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Sustainable energy system pathways: Development and assessment of an indicator-based model approach to enhance sustainability of future energy technology pathways in Germany (SEnSys)

Kai Nino Streicher

Master's programme
Science for Sustainable Development

Master's Thesis, 30 ECTS credits

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2014

’ Prediction is very difficult, especially about the future.’

By Nils Bohr or Mark Twain

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List of Abbreviations

BAU	Business-as-Usual
BMU	Federal Ministry of Environment (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit)
CMR	Cumulated Material Requirement (non-renewable)
CSD	Commission on Sustainable Development
CSP	Concentrated Solar Power
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
ELCALC	Electricity market model (DLR)
EUMENA	Europe, Middle East and North Africa (region)
FOM	Operation and Maintenance
GEMIS	Global Emissions Model for integrated Systems
GHG	Green House Gas
GUI	Graphic User interface
GW	Giga Watt (power)
GWh	Giga Watt hour (energy amount)
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IINAS	International Institute for Sustainability Analysis and Strategy
IPCC	Intergovernmental Panel on Climate Change
kWh	kilo Watt hour (energy amount)
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Electricity
MENA	Middle East and North Africa (region)
MW	Mega Watt (power)
NTC	Net Transfer Capacity
PV	Photovoltaic
REMix	Renewable Energy Mix for sustainable electricity supply (model)
SD	Sustainable Development
SEnSys	Sustainable Energy Systems (model)
SQL	Structured Query Language
TCOE	Total Cost of Electricity
TWh	Tera Watt hours (energy amount)
VBA	Visual Basic for Applications (script language of MS Office)
WACC	Weighted Average Costs of Capital
WCED	World Commission on Environment and Development

1. Abstract

After the nuclear fallout in Japan, Germany decided to back out from nuclear energy while at the same time changing the energy supply from fossil to renewable sources. This elaborate plan, known as *Energiewende*, will require significant economic and structural efforts that will have profound impacts on the environment and society itself. It is therefore crucial to identify possible technological pathways that can lead to a renewable energy supply, while reducing negative impacts on a holistic scope.

In order to analyse alternative energy technology scenarios in Germany, this thesis focuses on the development of an indicator-based numerical Sustainable Energy Systems (SEnSys) model approach. Other than previous approaches, the SEnSys model considers full aggregated impacts of technological pathways leading to future configurations. With the help of an exemplary case study on two alternative energy technology scenarios (*Trieb1* and *Trieb2*), the feasibility of the SEnSys model in evaluating sustainability is subsequently assessed.

The results can affirm the findings of previous studies concerning lower economic and environmental impacts for scenario *Trieb2*, with small shares of renewable energy imports, compared to scenario *Trieb1* based on only local but fluctuating renewables. Additionally, the results are in accordance with other relevant studies, while offering new valuable insights to the topic. Given a comprehensive revision of the identified uncertainties and limitations, it can be stated that the SEnSys model bares the potential for further analysing and improving sustainability of energy technology scenarios in Germany and other countries.

Keywords: *Energy Scenarios, Energy System Modelling, German Energy Transformation, Sustainable Energy Systems, Sustainability Indicators*

2. Introduction

From 2010 to 2011 the world was shocked by several severe events, which ranged from the fatal *Deepwater horizon* oil spill in the Gulf of Mexico, over armed conflicts in oil-producing countries like Libya and Syria to the hazardous nuclear accident of Fukushima, which all clearly demonstrated the necessity of an overall system change in energy supply (IEA, 2012a).

In particular the nuclear fallout of the Fukushima Dai-ichi power plants in Japan and its disastrous impacts on the environment and the population in 2011 (Buesseler et al., 2011), was leading to a rethinking in terms of secure energy supply in Germany, even among the former political supporters of nuclear energy (Droste-Franke et al., 2012). In result of this, the German Federal Government decided to back out of the nuclear energy programme to the end of 2022, while still holding on to their pledges on green-house gas emissions.

This substantial national energy transformation, widely known as *Energiewende*, marks a revolutionary cornerstone in the history of the German energy politics. Never before had all major political parties agreed on the necessity to abolish nuclear power and instead invest in high shares of renewable energies. The *Ethic Commission* initiated by the Federal Government and lead by the former minister of environment Klaus Töpfer, arrived at the conclusion that *the back out of the German nuclear energy programme as quickly as possible, is well reasoned by ethic principles, eligible from the commissions point of the view and in compliance with the realization of the measures possible* (Töpfer et al., 2011, p. 13).[1] In their closing words, the commission sees '*the German society as a whole already on the way to reach a future, where nuclear power will be dispensable*' for the nation's energy supply (Töpfer et al., 2011, p. 12).[2]

While the goal of a carbon and nuclear free energy supply in Germany is widely shared, the actual conversion and the final specifications of this future energy system are lively debated on a broad scale both in politics as well as among interdisciplinary scholars. To name a few examples, Droste-Franke et al. (2012) was investigating the balancing of renewable energies in the German electricity system with the help of storage, demand side and network technology extension, Kost et al. (2013) looked at the economic implications of the energy transformation, and finally Nitsch et al. (2012a)[3] were providing comprehensive scenarios on future energy systems for the German Federal Ministry of Environment (BMU).

In that way energy transformation is considered as a key point in the national as well as global sustainability debate, as stated in the famous *Brundtland* report on *Our Common Future*: '*a safe and sustainable energy pathway is crucial to sustainable development*' (WCED, 1987, p. 18). The WCED (1987) is also convinced that future energy systems will require a transformation to a generation based on renewable sources, as well as that '*the generation of nuclear power is only justifiable if there are solid solutions to the unsolved problems to which it gives rise*' (WCED, 1987, p. 18). Given that, it is obvious that the planning and layout of the German energy transformation requires (and will require further on) a holistic understanding and deliberate evaluation of possible implications for all the sectors of Sustainable Development (SD), namely the environmental, social and economic sector.

One of the particular challenges when it comes to a system change in energy systems and in particular for renewable power generation in Germany, is the prediction of availability along with the '*intermittent nature of sources, such as wind and solar radiation*' (Droste-Franke et al., 2012, p. 37). While higher shares of fluctuating renewable sources impair the stability of the power system as a whole, auxiliary technologies - like storage and network extension - can reduce the negative impacts of fluctuating renewables on the national power supply. However, their construction and operation would require a not negligible amount of resources and might have strong impacts on the natural and social environment. Furthermore, the secured supply criteria of the electricity system would demand for high capacities of renewable and back up capacities, due to the small secured capacity that local renewables can supply. To address this problem, Trieb et al. (2006) are proposing an alternative solution based on a relatively small share of imports from flexible renewable energies, to decrease the necessity of additional storage and inner-European grid capacity. According to the plan of Trieb et al. (2006), Trieb (2013a) and Hess (2013), high efficient Concentrated Solar Power (CSP) plants in the desert area of countries

[1] Own translation. Original quote in German: '*Der schnellstmögliche Ausstieg aus der Nutzung der Kernenergie ist ethisch gut begründet, aus Sicht der Kommission geboten und nach Maßgabe der Umsetzung der Maßnahmen möglich*' (Töpfer et al., 2011, p. 13)

[2] Own translation. Original quote in German: '*[...] Deutschland in der ganzen Breite der Gesellschaft längst auf dem Weg in eine Zukunft, die die Nutzung der Kernenergie verzichtbar macht.*' (Töpfer et al., 2011, p. 12)

[3] A English summary of the study can be found in Nitsch et al. (2012b)

like Morocco and hydro power from Norway, could be directly connected via special High Voltage Direct Current (HVDC) transmission lines to the main consuming centres of Europe or Germany respectively (see detailed description in Section 4.4.2). But similar to the additional storage and grid connection mentioned earlier, the construction of extensive HVDC lines and auxiliary technology would have a noticeable impact on the environment and society itself, and would furthermore require high and potentially risky investments in new technology solutions. As it can be seen from these examples, it is crucial to further assess the implications of different technological scenarios and pathways for the German energy transformation.

