electricity generated €ct/kWh* and the *total jobs per sales corrected* of the three models versus the WF12. The increasing costs

[27] In this and the following section, all models are numerically integrated using the Runge-Kutta4 integration scheme with a time step of 0.25 per year from 2001 on. To stick to the behaviour of the previous models, the initial value of the *new wind turbines capacity capacity* stock variable has been changed to 7225 instead of 8500 (the original initial value, or 6800 -the value previous to the initial value) as in the spreadsheet model and the sd0WF12 replication model using the Euler integration scheme.

[28] More comprehensive comparisons can be found in the working paper.

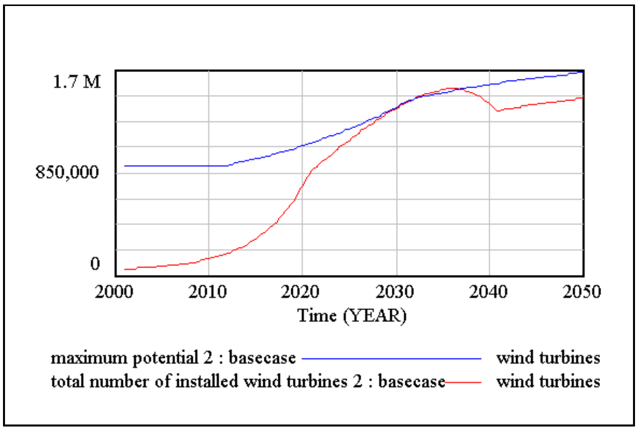

Figure 29: The*maximum potential* versus the *total number of installed wind turbines* in the base-case scenario of the sd2WF12 model.

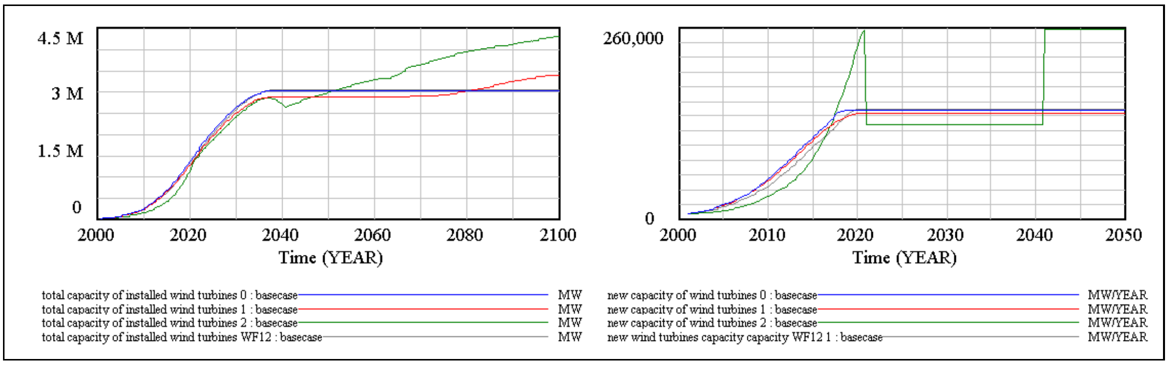

Figure 30: A comparison of the *total capacity* and the *new capacity* of the three models and the report.

of the third model in the left-hand side graph is caused by the increasing siting costs.

Finally, figure 32 compares the annual CO2 emissions avoided and the wind power share in the total world electricity generation. Note the difference between a constant specific emission assumption and a dynamic assumption (for example between *annual CO2 emissions avoided cte sd2* with constant specific emissions and *annual CO2 emissions avoided cte sd2*)

The development, simulation and evaluation of policy options is beyond the scope of this paper[29].

6 Conclusions

The static bottom-up *Wind Force 12* assessment spreadsheet has been turned here into a top-down system dynamics model. An assumption behind these top-down models is that the wind construction market is or will become a world market.

The transformation process has been described step-by-step and in great detail, in order to increase the confidence in the models. For that purpose, the models have been kept simple and

[29] In the working paper [4] the model is adapted and extended to the European and Belgian context, structural policy options (such as CO2 trading) are defined, simulated and evaluated on the economic, environmental, socio-cultural, technological-technical and security dimensions using a Multiple Criteria Decision Aid elimimation method. Within these dimensions, criteria such as effectiveness, efficiency, investment costs, clean electricity generated, CO2 and other emissions avoided, external costs avoided, fuel imports avoided, power grid stability and reliability, employment, electricity price and public expenditure are treated.

