Assessing the Potential of Offshore Wind Energy as an Innovative CO_2 Emission Reduction Option in the Energy System Model genEris

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1. Introduction

At least since the latest report of the Intergovernmental Panel on Climate Change (IPCC) it is common consensus that climate change is happening. It is no longer discussed whether the danger exists but how to deal with it.

And with very high probability the reasons are increasing greenhouse gas concentrations in the atmosphere. The gas mainly in charge of changing global average temperature is CO_2.

The increasing concentration is to a large extent due to the burning of fossil fuels and thus a result of the human energy consumption.

The consumption of energy will further increase in future as the global population grows and developing countries become industrialised nations.

Thus the energy supply and its carbon intensity play a crucial role if climate change is to be mitigated.

Reduction of emissions is possible by various measures. Different political and scientific approaches are: energy saving consumers, capturing and sequestration of carbon dioxid, more efficient technologies and/or replacing exhaustible energies (based on fossil fuels) by renewables.

This study focusses on the option of substituting fossil fuels by renewable energies that are less carbon intensive or do not cause any direct emissions at all.

A broad portfolio of technological options already exists. The so called clean technologies converse energy from wind, sun, water, biomass or geothermy into electricity or heat for instance. Nuclear power is another option of emission reduction which is mostly discussed separately as it covers high security related risks.

Subject of this study is to find out which contribution offshore wind energy can make to the energy supply in the electricity sector.

The computational basis is delivered by genEris, which is an Energy System Model written in GAMS, developed at the Potsdam Institute for Climate Impact Research (PIK). It calculates an optimal solution, examining which energy mix is the most cost efficient one during a certain time period.

Different emission scenarios are considered: implementation of offshore wind energy under business as usual (BAU) conditions and under politically determined emission constraints (450 ppm).

It is furthermore examined how offshore wind energy affects the additional mitigation costs occuring due to nuclear phase out.

2. The Energy System Model genEris

2.1 Introduction

genEris is an energy system model (ESM). It provides a bottom-up technology description in reasonable detail with the objective of minimizing the discounted intertemporal energy system costs.

genEris has been developed at PIK by Nico Bauer and further development is in progress. [1]

The model is written in the programming language GAMS that is particularly suitable for solving optimization problems and often used for the modelling of national or international energy systems and energy industry systems. There are also some other energy system models available but genEris allows the user to change the structure and adapt it to individual needs. [2]

The structure is separated from the data. Numeric and algorithmic contents are provided by solvers. The solver presently used by genEris is conopt3. This solver has been designed to solve non linear models by finding a local optimum. [6]

2.2 Basic structure of the model

The frame is given by the considered time period, the final energy demand and eventually emission scenarios as major boundary conditions.

Time period
The time period spans from 2005 (inital timestep t_0) to 2150 (t_{end}). The resolution is five years.
A spin up from 1900 is possible and time steps after 2100 are not taken into account for result interpretation to avoid misleading results from end effects.

Final energy demand
The final energy demand is determined exogenously. For the electricity sector for example it is supposed to approximately increase sixfold during the considered time. This development is comparable to the IPCC special report on emission scenario (SRES) B1/B2. [14]

Emission scenario
The scenario considers policy influences on the optimization problem. In the business as ususal (BAU) case only the minimum of costs has to be found. In case of additional emission constraints the mimimum of costs has to be found under the consideration of an emission cap (for example a stabilization of CO_2 concentration at 450 ppm). According

emission time paths are derived from the model MIND[1].

genEris considers different sectors of energy. These are electricity, heat, transport and others. Figure 2.2.1 gives an overview of the structure.
Different kinds of primary energy are transformed via conversion technologies into secondary energy which finally is transformed into final energy.

This basic structure is enlarged to a network by the possibility of own consumption and production of couple products.

Furthermore the model considers stocking possibilities and emission output.
Emission output is limited by an exogenously defined constraint. The possibility of carbon capturing and sequestration is also represented.

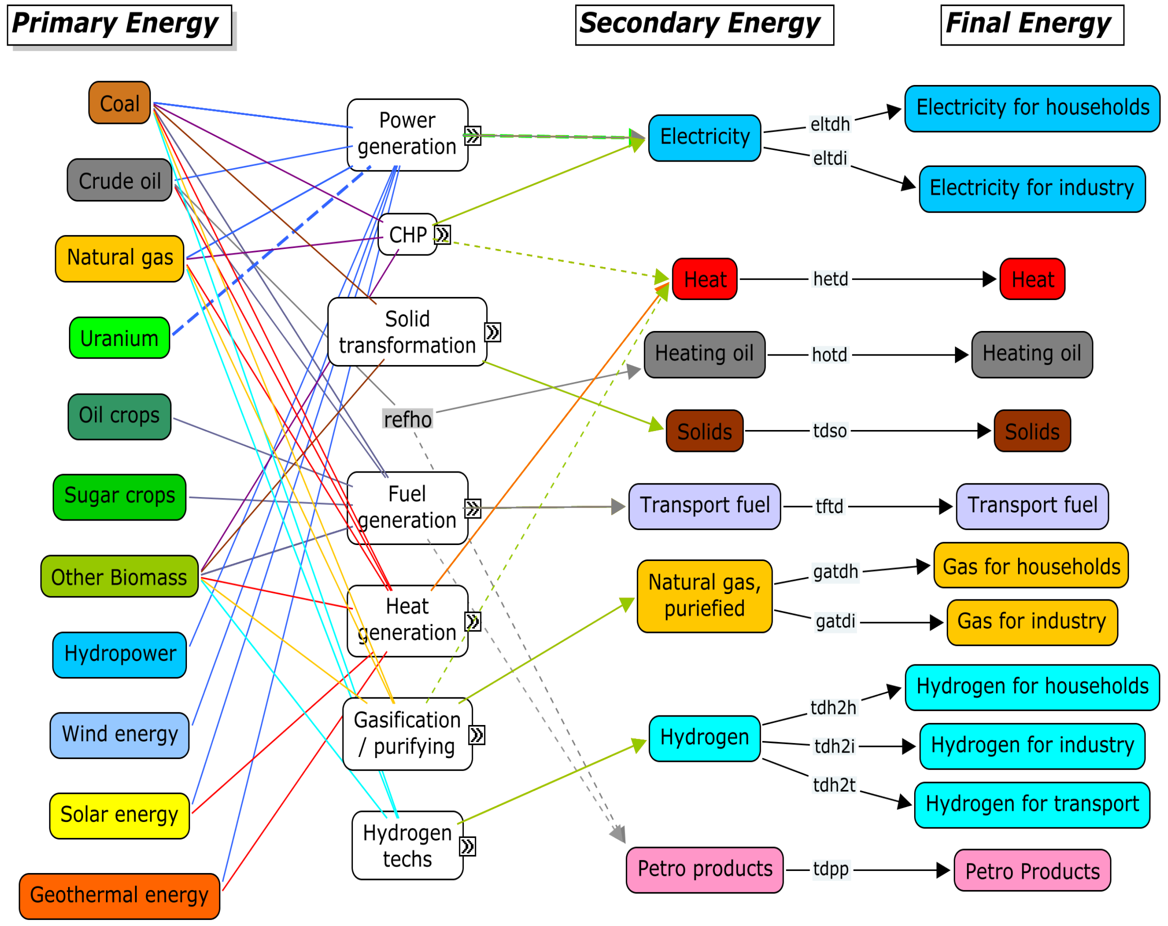

Figure 2.2.1 General structure of the genEris model

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[1] MIND: Model of Investment and technological Development. MIND was developed at PIK. It „is a hybrid model incorporating several energy related sectors in an endogenous growth model of the world economy“. [7]

The core of the system is a one dimensional transformation path.

For this study it is important to notice that only the electricity sector is considered.
The primary energy in question is the wind energy.

2.3 File organisation

The model information is organised in different files.
The core is the file `genEris.gms`, which contains the model equations.
`genErisData.gms` delivers the parameter definitions.
Sets and mappings are defined in the `genErisSets.inc`, while `genErisScalars.inc` lists the conversion factors of time units, energy units, magnitudes and others.

The concrete data are imported from `.prn` files.

2.4 Sets and Mappings

Important building blocks in the GAMS structure are sets, subsets and mappings.

The combination of sets, subsets and mappings in GAMS simplifies the readability of the model and the possibility of adding new components. The concept reduces the time needed for solving the problem due to the reduction of the number of built up equations and variables during the process.