This thesis therefore aims at the development and a subsequent assessment of an indicator-based numeric model that can, to some extent, represent the different aspects of SD in the German energy system.[4] The idea is to create a computer-based model that allows to assess future implications of choices in energy technologies, at least concerning the most relevant indicators.

In order to develop the so called Sustainable Energy Systems (SEnSys) model, several research objectives need to be addressed. To begin with, the model development requires a selection and successive data acquisition of relevant SD indicators for energy technology pathways. Along with that, it has to be determined how the specific indicators can be calculated and accordingly processed in the model, while representing the complexity of the electricity system.

Finally, this thesis will assess and accordingly discuss which new insights the SEnSys model can provide, with the help of an exemplary case study, for the sustainability discussion concerning the German energy system. This leads to the main objective of this thesis, which subsequently assesses the feasibility of this particular model approach for evaluating or even enhancing the sustainability of future energy options in Germany or other countries.

[4] As for the scope of this study, only the electricity sector is analysed, whereas interaction with other sectors is considered as additional load.

3. Background

In order to understand the development of the Sustainable Energy Systems (SEnSys) model, it is helpful to provide some basic and related background information on relevant topics. As for this chapter, the following topics are covered briefly:

- Introduction to the basics of system thinking, the scenario method and modelling approaches
- General information on energy and electricity system, as well as brief background information on the German energy system

For further or more advanced information about the specific topics it is referred to the general literature presented in each chapter.

3.1 System Thinking and modelling

System and modelling approaches are used nowadays worldwide for assessing question related to environmental or sustainability concerns (Olsson and Sjöstedt, 2004, p. xii). This chapter therefore provides an overview on the basics of system thinking as well as the scenario and modelling approaches as a particular application of system thinking.

3.1.1 General System Theory

Emerging from military operations research after World War II, *Ludwig von Bertalanffy* is considered to be one of the pioneering scholars of the modern General System Theory approach as stated by Olsson and Sjöstedt (2004, p. 7). Bertalanffy (1969)'s book *General System Theory: Foundations, Development, Applications*, was laying the corner stone for a whole new field of science, sometimes even referred to as a form of social movement among scientists of that age. However, it is worth mentioning that beside his theory, various other system approaches exist. From the antique Aristotle ('*the whole is greater than the sum of its parts*') over ecosystem examinations to the comprehensive social theories of for instance Luhmann (1970), system theories cover a wide range of scientific fields and approaches. However, as a presentation of all different approaches would be beyond the scope of this thesis, the following introduction to General System Theory is mainly based on the descriptions of Olsson and Sjöstedt (2004).

The core of the general system approach as understood by Olsson and Sjöstedt (2004, p. 1), is the idea to describe and accordingly gain information about complex structures and processes which occur in the real world. This is done by analysing and often simplifying the relevant input and output flows, as well as the interactions of the elements inside the chosen system borders. The overarching system can be connected or be a part of other systems, such as the internal elements can be a subsystem in themselves (Fig. 3.1).

Furthermore, General System Theory is interested in the dynamics or feedback mechanism of particular systems, in particular when the system is stressed by external or internal changes (Olsson and Sjöstedt, 2004). While in open systems different initial conditions and pathways can lead to the same future state, some systems feature a *hysteresis*, which means that the system

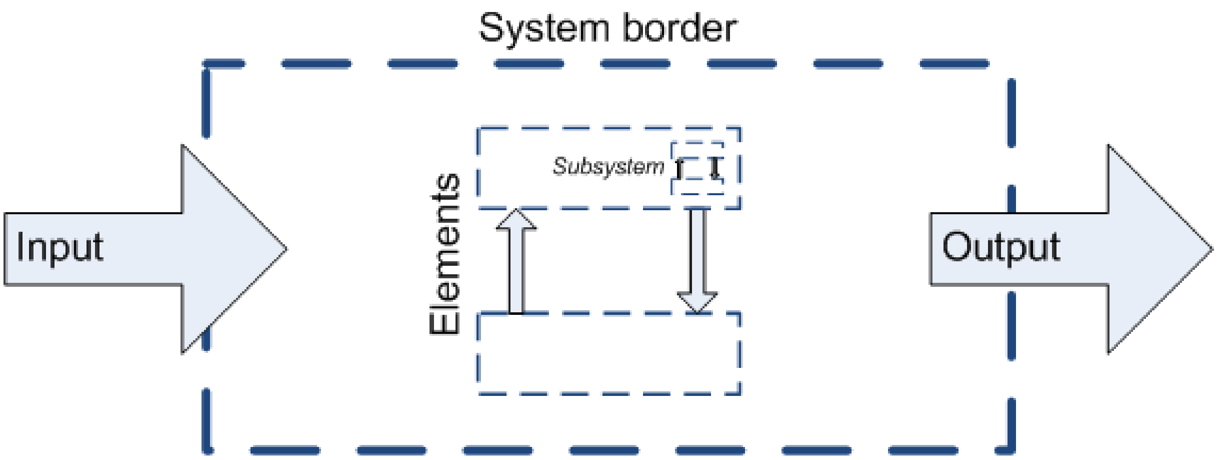

Fig. 3.1. Theoretical concept of general system theory

follows a certain path which was defined by its earlier state. This also called *path dependency* is a crucial factor when it comes to the transformation of existing systems into a new state, such as the transformation of a fossil based energy system to an energy supply mostly based on renewable sources. Moreover, Olsson and Sjöstedt (2004) state that certain changes in systems can lead to an irreversible shift of system dynamics. This so-called *point of no return* marks the critical threshold where the resilience of the system is exceeded, with sometimes unforeseeable consequences. To make matters worse, the observable impacts on the natural system due to changes can be delayed in some cases and accordingly struck by surprise. The challenges and implications of path dependency and resilience on energy system transformation will be discussed in more detail in the following chapters.

Being a rather descriptive method, General System Theory provides advantages for both scientists as well as political actors (or any other kind of decision maker) as it allows simplifying complex questions for interdisciplinary research and gives some form of credibility to the outcome (Olsson and Sjöstedt, 2004, p. 14). Hence, the method is often used in decision making process for any kind of socio-economic or technical system on global, national or local levels. However as mentioned by Olsson and Sjöstedt (2004), the selection of system borders, time spans or scales can have a significant impact on the results of the system analysis, leading to a nearly infinite variety of possible representations of the same natural phenomena, which accordingly challenges the credibility of the whole system approach.

3.1.2 Scenario approach

Being an integral part of system thinking, the evolving of the scenario approach can also be traced back to military operations during World War II (Ringland, 2006). By imagining and playing through potential future situations in the war, the military commanders could anticipate and accordingly prepare feasible tactics to counter any possible movement of their enemies beforehand. The potential of being prepared for future changes was later acknowledged in the business world, in particular by the oil company Royal Dutch/Shell, which used a scenario approach in the 1970s for a comprehensive risk assessment on a sudden rise in oil prices in Arabic countries. By anticipating the global oil crisis, Shell was able to react significantly faster than their unprepared competitors, giving them a remarkable competitive advantage. Boosted by this success, scenario thinking became an integral part of the management process in Shell and other companies worldwide (Grundy, 2008). Nowadays not only the business world, but also scientists are using the scenario approach for illustration and implications of future changes, such as the prominent example of the climate change scenarios by the Intergovernmental Panel on Climate Change (IPCC) on carbon dioxide emissions and global temperatures (IPCC, 2014).