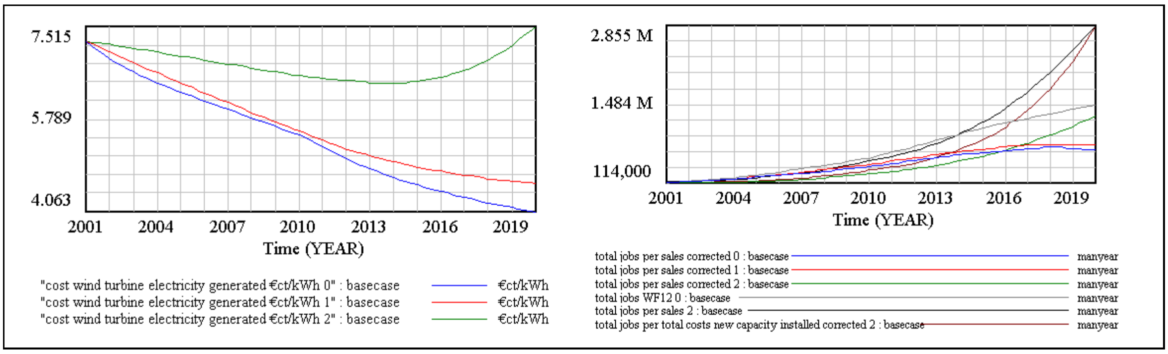

Figure 31: A comparison of the *cost of wind turbine electricity generated* and the *total jobs* created of the three models and the report.

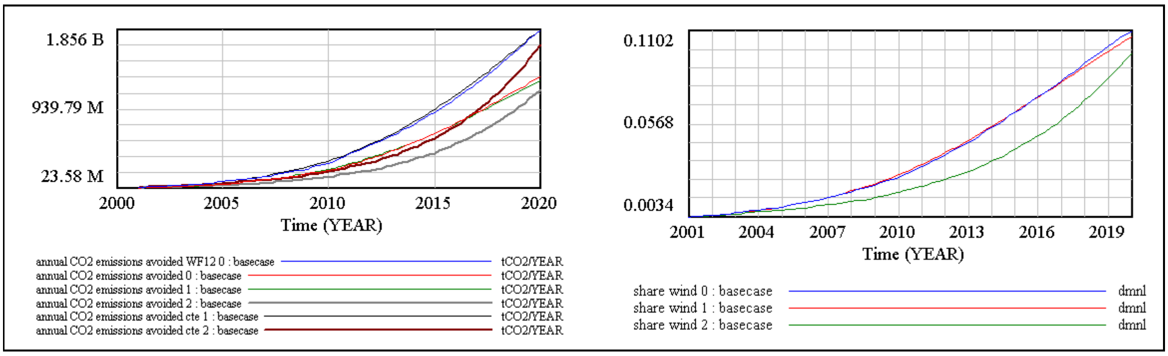

Figure 32: A comparison of the *annual CO2 emissions avoided* and the *share of wind power* of the three models and the report.

accessible. More elaborated models and simulations -dealing for example with value systems and institutions- have not been presented here but are or will be presented in working papers and papers, since these concepts have a great real-world importance -despite their high degree of fuzziness and the low degree of scientific knowledge about them.

Nevertheless, some conclusions could already be drawn at this stage concerning the *Wind Force 12* report, concerning the methodology used, and concerning world wind power.

The *Wind Force 12* report contains some typical errors which were found using a stock/flow replication model. Besides the advantages of the stock-flow representation, the obtained system dynamics structure could be simulated as well, enabling us to test sensitivity and hypotheses, and to simulate policies. Although the report was created taking into account some typical systems thinking concepts, the resulting replication model is extremely static.

The sd1WF12 model is a dynamic version of the same report, leaning too much on artificial concepts such as 'maximum potential'. The sd2WF12 model is closer to reality since it replaces the artificial constructions with the real-world dynamics of investments based on the expected generation costs and profitability. On the other side, it is less easily verifiable and further away from the report. The advantage of developing system dynamics models step-by-step from a credible but static source -from pure 'engineering' models to 'plausible nonsense' models-, is that the link with the 'credible' source is not lost. Although most variables of the sd2WF12 model have their own logic, the link with the spreadsheet model is still clear. It could also break down barriers for people not familiar with system dynamics. This is an easy way to explain these models and show their advantages and disadvantages to people not familiar to system dynamics.

The advantages and disadvantages of the different models are clear too. Here it is interesting to see step-by-step how and why the models become more sensitive to 'uncertainties in the progress ratio'[3, p8] (the sd1WF12 and sd2WF12 models) and to costs and prices (sd2WF12model). Quite simply: by not considering the dynamics, there will be no sensitivity!

The models discussed here are in system dynamics terms still quite reductionistic. Therefore other more holistic models have been developed. But the level of complexity is much too high to describe these models understandably in a 30-page paper. This is anyhow a problem for publishing system dynamics models.

A final conclusion could be that the dynamics puts the concept of the 'maximum potential' in a different light.

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