Sets and subsets
A set is a list of items. For example the set `enty` summarizes all energy types in genEris.

Further distinction is possible by the implementation of subsets. Members of one set can be members of one larger set.
For example primary energy types are summarised in another set. This set is then a subset of the set `enty`: `pety(enty)`, while the brackets indicate that `enty` is the set the subset `pety` belongs to.

Mappings

Mappings link the elements of different sets for different purposes and thus are multi-dimensional sets. GAMS allows up to ten dimensions for one mapping.
For example three sets are linked by one mapping as follows:

```
pe2se (enty, enty2, te)
     /pegas.seel.ngcc
     .
     .
     .
     /;
```

The mapping `pe2se` represents all conversion possibilities from primary energy carriers (members of the set `enty`) to secondary energy carriers (set `enty2`) via different transformation technologies (`te`). One covered conversion path is the combination of primary energy gas (`pegas`) to electricity (`seel`) via natural gas combined cycle technology (`ngcc`). [1]

2.5 Algebraic structure

The following section introduces the equations which are most relevant for this study.

Objective function (`goallp`)

Algebraic notation:

min Z
subject to

$$Z = \sum_{t=t_0}^{t_{end}} e^{-\rho(t-t_0)} \Delta t (C_F(t) + C_I(t) + C_O(t))$$

C_F	fuel costs
C_I	investment costs
C_O	operation and maintenance costs
Z	total energy system costs (discounted)
t_0, t_{end}	initial and final simulation time step
Δt	time step length
ρ	discount rate

genEris notation in `genEris.gms`:

```
goallp..
        objlp =e=
        sum(t,
                exp(-esmdisrate(t)*ts(t)*(ord(t)1))*
                ts(t)*
                (costfu(t)+costom(t)+costin(t))
         );
```

By minimizing the objective variable, the overall costs of total energy supply are minimized.

The corresponding solve statement is the following:

```
solve erislp minimising objlp using nlp;
```

- while `nlp` means non-linear programming. This method allows the inclusion of a non-linear equation (namely the learning equation) into the optimization. `erislp` names the model genEris in the code.

Contrary to exhaustible energies renewable primary energies are not subject to fuel costs. That means it is assumed that energies like wind, water, sun are available for free.

Capacity constraints for primary to secondary energy `capconstse`

General structure:

$$P(t,T) = \tilde{K}(t,T) \qquad \forall t \quad \forall T$$

In detail:

$$P_s(t,e_p,e_s,T) = \sum_{M_{T_s \leftrightarrow g}} \sigma(T) \cdot \nu(T) \cdot \nu_g(T,g) \cdot K(t,T,g) \qquad \forall t \quad \forall M_{p \rightarrow s}$$

$\tilde{K}$	'corrected' capacity of general energy production through technology T
P	production of general energy
K	capacitiy of technology T
T	technology (energy technology transformation in general)
P_s	production of secondary energy
ν	load factor associated with technology T
ν_g	scaling of the load factor ν dependent on grade level g
σ	share of main product in overall output of technology T
$M_{p \rightarrow s}$	definition of primary to secondary energy transformation
$M_{Ts \leftrightarrow g}$	combination of secondary energy technologies and grade levels

The output amount of secondary energy is determined by the installed capacity. However, the installed capacity is 'corrected' by the technology specific load factor and a second load factor considering the resource availability.

Potential constraint on secondary energy production from renewable energy `renconst`

$$\pi_T(g, T_{ren}) \geq \eta(T_{ren}) \cdot v(T_{ren}) \cdot v_g(T_{ren}, g) \cdot K(t, T_{ren}, g) \qquad \forall t \quad \forall M_{T\leftrightarrow g}$$

η	efficiency of technology T
π_T	maximal production of secondary energy from non-exhaustible resource via T_{ren}, g
T_{ren}	renewable energy transformation technologies
$M_{T\leftrightarrow g}$	combination of technologies and grade levels

The corrected installed capacity and with it the production amount of secondary energy is limited by a maximum potential.

Learning equation `llearn`

$$I(t, T_L) = \alpha(T_L) \cdot \hat{K}(t, T_L)^{\beta(T_L)} + \iota_L(T_L) \qquad \forall t \quad \forall T_L$$

I	specific investment costs for adding capacity of a learning technology T_L
$\hat{K}$	cumulated capacity of technology T
ι_L	floor costs of a learning technology
T_L	technology which develops through learning
α, β	learning parameters of a learning technology T_L

Some technologies are defined as learning technologies. That means their specific investment costs decrease during time by a certain degree. The learning parameters are dependent on the initially installed capacity and a learning rate. The learning rate describes the percentage of investment costs decrease with each doubling of cumulated capacities.[1]

Appendix A.1 gives an overview on the algebraic structure. A.2 lists all equation abbreviations considered in genEris.

3. Offshore wind energy in genEris

3.1 Introduction

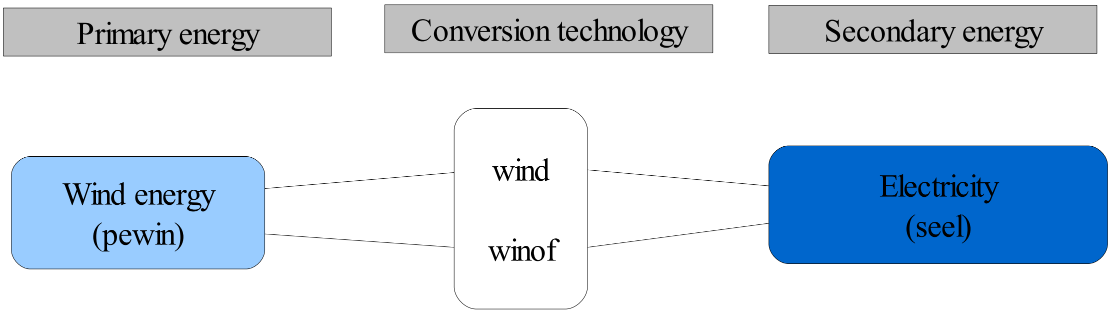
Due to longtime experience with onshore wind energy technology characteristics of offshore wind energy are strongly related to the ones of onshore wind energy.
In the meantime onshore wind energy has gained a strong position in the energy market.
In Denmark already about 20% of electricity demand is supplied by wind, whilst in other regions, such as Asia or South America markets are just being opened up. [12]
Especially in Europe, where wind energy on land is already well developed and implemented the focus turns to offshore wind resources.

However, there are some substantial differences in the conditions. Some are advantageous and make offshore wind energy attractive, others are harsher and require significant alterations of the onshore technique.

What makes offshore wind energy attractive are mainly the more regular wind supply and higher average wind speeds. Exemplary measured average wind speeds in Germany in 50m height range from 3m/s in the Alps and 7m/s in coastal areas to more than 8m/s on offshore terms.[15]
Due to the less rough surface of the sea the friction force is reduced and a lower hub height is needed.

New requirements on construction and technology derive from hydrodynamical impacts due to waves, flows, tides and ice. Furthermore the atmospheric conditions are different. Higher atmospheric humidity as well as saline content cause danger of corrosion.
Another challenge is the sea ground. It is more difficult and expensive to examine, and erosion might occur. [9]

Offshore wind energy is introduced as one conversion technology. No additional primary energy has to be added as renewables are limited by technology-specific capacity constraints in genEris (contrary to primary energy specific potential capacities as it is the case for biomass and exhaustible primay energy).
So there is one primary energy (`pewin`) that can be transformed into electricity by two conversion technologies: onshore (`wind`) and offshore (`winof`) wind power plants.



When wind power plants were first developed a wide variety of techniques existed, such as asynchron or synchron generators, pitch or stall regulation, two or three blades and others. But tendency showed a standardisation to a most successful construction and technology.
As development of offshore power plants is yet strongly dependent on onshore conditions the same refers to offshore plants.
With proceeding implementation, when it becomes economically more efficient, development of offshore technology might seperate from onshore development. For example plants with only two blades can be imagined as the asthetic aspect is no longer relevant.

Characteristics of offshore wind energy are represented in genEris by the parameter definitions.