Peter Schwartz, one of the influential actors in scenario thinking, states that the term *scenario* itself goes back to the old name for a script used in stage performance or in the film industry (Schwartz, 1996). He further defines scenario thinking as '*a tool for ordering one's perceptions about alternative future environments in which one's decisions might be played out*' (Schwartz, 1996, p. 4). An alternative definition of scenarios is provided by Trieb et al. (2006):

> *'A scenario is not a prediction. A scenario is one of many possible ways to reach a certain future situation. It will require a social and political effort to reach that goal, it will not happen spontaneously.' (Trieb et al., 2006, p. 111)*

In that way, scenarios can help to examine and compare possible future outcomes as well as to find appropriate ways to reach them. In general, scenarios should be '*internally consistent, logical and plausible constructs of how the future might unfold'*, as stated by the International Energy Agency (IEA) in their report on *Scenarios for a Sustainable Future* (IEA, 2004, p. 20). The IEA is further explaining that scenario building consists of five principal phases. First the problem itself needs to be defined, to know which information, opinion or data needs to be gathered in the second phase. The data acquisition is followed by the identification and subsequent ranking of key factors in correlation to the problem defined. In the final phase, all the information and factors are used for the so-called *storytelling*, which is the main part of the scenario building. The storytelling can be supported by mathematical models, as will be explained in more detail in the next chapter. In addition to that, scenarios are usually divided into four main types of scenarios, according to IEA (2004):

- Business-as-Usual (BAU) scenarios, to project a present trend into the future
- Policy scenarios, to examine the impacts of a certain policy action
- Exploratory or descriptive scenarios, to compare different (technical) configurations
- Normative or descriptive scenarios, to define a certain future configuration

As for this thesis, the two last types are the most appropriate, as they allow to set certain (sustainability) goals for a future energy systems and to find feasible technical pathways leading to the chosen situation. This is in accordance with the IEA (2004) study, that was also using a normative scenario to set up a visions of a sustainable energy system and to discuss what measures would be required now and in the future to reach that goal.

While on one hand Gallopin (1997) states that '*scenarios can offer guidance to the national and international policy community for converting the sustainability principle into practical policies and actions*', it should also be mentioned that on the other hand the scenario approach itself is rather subjective to the values of their creator and their respective world view (Gallopin, 1997, p. 5).

3.1.3 Modeling approach

Due to the complexity and interdependency of energy systems, the evaluation of future scenarios is most of the time coupled with a mathematical model of the energy flows and relevant technical, economic or social parameters (Weber and Martinsen, 2013). In that sense, mathematical models are an effective way to examine complex and interconnected systems, such as the energy supply of a country, according to Gallopin (1997). Given the various technologies and stakeholders involved in the process, a computer based simulation can be helpful to evaluate possible responses of the system to certain changes. This is in particular true for dynamic systems that imply changes over time, such as the availability of renewable resources. Among others, an extensive energy system model might incorporate one or more of the following aspects, as listed by the IEA (2012a, p. 61):

- Technological progress
- Market development
- Institutional, regulatory and legal frameworks
- Acceptance by social framework

While many scholars in the field of energy system analysis promote the use of models, it should be mentioned that the method meets some criticism. The IEA (2004) for instance points out that dramatic changes and qualitative aspects - such as social power relations and respective frameworks - are difficult if not impossible to simulate. Along with that, mathematical models bare the risk of uncertainties and error sources, again in particular when it comes to '*representing complex and open human systems*' (Gallopin, 1997, p. 7).

3.2 Energy systems

Energy is an integral part of life on earth, as all biochemical processes require some form of energy. The same is true for any socio-economic systems, from industries to single households. But as mentioned earlier, the generation of energy and all related upstream chains can have a significant impact on local and global ecosystems and accordingly on the livelihood of people. Given that, it is crucial to plan and design national energy systems on a long term scale, as energy technologies and their implications usually account for decades to centuries (IEA, 2004, p. 13).

3.2.1 Electric energy

Among different forms of energy, electricity is one of the most versatile as it can be transformed into any other kind of energy, such as mechanical or thermal. However, this advantage comes with a major drawback, as electricity cannot be saved directly and has to be produced in the exact same moment of use. If the voltage and frequency of the electricity system are reaching too high or low levels, blackouts can occur, which might lead to a total breakdown of the whole system (IEA, 2012a). Thus, an adequate balancing of power generation and consumption is required by the means of anticipatory resource planning, demand side management, network extension for spatial balancing and storage of excessive energy (Droste-Franke et al., 2012, p. 4).

When it comes to renewable energies, these challenges become even more severe as most of the renewable energy sources (in Europe) are spatially and temporally fluctuating. Therefore future energy systems will have high requirements for flexible energy technologies, instead of the base-load technology used nowadays (IEA, 2012a). With higher shares of fluctuating renewables, the full load hours of conventional power plants decrease while the respective operating costs increase, making them uneconomical in the long run. Hence, adequate market mechanisms might become important in the future to ensure sufficient reserve capacity for times of low renewable yields.

3.2.2 German energy system

Germany is in the worldwide focus of the renewable energy discussion, due to its elaborate plans to transform its entire energy system to low carbon production, while phasing out nuclear power at the same time. This so-called *Energiewende* is not only a technical challenge, but rather a socio-political process that involves various actors from politicians over energy providers to single citizens. In order to transform the German energy system, all those actors have to find a way to agree on common goals or frameworks and work collaboratively to reach them consequently.

Notwithstanding, the *Ethic Commission of the Federal Government*, initiated to broadly discuss the energy transformation, states that Germany could be the role model for a non-nuclear and mostly renewable energy transformation in an industrial country (Töpfer et al., 2011). Already since 1990, the politics in Germany support the use of energy generation from renewable sources, with such measures as electricity feed-in tariffs and direct government grants (Droste-Franke et al., 2012). This was resulting in a boom of non-hydro renewable energy technologies (mostly wind and Photovoltaic (PV)), and thus increasing the share of renewables in electricity consumption from 3.8% to 15.4% in 2010. Along with that, the Federal Government was setting itself comparably ambitious goals for Green House Gas (GHG) emission reductions, starting with a 40% reduction by 2020 up to 80-95% at the end of 2050 (Droste-Franke et al., 2012).

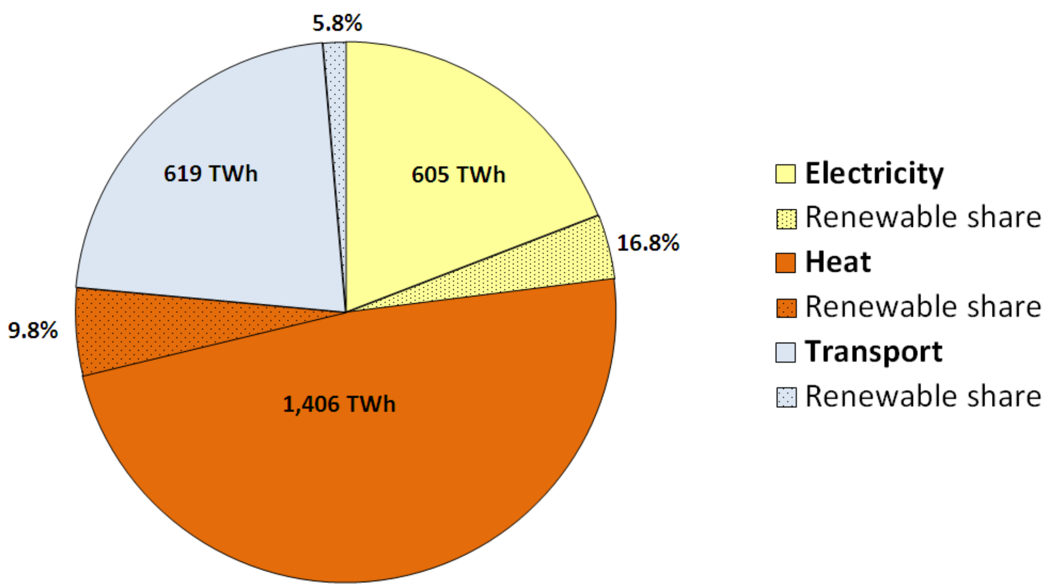

Fig. 3.2. Total final energy consumption 2010 in Germany by sectors, and their respective share of renewable sources (data from BMU (2011))

To put the energy transformation into the right context, it is helpful to have a look at relatively recent numbers of energy consumption. Despite its size, Germany - as a high technological and industrialized country - is among the world biggest consumers of energy. In the year 2010, with around 4,110 TWh, the total primary energy consumption of Germany ranked on the 6th position after Japan (6,402 TWh) and before Canada (3,793 TWh) according to EIA (2014). After noticeable transformation and distribution losses of around 36%, the final energy consumption accounted for approximately 2,600 TWh (BMU, 2011).

As indicated by Fig. 3.2, more than the half of the final energy in 2010 was consumed for heating purposes, while the electricity and transport sector both account for around 23% of the total final energy consumption. The highest relative share of renewable sources with 16.8% occurs in the electricity sector. In total more than 10% of the final energy in 2010 was coming from renewable sources. With high incentives and efforts in the electricity sector the share of renewables could be raised further in the last three years, so that in 2013 almost a quarter of the electricity produced was eventually coming from renewable sources (DESTATIS, 2014). In May 2014, renewable energy production reached momentarily 74% of the peak power demand, leading to negative market prices and setting an all-time record for the countries renewable power generation (Renewables International, 2014).

4. Materials and Methods

As mentioned in Chapter 2, the development of the SEnSys model in this thesis required several sub-tasks to be done. This chapter presents the materials and methods that were used to compile the model and finally make it run. The main steps in the development of the SEnSys model were:

- Selection and data collection for relevant energy related sustainability indicators
- Transformation of the complex energy system into a simplified numerical model, together with user interface and software solution
- Selection of an exemplary case study, for the assessment of the finished model

Except for the Electricity market model (ELCALC) model (see Section 4.3.2), all steps required for the development of the SEnSys model were part of the work for this thesis.

4.1 Identifying sustainability indicators

As for most studies in sustainability science, the general starting point of this system analysis was also represented by the famous quote of the so-called *Brundtland report* from the World Commission on Environment and Development (WCED) on *Our Common Future*:

> *'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' (WCED, 1987, p. 16)*

This widespread definition of SD is followed by a less-known secondary aspect called *idea of limitations*, which refers to the thresholds of social and ultimately natural systems. The WCED (1987) further defines this concept as a flexible approach that determines necessary limitations in relation to the '*present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities*' (WCED, 1987, p. 15). Based on this general concept, the analysis of sustainability goals in this study started by looking at critical thresholds in particular for Germany, which could be exceeded by the choice of technology pathways. This is in accordance with the study of Rockström et al. (2009b) who were identifying *Planetary boundaries*, to evaluate safe operating spaces for human activities. Their study revealed nine critical thresholds for the planet, whereas the nitrogen cycle and in particular the loss of biodiversity did already overshoot the estimated boundaries by far.

When it came to boundaries of SD, it was necessary to further define the principle understanding of sustainability in terms of critical thresholds. For this study, a weak sustainability approach was chosen, which can accept substitution of natural capital as well as impacts on the environment and social system, as long as their respective self-repairing ability is not exceeded (Olsson and Sjöstedt, 2004). This feature of a system to endure stresses up to a certain point is also referred to as *resilience* in the sustainability discussion (Pisano, 2012). Based on this concept, ultimate sustainability boundaries were determined, which are presented in Fig. 4.1.

The concept for this analysis defined the natural boundaries - our planet - as the overall limitations of development, similar to Rockström et al. (2009b). Subsequently, inside these natural borders,

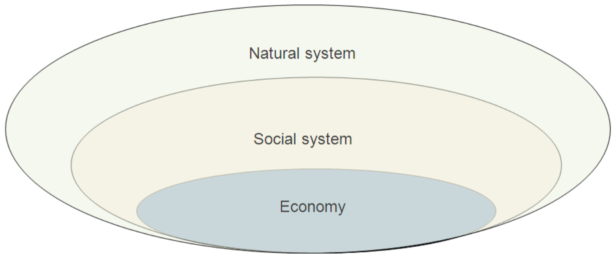

Fig. 4.1. Ultimate sustainability boundaries from a system perspective

all forms of social systems can exist; again able to replace natural capital but not to exceed the respective limitations. From the boundary point of view, the economic system can then be seen as a social construct that can exist inside the social system as long as society as a whole accepts it. It is worth mentioning that this concept is valid for system boundaries and does not reflect a weighting when it comes to sustainability indicators, where economic factors could be limiting. However, in the long term, slow natural processes such as the nutrient circle define the final resilience of a system (Olsson and Sjöstedt, 2004).

4.1.1 Literature review on sustainability indicators for energy technologies

To identify sustainability indicators for energy technology pathways, a literature review on general as well as energy specific SD indicators was compiled. The resulting indicators were then evaluated in terms of whether they can be influenced by the choice of energy technology from a European - or in particular German - perspective. It is worth mentioning, that the choice of indicators would be different in another context, such as for developing countries.

As a backbone for the indicator selection, this study was choosing the results of the *Work Programme on Indicators of Sustainable Development* compiled by the Commission on Sustainable Development (CSD) from 1994 to 2001 (DESA, 2007). From a total of 43 indicators based on the three pillars of SD and submerged into 14 categories, 18 indicators were identified as being directly related to the choice of energy technologies in Germany, as shown in Appendix A.1 - Fig. A.1.

To give some examples for the choice of indicators, indicator *III.12) health status and risks* was for instance chosen due to the negative impacts on public health that could emerge from energy generation, such as the burning of fossil fuels. As for environmental indicators, *XI.31) species* is for example related to the impacts on local ecosystems from the construction of energy technologies, such as wind power or hydro pump storage plants. Finally, for economic indicators, *XIV.42) waste generation and management* represents exemplary the negative impacts from toxic waste due to energy generation, such as radioactive waste from nuclear power.

While the list of DESA (2007) offers an international set of indicators, this study was also incorporating nation specific sustainability goals. One official source of such indicators is the SD strategy paper *Perspectives for Germany* from the German Federal Government (2002). Their list on sustainability indicators was later updated in the official *National Sustainable Development Strategy* of the Federal Republic of Germany in 2012 (German Federal Government, 2012). Similar to DESA (2007), energy technology relevant indicators were extracted from the German