3.2 Parameters

The parameters describing the conversion technology are:

`inco0`	initial investment costs [$US/kW]
`omf`	fixed operation and maintentance costs as a share of the initial investment costs
`omv`	variable operation and maintenance costs per unit of produced energy
`mix0`	share the technology contributes to its main product output amount at t_0
`ccap0`	initital cumulated capacity [TW]
`cap0`	capacity development in time steps prior to t_0
`omeg`	depreciation factor according to lifetime
`incolearn`	investment costs reduced by learning in the long run [$US/kW]
`learn`	learning rate
`eta`	conversion efficiency
`nu`	load factor, percentage of operation time
`nur`	load factor dependent on grade level (grade: weight factor)
`maxprod`	maximum output (according to grade level)

Cost related parameters

Investment costs `inco0`
Investment costs include costs for turbine, transmission cable (to coast and between turbines), electricity systems, operating and control systems and others (like environmental analysis).
The foundation is considerably more expensive compared to onshore installations.
As development of turbine, foundation and way of installation is still in progress cost data vary but can be assumed as 1,700$US/kW. [3]

Operation and mainentance costs `omf`

These costs are significantly higher for offshore turbines due to the sea conditions and are assumed to 0.05% of the investment costs (for comparison: 0.025 for onshore turbines). [3]

Capacity related parameters

Initial cumulated capacity `ccap0`

An initial cumulated capacity of 0.00305 TW is assumed (0.066 TW onshore) for timestep t_0, year 2005, while literature expects high yearly growing rates of up to 30%. [3]

Initial capacity `cap0`

As the model considers lifetime and related depreciation installed capacity prior to the initial timestep t_0 is also taken into account. Based on absolut values (for installed capacity) a spin up factor is created that represents the capacity addition prior to 2005. For offshore wind energy the spin up starts at year 1990, t_{-3}. [16]

Contribution to electricity output `mix0`.

The contribution is still quite low, 0.00136%. [11]

Learning effects

Learning rate `learn`

The learning equation is the only non linear contribution in the mathematical structure.
The learning rate describes the cost reduction with every doubling of installed capacity. The more capacity is installed the sooner specific costs will decrease. A learning rate of 0.12 is assumed. [17]

Difference investment costs - floorcosts `incolearn`

Literature assumes a value of 680 $US/kW as the lower limit of investment costs.
Investment costs are not expected to drop below this value. [11]
Therefore, the difference `incolearn` is 1700 $/kW - 680$/kW = 1020 $/kW.
By mistake, the floor costs number 680 $/kW has been used for `incolearn` in the experiments. However, later experiments with the correct `incolearn` number showed, that the effect of this mistake on the model results are neglectable. E.g., changes in the objective function are found to be on the order of 10^{-3} or below.

Assessment of potential

Maximal production `maxprod`

Literature commonly discusses five different potential types:

The **theoretical potential** names the physical maximum an energy source can supply.

The **conversion potential** considers the technology specific efficiency factor and is thus dependent on technological progress. It expresses the secondary energy amount that can be gained by a technology under optimal conditions.

The **technical potential** relates to the conversion potential and furthermore takes into account restrictions due to landuse competition, structural or ecological objections.

The **economical potential** names the economically usable share of the technical potential and is influenced by economic and political conditions.

The **sustainably usable potential** considers sustainability aspects such as ecological and socio-economic restrictions. [10]

Additionally to the general uncertainty on offshore wind energy potential in literature it has to be carefully examined which potential is considered.
For the genEris energy system model the technical potential is most appropriate.

As data on global wind energy potential are still very scarce it makes sense to transform information on European conditions to a global scale. Figure 3.2.1 shows the distribution of offshore wind energy potential in Europe dependent on water depth and distance from shore.
This dependence makes it possible to relate the potentials to grade levels which yields 12 grades. A 13th grade is assumed to cover projected future offshore plants in water depth deeper than 40m, which affords innovative swimming platforms. For further details on grade definition see section Load factor, following page.

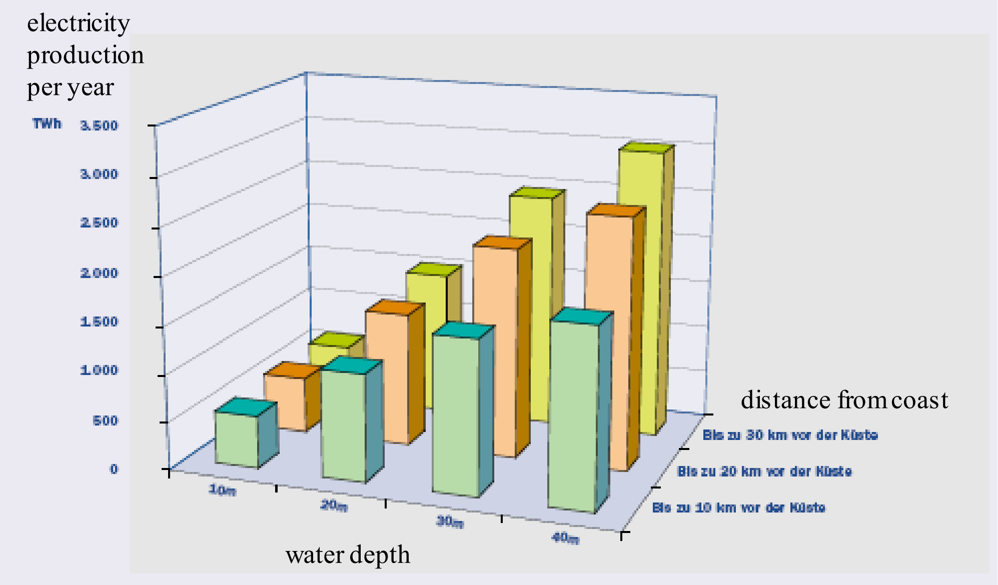


Figure 3.2.1 European distribution of offshore wind energy potential [11]

For Europe a technical potential of about 3,000 TWh/a (10.8 EJ/a) is assumed. Due to different restrictions the usable potential is reduced by the factor 10 to about 300 TWh/a (1.08 EJ/a). Restrictions are due to environmental protection areas, military zones, shipping routes and others. [11] Appendix A.3 illustrates the sea use competition.

Carefully a global potential of wind energy resources is estimated to 133 EJ/a. [13] As restrictions valid for Europe can be assumed on a global scale as well a global wind energy potential of 13.3 EJ/a is assumed. This value also corresponds to the presently defined value of onshore wind potential, i. e. 39.9 EJ/a. This means the potential of offshore wind energy is about 33.3% of the onshore potential which is a realistic relation.

The grade-based potential levels deriving from figure 3.2.1 for Europe are then scaled with respect to the global total potential value, assuming a similar structure of the offshore sites in terms of water depth and distance from coast.

Appendix A.4 gives an impression of the global distribution of wind energy potential expressed by global yearly average full load hours (that are related to mean wind speeds). It shows that good conditions can be found in Northern Europe, Northern America, and in parts in South America and South Africa.

Technical parameters

Depreciation and lifetime `omeg`
Lifetime of offshore wind power plants is assumed to be 25 years. [5] The depreciation factor changes from 1 at the first time step to 0.5 five timesteps later.

Efficiency `eta`
The maximum coefficient of power of wind is 16/27, that is the Betz coefficient c_p. The theoretically attainable power is therefore limited to 60% of the wind power. [18]
This share is further reduced in reality and can be assumed as 0.45.

Load factor `nu, nur`
Offshore power plants have a reduced technical load factor compared to onshore plants. The load factor is approximatly 0.92 (nu) and changes with distance from the shore. [9]
As figure 3.2.2 shows it is influenced by availability and accessibility and decreases with distance from shore.

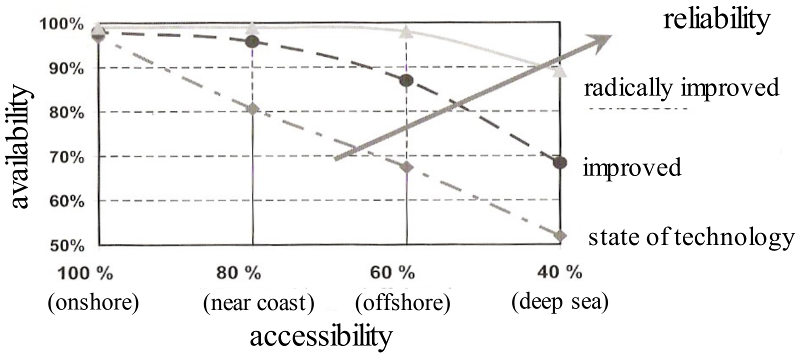


Figure 3.2.2 Reliability of offshore wind turbines [9]

In the model a maximum load of 0.45 is assumed for the first grade.
The grades are determined by the above mentioned change of reliability (technical load factor) on the one hand and by varying costs on the other hand. The costs vary according to water depth and distance. Fixed costs mainly increase with water depth due to more expensive foundations. Variable costs mainly grow with distance because of difficult and costly maintenance.
According to the above mentioned distribution of potential 13 grades have been developed in genEris.