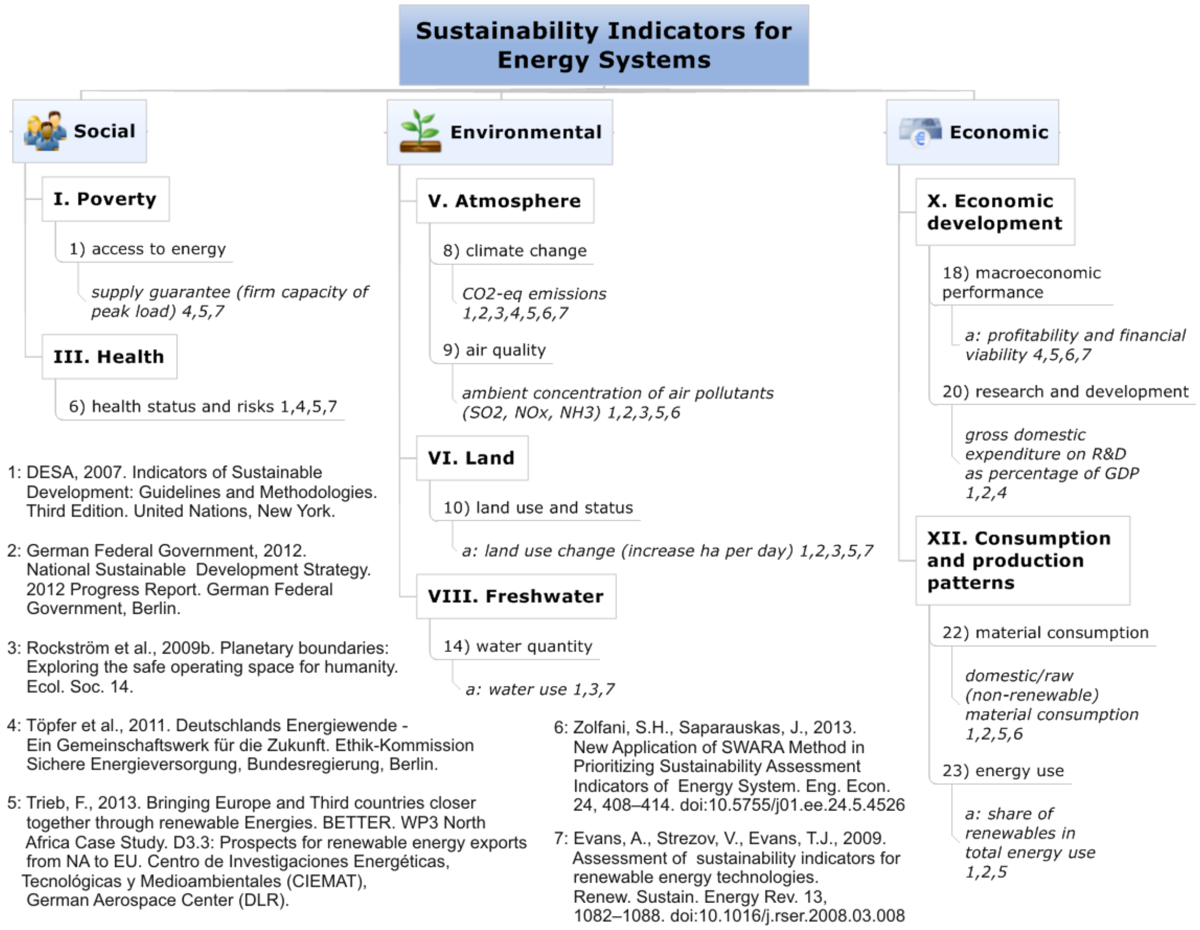

Fig. 4.2. Overview on common sustainability indicators for energy systems

Federal Government (2012) collection. The full list of indicators can be found in Appendix A.1 - Fig. A.2.

Beside these two official sources for sustainability indicators, one more general indicator set from the study of Rockström et al. (2009b) on *Planetary Boundaries* was added. Moreover, the scope of this indicator analysis included two specific indicator sets for Germany from Töpfer et al. (2011) and Trieb (2013a), as well as two more generic indicator sets for assessing energy systems by Zolfani and Saparauskas (2013) as well as Evans et al. (2009). In addition to that, own indicators (mostly social), based on discussions with interdisciplinary experts of the field from the German Aerospace Center (DLR), were included to supplement the collection. Fig. 4.2 provides an overview on the most common indicators, which were mentioned at least three times in the different sources.[1] A comprehensive list on the whole range of indicators is presented in Appendix A.1 - Fig. A.3.

[1] Indicators with analogue meaning were united in single indicators. For instance the *climate change* indicator from DESA (2007) was united in CO_2eq *emissions* indicator of other sources.

4.1.2 Selection process of sustainability indicators

The indicators identified in the previous chapter were further analysed for their potential as exemplary indicators for the SEnSys model. For that purpose, a selection method for comprehensive indicator sets promoted by DESA (2007) was chosen, which sort all indicators in terms of relevance and data availability. In this study, a simplified procedure for determining the relevance of the various indicators was used, which equated the frequency of the indicators in the previous literature review with their overall relevance to SD in general and energy systems in particular. As for data availability, the workload for getting the relevant data was estimated and applied, in order to stay in the scope of the study. The resulting matrix for this analysis is presented in Table 4.1.

Table 4.1
Selection matrix for sustainability indicators in this study, based on frequency and estimated workload for data acquisition. Bold indicators were adopted for this study.

WORKLOAD - DATA ACQUISITION ——>	<—— FREQUENCY **7-5**	**4-3**	**2-1**
low	**CO2-Emissions** **air pollutants**	**profitability and financial viability** **supply guarantee** **share of renewables**	**diversification of supply**
medium	**land use change**	**non-renewable material consumption**	cost distribution/affordability import dependency water use employment energy productivity arable land use forest cover imports (developing c.) strategic flexibility waste generation radioactive waste primary energy consumption land degradation
high		**health status and risks** research and development	nitrogen surplus threat status of species conflict prevention hazard vulnerability oganically farmed land water intensity waste water treatment fragmentation of habitats animal species competitive capacity

From the matrix, it is obvious that CO_2 *emissions* and *air pollutants* were chosen as indicators for the SEnSys model. The same is true for all indicators, which have a low workload for data acquisition. From all the indicators that feature a medium workload, only the one in the first two frequency classes were selected. Additionally, *health status and risks* - as the most relevant indicator from the high workload class - supplemented the selection. It is however recommended for further studies to broaden the selection of indicators, as the chosen indicators are not equally distributed among the three dimensions of SD. The implication of the chosen selection procedure and the significance to the results will be discussed in more detail in Section 6.2.1.

Given the aim of the study, to develop an indicator-based numeric model, only quantitative data was acquired. An extensive qualitative assessment of a dynamic system, like the energy supply of a country with all its interconnected components and possible configurations, would have been way beyond the scope of this thesis, as qualitative research usually requires a considerably higher manual and personal effort. It is however recommended for further studies to include qualitative data into the model, in order to strengthen the social dimension of this research (Ashley and Boyd, 2006). Again it is referred to Section 6.2.1 for a more detailed discussion on the implications of the choice of indicators.

4.2 Data collection for sustainability indicators

In order to allow a feasible research on quantitative data for the selected indicators, it was necessary to divide some indicators into sub-indicators, which could be given as a numeric value together with their respective unit. The unit had either to be related to the capacity or the energy produced. This allowed using the numeric value as a factor that could be mathematically connected to the different energy technology configurations. While *CO_2eq emissions* were already in a feasible format, *air pollutants* for instance had to be divided into different chemical substances. The selection of sub-indicators is explained in more detail in the following chapter.

Except for health costs (see Section 4.2.4), all selected indicators had to be given as technology specific factors. Fig. 4.3 shows the range of energy technologies that were used in this study to represent the spectrum of the German energy system. *Renewable*, *fossil* and *import* were the three general sectors in which the technologies were divided. In addition to that, the technologies were subdivided into their supply characteristics, namely base load, flexible or fluctuating. The total range of the data acquisitions covered 15 power generating technologies plus 4 auxiliary technologies like storage and transmission systems (see Section 4.2.5).

To stay in the scope of the study, it was necessary to limit the factors that were analysed to one single source and value each. If a source provided more than one factor or a range of values the middle factor was chosen respectively. While the first year for all datasets was set to 2010 (reference year), the SEnSys model provided the possibility for all the factors to change over the course of years. This allowed considering learning or experience curves, due to technological development or external factors such as resource scarcity (Pan and Köhler, 2007). However, due to the scope of this study, learning curves could only be reflected for economic indicators (see Section 6.2.2). In the end, the calculation of all indicators in the model period of 2010 to 2060 required to collect more than 2,400 datasets from various sources.