Appendix A.5 gives an overview on the standard parameters.

3.3 Implementation of the offshore wind technology

As stated above the model is organised in different files.

For introduction of a new technology the basic file `genEris.gms` needs not to be modified.
Due to the organisation in sets and mappings changes basically are undertaken in the `genErisSets.inc` file.
Concrete data are added in the corresponding `.prn` files. All data of the `.prn` files are summarised in one excel file where changes can be made and then saved separately in the `.prn` files.

Implementation of a new primary to secondary technology in `genErisSets.inc`:
The new technology is added in the main technology set te and in all corresponding subsets like subsets for technologies with vintage depreciation scheme, learning technologies, renewable energy technologies and so on.
It then has to be added to the corresponding mappings, eventually with information on the number of grades or timesteps (lifetime).

Running an experiment

The program is performed by running the `genEris.gms` file.
Different model status reports are possible:
Infeasible solution: The solver was not able to find a feasible solution. The solution does not fulfill all constraints.
Feasible solution: The solver was able to solve all equations but not to find an optimal solution. It states that still a gradient exists above a tolerance level.
Optimal solution: All equations are fulfilled and an optimal value is found for the objective variable.

Output data are stored in `.put` files.
They can be visualised by MATLAB files. Different options are offered to select the most appropriate output format or data. Further MATLAB files for special needs can be created.
One MATLAB file offers the storing of the output data in a separate directory so they are available anytime without running the experiment again.

4. Analysis and results

Output data are visualised as shown in figure 4.1.1. Each graphic shows the calculated mix of energy conversion technologies of the electricity sector. For explanation of the abbreviations used please see Appendix A.6.

The vertical axis scales the electricity demand, the horizontal axis the time period.

The initial electricity demand is assumed to 58,91 EJ/a at t_0 = 2005 and approximately increases sixfold to 359,96 EJ/a in t_{end} = 2100.

Basically two emission scenarios are observed. First the role of offshore wind energy is examined in both scenarios, considering the standard parametrisation. Then the influence of single parameter variations is observed.

4.1 Business as usual scenario

Figure 4.1.1 shows the use of technologies in the business as usual scenario before offshore wind energy was introduced. The dominating technology is pulverised coal (`pc`). While the share of biomass and wind increases, gas and oil related energies are only considered according to their initial capacities but run off by 2050. When the electricity demand cannot be fulfilled by `pc` and biomass any more solar photovoltaic (`spv`) and nuclear power (`lwr`) are taken into account.

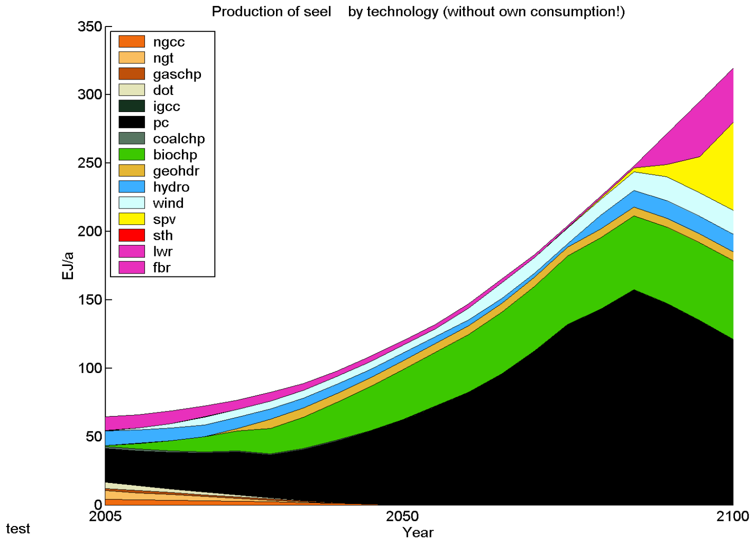


Figure 4.1.1 Business as usual, standard parametrisation, without offshore wind energy

Figure 4.1.2 shows the results after inclusion of offshore wind energy. Offshore wind energy is only competitive from about 2070 on and competes with pulverised coal and to a small extent with nuclear power.

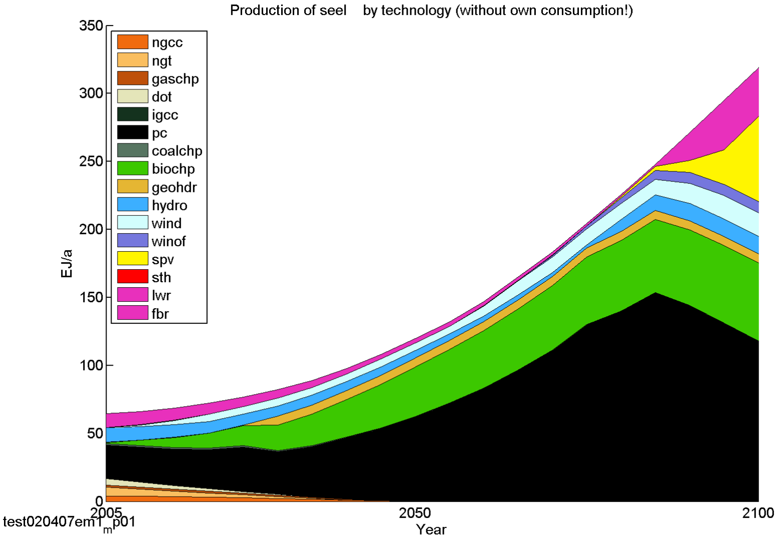


Figure 4.1.2 Business as usual standard parametrisation, considering offshore wind energy

4.2 Policy scenario 450 ppm

Considering an emission constraint of 450 ppm the shares of energies change significantly. While pulverised coal still plays a role in the short run, energy from biomass, natural gas combined cycle (`ngcc`) and nuclear power dominates the transition period. In the long run especially `ngcc` with carbon capturing (`ngccc`) becomes important and `spv` is built up extensively as a backstop technology.

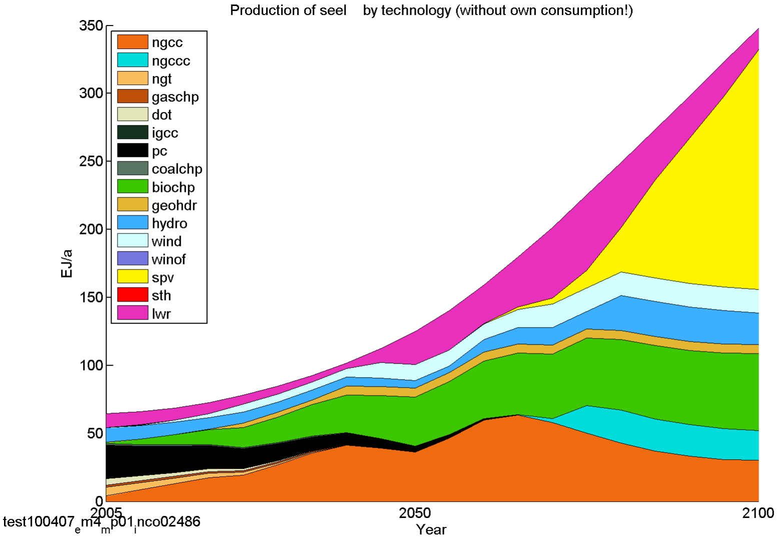


Figure 4.2.1 Policy scenario standard parametrisation, without offshore wind energy

If offshore wind is included, it replaces about two thirds of the `ngccc` contribution from 2070 on. The use of hydropower is slightly reduced while nuclear power increases a little bit. But these shifts are not relevant compared to the effect on `ngccc`.
During the transition time offshore wind power mainly competes with nuclear power.

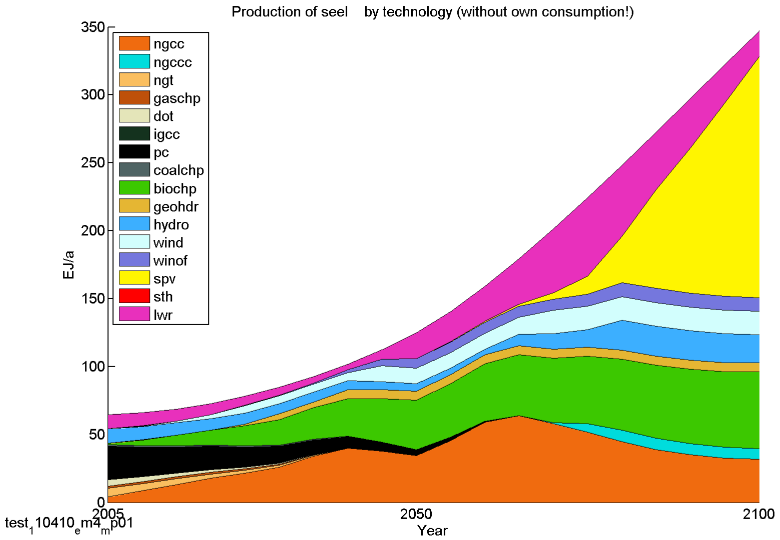


Figure 4.2.2 Policy scenario standard parametrisation, including offshore wind energy

The most important driving force is the costs of the technology.
In figure 4.2.3 the costs per electricity output of learning technologies are plotted. The lower plot shows costs at floor cost level. As one can see from the second plot costs of `winof` and `spv` reach a similar level at floorcosts. Contrary to `ngccc` these costs are significantly reduced compared to the corresponding initial costs.

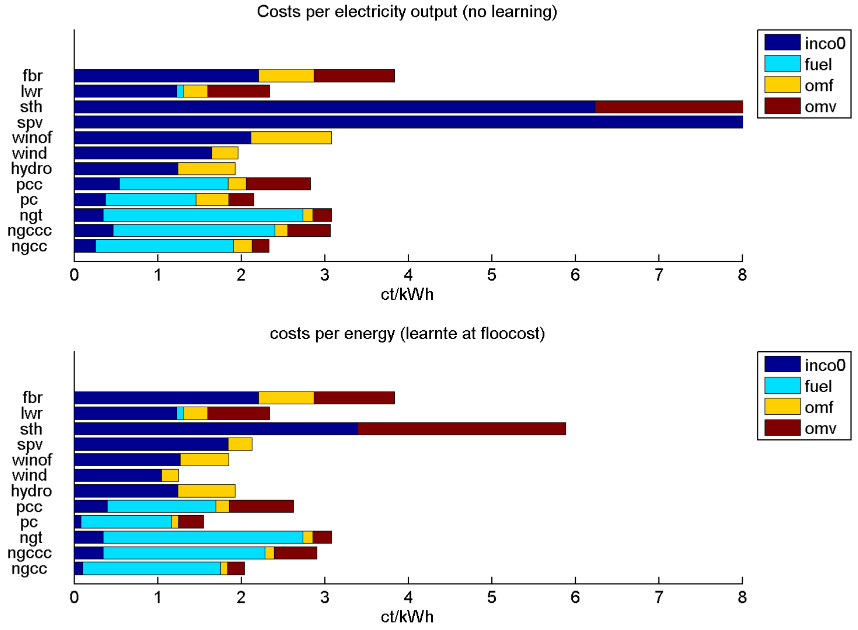


Figure 4.2.3 Costs for electricity output

4.3 Experiments

For examination of single parameter influences different experiments have been conducted.

An overview on the most important experiments is shown in table 4.3.1.

Scenario	Parameter	Value
BAU	maxprod	26.5
BAU	maxprod	133.0
450	maxprod	26.5
450	maxprod	133.0
450	inco0	1100
450	inco0	1900
450	inco0	2100
450	inco0	2500

Table 4.3.1 Parameter variation

Furthermore parameters `omeg` (depreciation factors, lifetime) and `learn` (learning rate) were varied. According to uncertainties in literature a lifetime of 20 years was implemented (standard: 25 years) and a learning rate of 0.2 (standard: 0.12).
But neither variation of `omeg` nor of `learn` showed any significant changes in the results.

4.3.1 Experiments on BAU

Variation of potential

As determining a certain value for the global offshore wind energy potential was quite difficult so far and furthermore the value strongly depends on the definition of the potential it is interesting to examine how the role of offshore wind energy changes with varying potential.

If the potential is doubled in genEris offshore wind energy strongly competes with pulverised coal even on terms of business as usual development, as figure 4.3.1 shows. It furthermore displaces energy from solar photovoltaic in the long run.

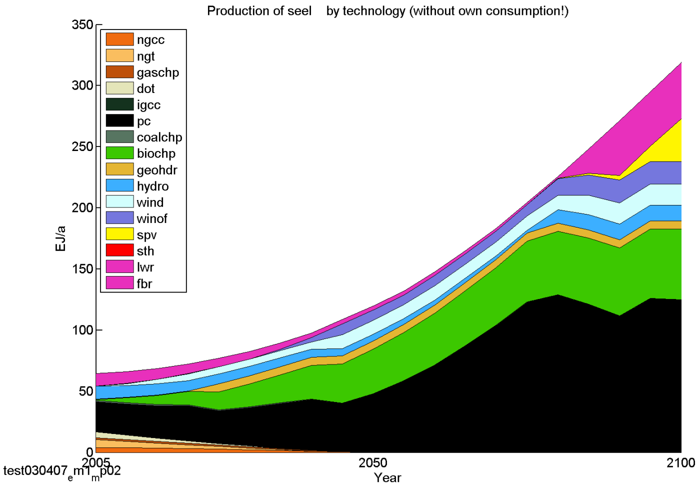


Figure 4.3.1.1 Business as usual, doubled potential

Impressing changes occur when the potential is increased tenfold. This value of potential can be interpreted as a technical potential ignoring restrictions due to sea use competitions, or asthetic aspects for instance.

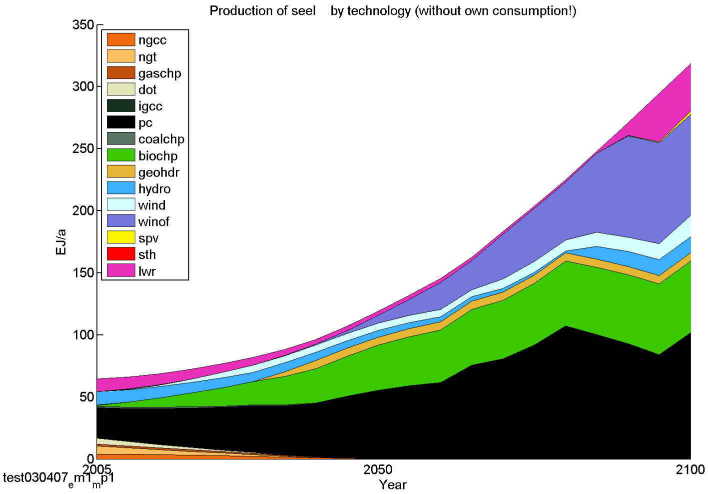


Figure 4.3.1.2 Business as usual, 10 times higher potential

Variation of the potential shows a strong dependence of offshore wind energy use from the potential. According as the potential is defined, offshore wind energy can play a major role especially in the long run. It also shows how important political values could become for offshore wind energy development, as restrictions taken into account might be dependent on political decisions.

4.3.2 Experiments on 450 ppm constraint

Variation of potential

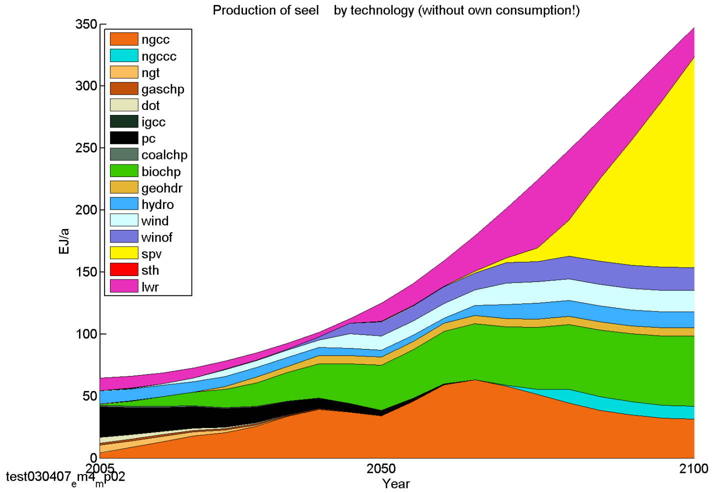


Figure 4.3.2.1 Policy scenario, doubled potential

Doubling the potential offshore wind energy again competes with `ngccc`, `hydro` and `spv` (as shown in figure 4.3.2.1).