Most of the technical and economic data was adopted from the comprehensive study on German energy futures by Nitsch et al. (2012a), who provided an extensive appendix for all their specific technology parameters.[2] The entire data for life cycle impacts was derived from the Life Cycle

[2] A English summary of the study can be found in Nitsch et al. (2012b)

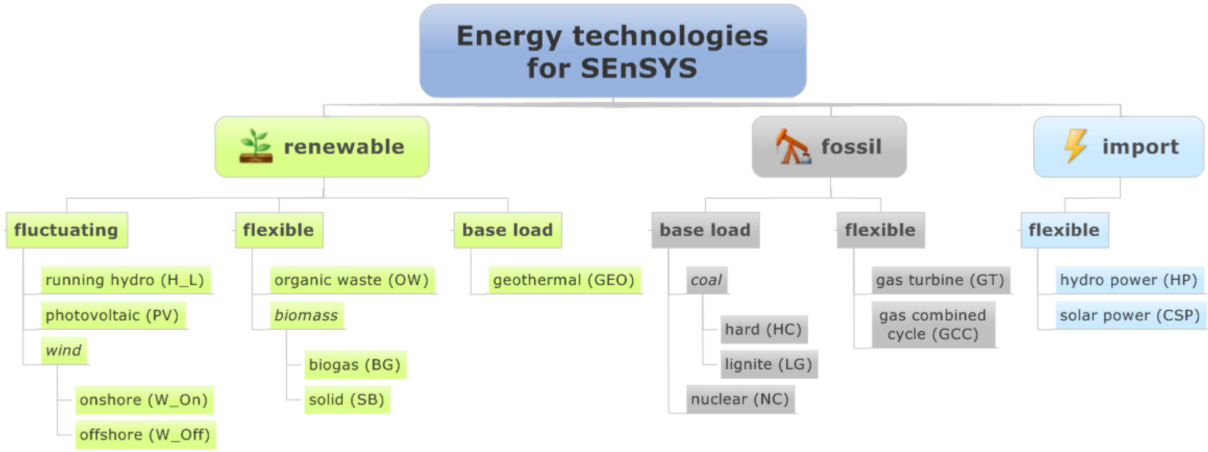

Fig. 4.3. Range of energy technologies and Technology-ID used for the SEnSys model

Analysis (LCA) database GEMIS. As for data on land use, own calculations based on area requirements of exemplary plants supplemented various other sources. More details about the calculation and sources of specific indicators and factors can be found in the following chapters. Fig. 4.4 provides an overview on the common sources used for the different indicators and technologies. The full data selection, including learning curves can be found in Appendix A.2 - Table A.1 and following.

4.2.1 Technological parameters

Two basic technological parameters were required to be researched for the SEnSys model. The first one, being the *capacity credit* of the technologies, which describes the amount of connected capacity that can be assured at any time (Trieb et al., 2006). This factor was necessary for the secured or firm capacity indicator, being the major requirement for any energy technology pathway (see Eq. (4.1)).

$$P_{firm} = \sum_{i=1}^{n} (P_i \cdot CC_i) > P_{peak} \cdot f_{security} \tag{4.1}$$

with

P_{firm}: Firm or secured capacity

P_i: Power of technology i

CC_i: Capacity credit in percentage

P_{peak}: Peak load

$f_{security}$: Security factor of firm capacity

Additionally, the average economical lifetime of the different technologies needed to be defined.[3] Both values were mostly adapted from Nitsch et al. (2012a) and Trieb et al. (2006), supplemented by Winkler et al. (2013) and OECD (2010). No integrated indicators were required from this category.

Beside this two technology specific factors, the *share of renewables* and the *diversity of supply* were chosen as generic indicators for electric energy systems. As for the *share of renewables*,

[3] In order to fit the SEnSys model, the lifetime was rounded to decades where applicable

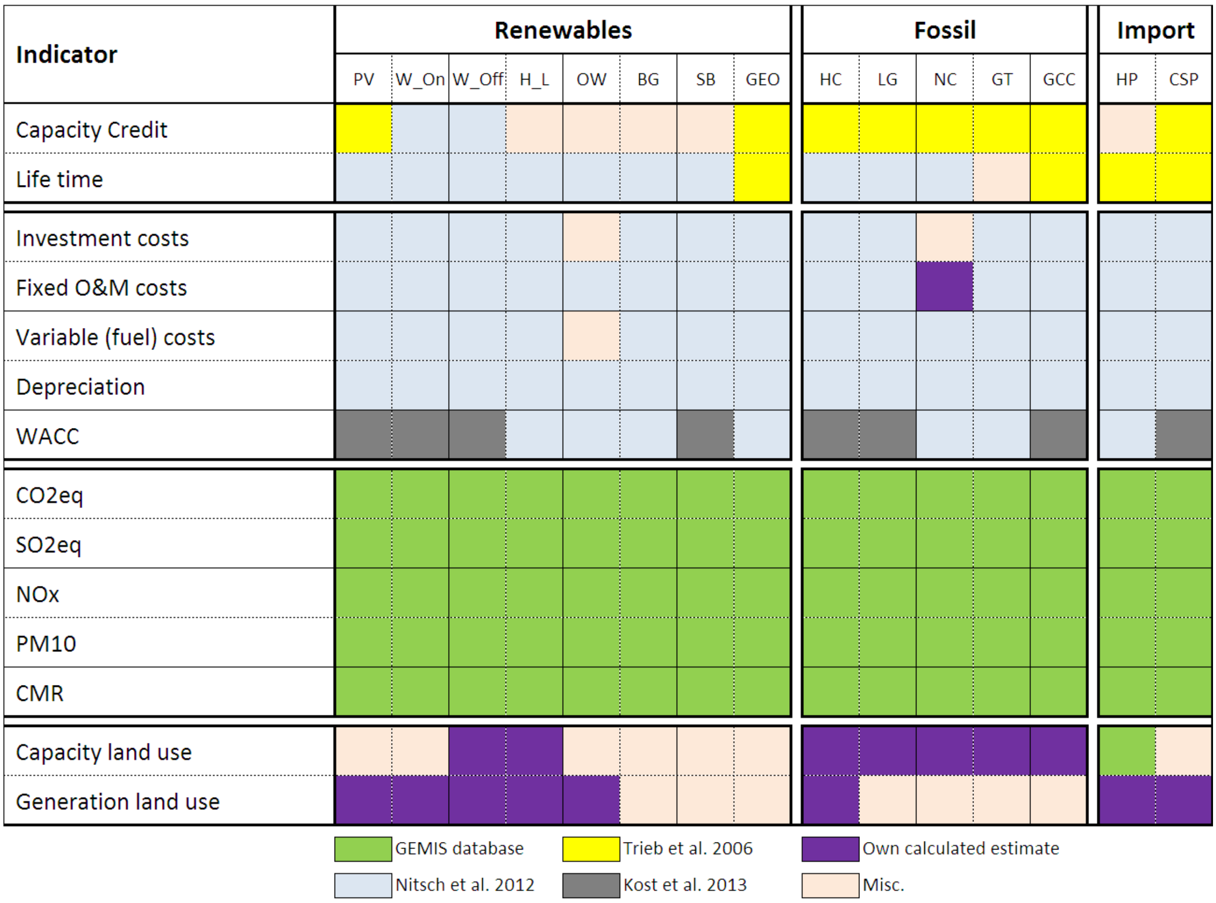

Fig. 4.4. Overview on most common sources used for data acquisition for indicators and technologies. The used abbreviations of energy technologies (Technology-IDs) can be found in Fig. 4.3

the used energy of all renewable sources was divided by the total amount of used energy in the given year, after Eq. (4.2).

$$SR = \frac{E_{renewable,used}}{E_{total,used}} = \frac{(E_{renewable,produced} - E_{renewable,excess})}{(E_{total,produced} - E_{renewable,excess})} \tag{4.2}$$

with

SR: Share of renewables in year i

E: Energy amount in year i

The diversification of energy supply could be seen as an indirect measure for fuel dependency and supply guarantee and was therefore included in this study. While the IEA (2004) propose to use the *Shannon-Wiener index*[4], Stirling (2007) argues for a more advanced method, considering the variety, balance as well as disparity of the chosen system.