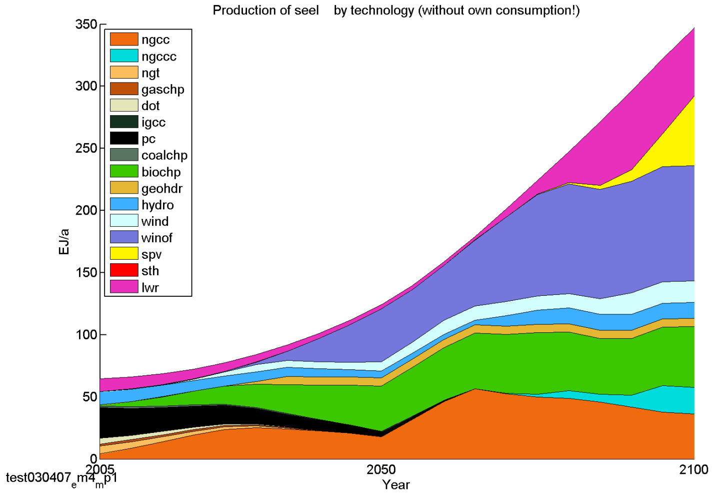


Figure 4.3.2.2 Policy scenario, potential 10 times higher

In the 450 ppm scenario as well as in the business as usual scenario the use of offshore wind energy increases significantly in the transition period and especially in the long run if the potential is defined ten times higher. Thus the share offshore wind energy can contribute is strongly related to its potential.

4.3.3 Variation of specific investment costs

The contribution of offshore wind energy to the energy mix is also dependent on the specific investment costs. Variation of investment costs show that if the costs were of the same level as costs for onshore turbines offshore energy would be implemented extensively already in 2020. Offshore wind energy would be less considered if investment costs rose above 2,000 $/kW. If investment costs exceeded 2,500 $/kW offshore energy was not competitive.

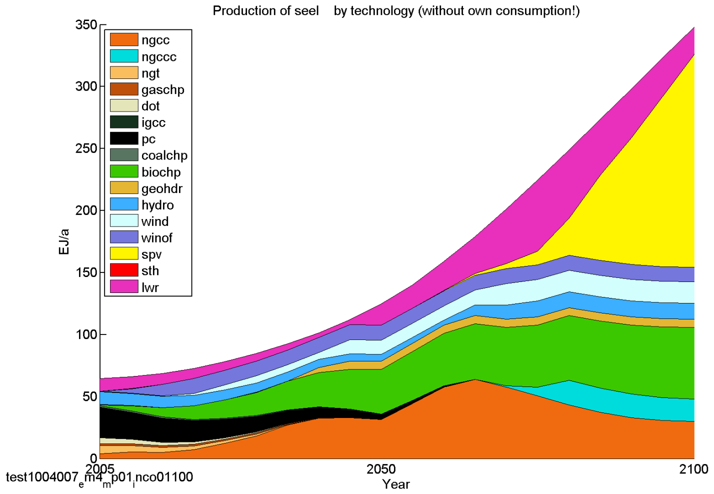


Figure 4.3.3.1 Policy scenario, specific investment costs: 1,100 $/kW

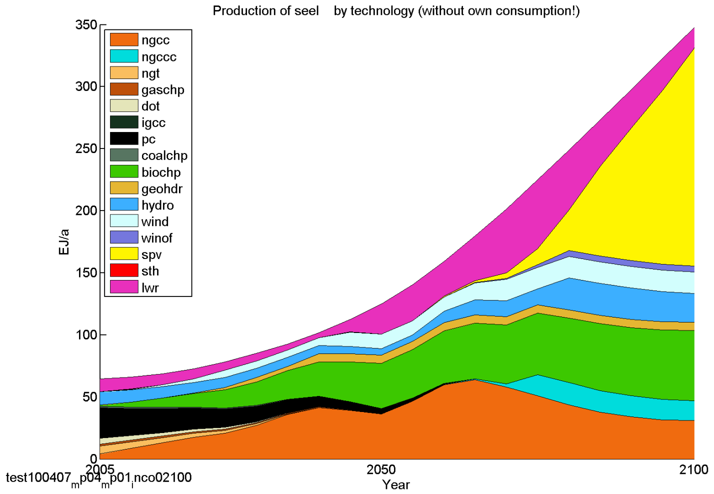


Figure 4.3.3.2 Policy scenario, specific investment costs 2,100 $/kW

4.4 Comparing results to projections of the Global Wind Energy Outlook 2006

In their Global Wind Energy Outlook 2006 Greenpeace and the Global Wind Energy Council (GWEC) examined three scenarios on future wind power implementation. Their core results predict that wind power could supply 17.7% (15 EJ/a) of the world's electricity by 2050[2]. [12]
This result corresponds to the value genEris calculates for 2050 (if the standard parameter for offshore wind potential (13.3 EJ/a) is implemented): on- and offshore wind energy would supply 14.2% of the worlds electricity needs respectively 17.03 EJ/a.

If the offshore wind potential is doubled (experiment 1, policy scenario) in genEris the result corresponds approximately to the results of the GWEC's 'advanced' scenario.
While the BAU case with the standard offshore potential (13.3 EJ/a) meets the results of the GWEC's 'reference' scenario.

4.5 Role of offshore wind energy regarding mitigation costs on terms of nuclear phase out

Examination of the objective value shows a significant influence of offshore wind energy implementation on mitigation costs under nuclear phase out.
Nuclear phase out means that no additional capacity will be installed and existing capacities run of according to the depreciation scheme.
The mitigations costs are additional energy costs that occur when the 450 ppm constraint is to be fulfilled (compared to the business as usual case).
Previously calculated results state an increase of mitigation costs of 4.62% under nuclear phase out.
Without additional constraint on `lwr`, `lwr` contributes an important share of electricity generation especially in the period of approximately 2050 to 2080. In case of nuclear phase out, it is replaced in the mentioned period by `ngccc` (amongst others). In contrast to `spv` with its high initial investment costs, `winof` can be applied already in approximately 2050 to substitute `lwr`. Due to the lower electricity generation costs of `winof` (compared to `ngccc`), the mitigation cost increase is substantially decreased to 1.02%.
This means offshore wind energy delivers another cost-efficient alternative if nuclear power is to be replaced.
Table 4.5.1 shows the model's results when offshore wind energy is included.

---

[2] Greenpeace / GWEC definition of scenarios: 'reference': most conservative (data source: International Energy Agency (IEA)),
'moderate': considers political support on renewable energies,
'advanced': most ambitious, based on data that support a wind energy contribution of 12% in 2020

Scenario	Energy system costs	Mitigation costs
450 ppm	210423.54	
BAU	198998.29	
		11425.25
450 ppm – nuclear off	211380.91	
BAU – nuclear off	199839.22	
		11541.69

Difference mitigation costs 'with nuclear' – 'nuclear off': 116.4
Relative mitigation costs increase: 1.02 %

Table 4.5.1 Mitigation costs under nuclear phase out

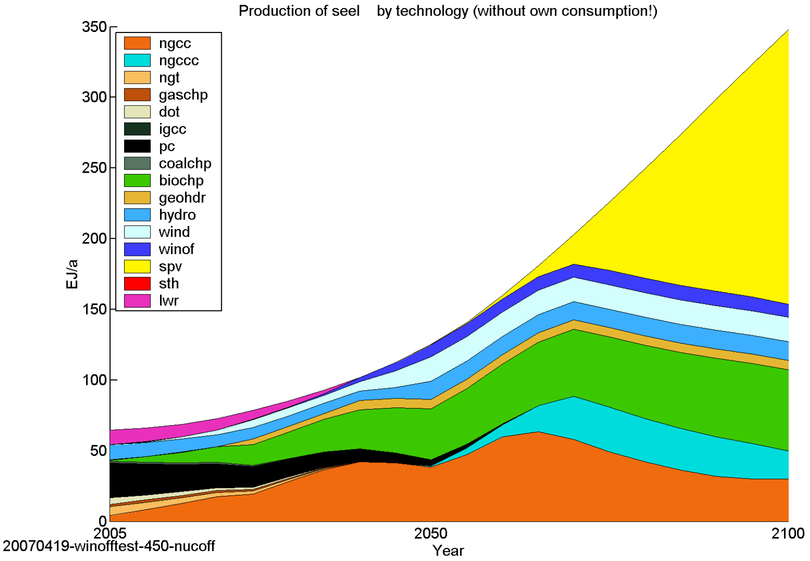


Figure 4.5.1 Policy scenario, energy mix on terms of nuclear phase out

5. Conclusions and recommendations on future research

Over the past decade the global market for wind energy has expanded faster than other renewable energies. The possibility of locating wind turbines in the sea bed has opened up new options for wind energy.