[4] Accidentally, the IEA calls their chosen index *Sterling index*, while the index used is actually the *Shannon-Wiener index* , as presented for instance by Lo (2011)

$$D = \sum_{ij}(d_{ij} \cdot p_i \cdot p_j) = \sum_{ij}(d_{ij} \cdot \frac{E_i \cdot E_j}{E_{total}}) \quad (4.3)$$

with

D: Stirling diversity index

d_{ij}: Disparity between technology i and j

p: Share of technology

E Energy amount

The *disparity* between the different technologies from Eq. (4.3) was calculated after a simplified approach based on the work of Solow et al. (1993). Pairs of technologies were differentiated first by category (renewable, fossil, import), then system integration (e.g. base load, flexible, fluctuating), followed by the source (e.g. sun, wind, coal) and finally by all technologies. For each difference in the previous aspects one point (node) was added. The sum of all nodes that had another value was given the estimated disparity between the technologies as presented in Fig. 4.5.

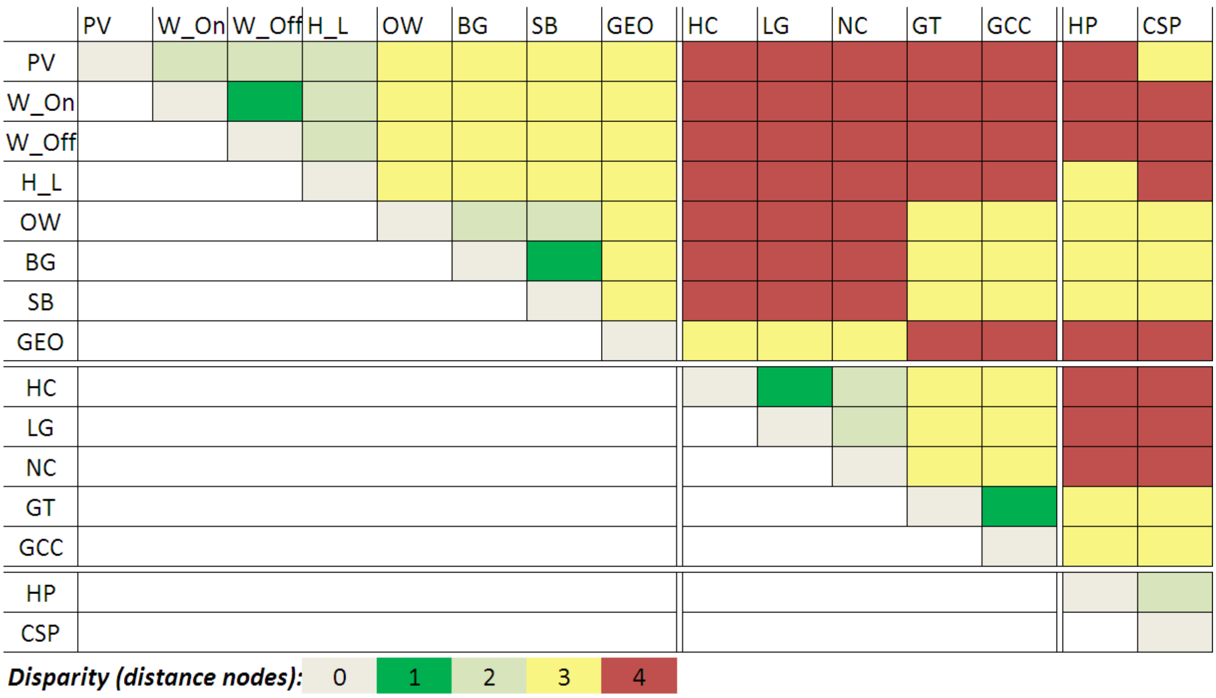

Fig. 4.5. Estimated disparity between technology pairs used for the calculation of diversity in this thesis

In this way, the pair of CSP and PV for instance resulted in a disparity factor of 3, due to a difference in category (PV: renewable, CSP: import), system integration (PV: fluctuating, CSP: flexible) and technology (PV, CSP). As the source of both technologies (sun) was the same, no extra node was added. No difference was made between the four aspects, so that no specific weighting was applied to the method.

4.2.2 Economic evaluation

In order to calculate the main indicator *profitability and financial viability*, several sub-indicators needed to be defined. Based upon the calculation procedure of Kost et al. (2013), the overall indicator for the economic evaluation was assigned to be the total cost of electricity. The total cost is a macroeconomic indicator, which estimates all costs that have to be paid for a respective electricity generation. While it includes investment, fixed and variable costs for all required plants, it does neither represent market dynamics for end-consumer (e.g. electricity stock exchange) nor a business perspective for the plant operator. As for this analysis, the total costs do not reflect external costs from negative impacts on the environment or society. It is however recommended to include external costs for further studies into the calculation of the total costs of electricity generation (see Section 6.2.1).

If the total costs are divided by the amount of energy produced in the same period one gets the so-called Levelized Cost of Electricity (LCOE), which is a widespread economic performance indicator for energy system analysis, usually given in cent per kilo Watt hour (kWh). For calculating the total costs or the LCOE respectively, the following sub-indicators are required:

- Investment costs
- Fixed Operation and Maintenance (FOM) costs
- Variable or respective fuel cost
- Depreciation period (of the investment)
- Weighted Average Costs of Capital (WACC) (technology specific interest rate for investment, due to profitability and risk assessment (Kost et al., 2013))

The first step was to calculate the annuity costs (over the depreciation period[5]) with Eq. (4.4) adapted from Hess (2013, p. 106).

$$IT = (\overline{IC} \cdot C_{add}) \cdot \frac{(WACC - 1) \cdot WACC^d}{WACC^d - 1} \tag{4.4}$$

with

IT: Annuity

$\overline{IC}$: Average investment cost in decade

C_{add} Total additional capacity for decade

$WACC$: Weighted Average Cost of Capital factor (e.g. 1.06 for 6% WACC)

d: Depreciation period

In the second step, the fixed FOM costs had to be calculated over the entire life time with Eq. (4.5).

$$FOM = I_0 \cdot f_{fom} \tag{4.5}$$

with

FOM: Annual fixed operation & maintenance costs

I_0: Investment cost in first year

f_{fom}: fixed OM costs factor in percentage (of investment)

[5]Likewise the lifetime, the depreciation period was rounded to full decades

The variable costs in this thesis were assigned only to the fuel costs of the plants and did therefore not cover any additional charges due to operation of the plants respectively. As the variable costs were already given in the normal form of factors required for the SEnSys model - per energy amount - no special calculation was required.

All the monetary values derived from Nitsch et al. (2012a) were already given in real values of 2010. Hence, no further discounting was required for future investment and variable costs in this study.[6]

To get the final total cost, all the cash flows from the different years were summed up after Eq. (4.6).

$$TC = \sum_{i=1}^{n} (IT_i + FOM_i + VC_i) \tag{4.6}$$

with

n: Life time

IT_i: Annuity capital costs in year i

FOM_i: Fixed OM costs in year i

VC_i: Variable costs in year i

The depreciation period will be in most cases shorter than the lifetime, so that after the depreciation period the annuity capital costs will be equal to zero. Again, to get the LCOE, the Total Cost of Electricity (TCOE) had to simply be divided by the energy produced during the time span.

Similar to the technological indicators, the most data for the economic factors was coming from Nitsch et al. (2012a). Their data included learning curves for investment costs as well as several price advance scenarios for fuel costs. For this thesis the price advance scenario *B (moderate)* was chosen. As for the WACC, the comprehensive study on LCOE of Kost et al. (2013) was used, which was complemented by the generic WACC of 6% from Nitsch et al. (2012a), whenever no specific factor was available. In addition to that, a few factors which were not represented by Nitsch et al. (2012a) were adapted from IEA (2012b) and EIA (2013).