Political guardrails have been defined to mitigate climate change. To meet these targets the energy strategy is rethinked and focus turns to energy supply from renewable energies.

As this study shows offshore wind energy is a competitive energy source and can contribute a certain share to avoid CO_2 emissions, especially in the long run.

Offshore wind energy has been introduced into the energy system model genEris, parameters defined and fitted into the context of the model. During several experiments the influence of parameter variations within uncertainty ranges has been tested.

Yet installing turbines in the sea is more expensive than installation of onshore turbines. However, the model shows the increasing importance of the innovative offshore technology as costs decrease due to learning effects. The results furthermore document a strong dependence of offshore wind energy use from the considered potential. Taking into account a technical potential neglecting socio-economic and other restrictions offshore wind energy plays an important role even on terms of business as usual development.

This issue points at recommendations on future research. As offshore wind energy is quite a young technology and assumptions on the global potential still vary to a great extent it might be helpful defining an own estimation on the potential (based on meteorological data and information on sea bed topography) or view future assumptions in literature.

Furthermore the issue of grid connection has not been considered in the model yet.

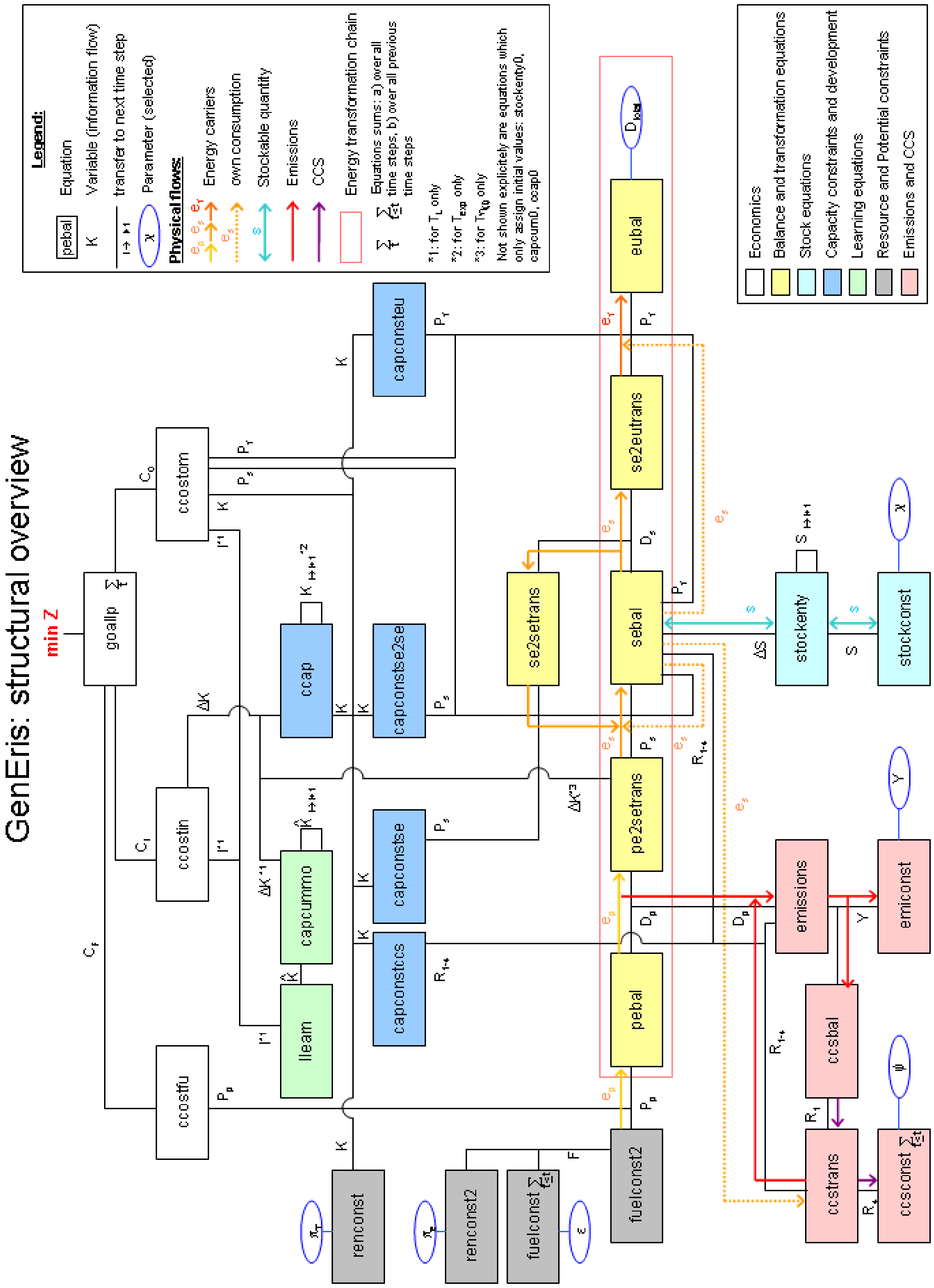
During this study the costs for grid connection have been represented indirectly by the grades (scaling of load factors). However, costs for grid connection might be separated from investment costs for offshore turbines in future, if responsibility is transformed to the grid offering industry. This is due to political decisions.

Special focus was put on the meaning of nuclear power. Debates on mitigating CO_2 emissions often point out nuclear power as one option of reducing emissions.

Previously genEris calculated a mitigation costs increase of 4.62% if nuclear power is phased out. This study showed that – taking offshore wind energy into account – additional mitigation costs increase by just 1.02% on terms of nuclear phase out.

Appendix

A.1 Overview of the algebraic structure of genEris



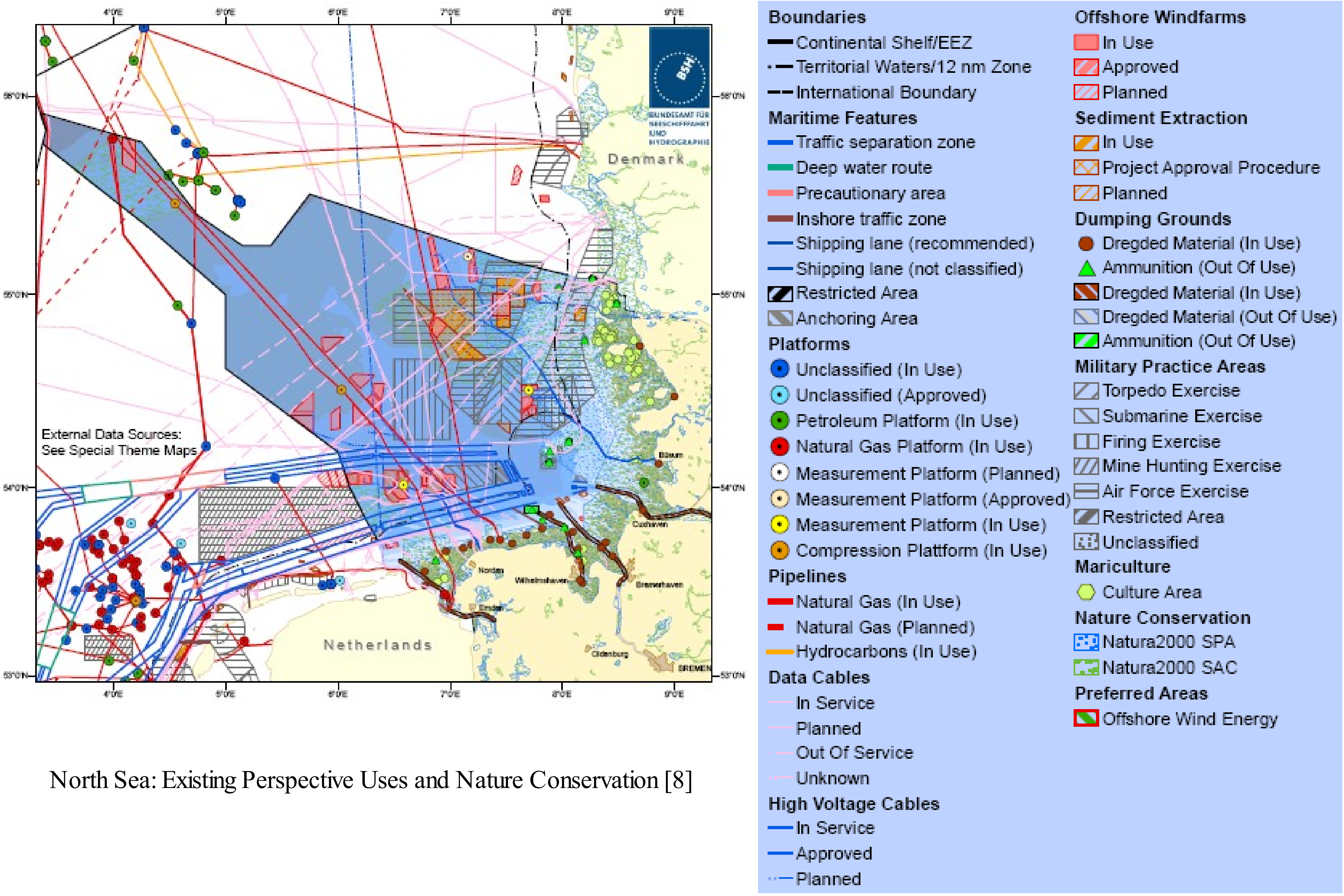
A.2 Excerpt from genErisListEqu.inc

Short explanation of equations

```
goallp         "definition of the objective function"

ccostfu        "costs of fuels"
ccostom        "costs of o&m"
ccostin        "costs of investment"

ccap0          "initial condition for capacities"
ccap           "definition of available capacities"
ccapvin        "definition of available capacities vintage"
ccapexp        "definition of available capacities
               exponential depreciation"

capconstse     "capacity constraint for secondary energy (SE)
               production"
capconstse2se  "capacity constraint for SE to SE
               transformation"
capconsteu     "capacity constraint for EU production"

capcum0        "cumulative net capactiy"
capcummo       "increase of cumulative net capacity"
capcum0learn   "cumulative net capactiy for learning
               technologies"

pebal          "balance of primary energy (PE)"
sebal          "balance of SE"
eubal          "balance of final energy (EU)"
fuelbal        "balance for fuels"

pe2setrans     "energy tranformation PE to SE"
se2eutrans     "energy tranformation SE to EU"

se2setrans     "energy transformation SE to SE"
sum2tetrans    "addition of energy types"

fuelconst2     "constraint on cumulative fuel use"
fuelconst      "constraint on fuel use"

renconst       "constraint on annual production"
renconst2      "constraint on annual production"

emissions      "determination of emissions"
emiconst       "emission cap"

ccsbal         "balance equation for ccs"
ccstrans       "transformation equation for ccs"
```

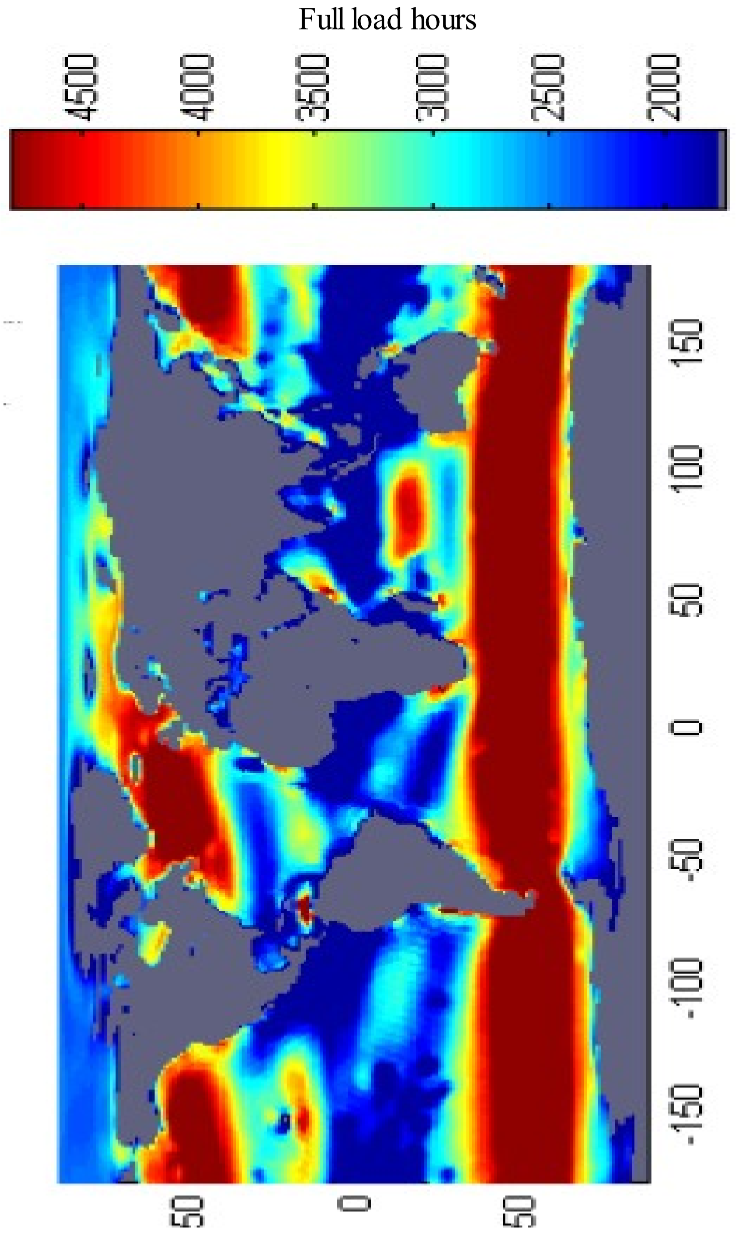
```
capconstccs    "capacity constraint for ccs"
ccsconst       "ccs constraint for sequestration
               alternatives"

llearn          "calculation of investment cost for
               learning technologies"

stockenty      "calculation of stocks"
stockenty0     "initial value for stocks (at t=t0)"
stockconst     "constraint on stock maximum for quantities"

deltacapconst  "constraint on maximum annual capacity
               addition"
emiconst2      "maximum emission path constraint"
```

A.3 Sea use competition, North Sea



North Sea: Existing Perspective Uses and Nature Conservation [8]

A.4 Global average full load hours



Global average full load hours, related to average wind speeds [4]

A.5 Standard parametrisation

Parameter	Value	Unit
inco0	1700	$ per kW
mix0	0.0000136	none
eta	0.45	none
nu	0.92	none
omf	0.05	none
incolearn	680	$ per kW
ccap0	0.0035	TW
learn	0.12	none
omeg	1.000	none
	0.975	
	0.850	
	0.700	
	0.500	
cap0	16.590	none
	5.603	
	1.000	
nur	0.496	none
	0.465	
	0.440	
	0.433	
	0.411	
	0.402	
	0.383	
	0.372	
	0.355	
	0.347	
	0.321	
	0.296	
	0.055	
maxprod	2.18	EJ/a
	2.08	
	0.14	
	0.29	
	1.11	
	1.01	
	1.35	
	0.04	
	0.60	
	0.48	
	1.07	
	1.64	
	1.33	

A.6 Excerpt from genErisSets.inc

where technologies are defined; explanation of abbreviations

```
sets

te      energy technologies

ngcc                natural gas combined cycle
ngccc               natural gas combined cycle with capture
ngt                 natural gas turbine
gastr               transformation of gases
gaschp              CHP using gas
gashp               HP using gas
dot                 diesel oil turbine
igcc                integrated coal gasification cc
igccc               integrated coal gasification cc with
                    capture
pc                  pulverised coal power plant
pcc                 pulverised coal power plant with capture
coalchp             chp coal
biochp              CHP bio
geohdr              geothermal electric hot dry rock
geohe               geothermal heat
hydro               hydro electric
wind                wind power converters
winof               wind power converters - offshore
spv                 solar photovoltaic
sth                 solar thermal electricity generation
solhe               solar thermal heat generation
lwr                 light water reactor (nuclear)
```

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