4.2.3 Life cycle impacts

Besides economic indicators, this study set a big focus on *life cycle impacts* from the different energy technologies throughout their lifetime. Except for land use, all the data for the LCA factors were derived from the public domain LCA tool GEMIS in its newest version 4.8.1, developed by the International Institute for Sustainability Analysis and Strategy (IINAS).[7]. In order to get LCA data from the database, it was necessary to choose a comparable technological process in GEMIS, which represents each energy technology accordingly. GEMIS provides a full range of energy technologies with different specifications, such as the used input substrate of a biogas plant. Furthermore, the tool would have allowed changing certain parameters such as full load hours inside the process. However, the scope of the study did only allow determining

[6]The values in Nitsch et al. (2012a) were originally given for the reference year 2009. So in order to have the present value of 2010, all values where simply increased by 1.1%, which was the actual inflation rate in Germany from 2009 to 2010, according to BMWI (2014).

[7]The full version of the LCA tool can be downloaded from IINAS (2014)

one specific process per technology with given standard parameters. Further studies could increase the possible specification per energy technology and even change relevant parameters to achieve a better fit with the current state of technology (see Section 6.2.2). The generic processes assigned to the different technologies are shown in Table 4.2.

Table 4.2
Selection of standard processes in GEMIS for the used energy technologies

	Technology	GEMIS Process	Functional Unit
renewables	photovoltaic	solar-PV-multi-framed-with-rack-DE-2010	MW
	wind onshore	wind-turbine-DE-2010-inland	MW
	wind offshore	wind-turbine-DE-2010-offshore	MW
	running hydro	hydro-ROR-big-DE-2010 (update)	MW
	organic waste	bio-waste-cogen-ST-DE-2010	GWh
	biogas	biogas-manure-ICE-500-DE-2010/en	GWh
	solid biomass	wood-wastes-A1-4-cogen-ST-DE_2010	GWh
	geothermal	geothermal-ST-ORC-DE-2010	GWh
fossil	hard coal	coal-ST-DE-2010	GWh
	lignite	lignite-ST-DE-2010-Lausitz	GWh
	nuclear	nuclear-powerplant-PWR-DE-2010	GWh
	gas turbine	gas-GT-DE-2010	GWh
	gas combined cycle	gas-CC-DE-2010	GWh
import	hydro power	hydro-dam-big-NO-2000	MW
	solar power	solar-CSP-ES-2020	MW

For all fossil energy technologies, the functional unit was assigned to one Giga Watt hour (GWh) in the SEnSys database, which means that all the impacts from cradle to grave were summed up and subsequently divided by the energy produced throughout the entire lifetime. However, as most life cycle impacts of renewable energies occur during construction and decommissioning respectively, these impacts are not always directly coupled with the produced energy. Therefore, this study was using a simplified approach by assigning one Mega Watt (MW) as functional unit to all renewable energies that are running by natural primary energy sources such as wind and sun. An overview on the related functional unit for each technology in this study is given in Table 4.2.

The Cumulated Material Requirement (CMR) factor was treated differently, as all material requirements in this study were seen as independent of energy production and therefore given one MW as functional unit. The GEMIS database is summing up the following materials as not renewable: natural gas, oil, ores, iron-scrap, minerals.

As the standard functional unit in GEMIS was assigned to one GWh, some of the LCA factors had to be converted to *per MW* after Eq. (4.7). Appendix A.3 - Table A.2 shows the detailed calculation for each technology and factor. Additionally, this approach required to sum up each life cycle impact - both from plant construction as well as energy production - subsequently in an overall indicator.

$$f_{MW} = \frac{f_{GWh} \cdot E}{P} = \frac{f_{GWh} \cdot \frac{P \cdot FLH \cdot LT}{1000}}{P} \tag{4.7}$$

with

f_{MW}: LCA factor given per MW

f_{GWh}: LCA factor given per GWh

E: Total energy produced over lifetime in [GWh]

P: Power of the plant in [MW]

FLH: Average full load hours of the plant in [h/a]

LT: Lifetime of the plant in [a]

For land use data, it was considered that the results of the GEMIS tool were not detailed enough for this analysis. In order to represent the difference between installed capacity (area for plant) and energy use, it was decided to break down the land use to both categories and sum them up subsequently. For that reason, two specific papers on land use estimates on generation of energy from Fthenakis and Kim (2009) and Arent et al. (2014) were used. As both sources, did not fully cover all the energy technologies used in this study, supplementary data were acquired from EPRI (1997), McDonald et al. (2009) as well as Schmidt and Mühlenhoff (2009).

However, most of the sources did not provide technology specific land use of the power plant and its neighbour infrastructure. Therefore it was decided to manually calculate this *capacity land use* from generic land use factors. This was done by choosing representative plants for the respective energy technologies from the power plant database of the German *Federal Network Agency* (Bundesnetzagentur, 2014). With the help of the online tool *ACME Planimeter*, the area covered by the particular plant was measured roughly with satellite data from *Google Maps* (Poskanzer, 2014). This estimated land use was then divided by the respective capacity from the power plant list, to get the land use of the single plants. All the *capacity land uses* (from different plants) of the same technology were compared and a representative compromise for a generic land use factor was chosen (see Appendix A.3 - Table A.3).

4.2.4 Social indicators

As the scope of this study did not allow an extended research on (qualitative) social indicators, there is only one indicator available for this dimension of SD. In order to assess to some extend the social implications of energy technology pathways, an integrated indicator on public health costs was chosen. In accordance with Krewitt (2007), the health costs in this study were only related to air pollution that occurs during construction and operation of the different power plants.

The most relevant air pollutants, which are widely used for public health estimates are SO_2eq, particular matter (PM_{10}) as well as NO_x (Kareda et al., 2007; Krewitt, 2007; Streimikiene and Alisauskaite-Seskiene, 2014). These three major sources of air pollution were then used for an estimation of the health impacts, measured as external costs based on the study of Krewitt (2007). In this German study on external costs of power generation, the following health costs were assigned to the different pollutants:

- SO_2eq: 3.06 €/kg
- NO_x: 3.12 €/kg

- PM_{10}: 12.00 €/kg

It was decided not to add the health costs or any other external costs to the total costs, but to keep them as a separate indicator. In that way, the health costs indicator was only used to integrate the different air pollutants into a common unit. However, it is recommended to integrate all external costs in further studies into the calculation of the total costs in order to reflect some of the negative effects of certain technologies on the social and natural environment. This question will be discussed in more detail in Section 6.2.1.

4.2.5 Storage and energy transmission technology

The assessment of sustainability for energy technology pathways in Germany required incorporating major auxiliary power technologies, such as storage and transmission. The scope of the study did however not allow extensive research on data for these technologies. Hence, for energy storage only two systems were included, which were seen as representative for energy storage technology in Germany, according to Trieb (2013b):

- pumped hydro storage: as a category for conventional energy storages such as pumped hydro and compressed air
- hydrogen storage: as a category for innovative energy storages such as power to gas

Electricity grid connections inside Europe for import and export were represented by the necessary transfer capacity between Germany and the respective neighbour countries. As for this study, this capacity was given as Net Transfer Capacity (NTC), which is the available transfer capacity between two countries, taking into account a rigid security margin (ETSO, 2001). Other than that, HVDC overhead technology was chosen for long transmission lines, such as solar power transmission from the Middle East and North Africa (MENA) region. The HVDC line was given the same capacity as the planned CSP plants in the model.

Along with that, a quick research was compiled to find representative data that could be included into the analysis, preferably from technical literature. Fig. 4.6 provides an overview on the used sources for the estimation of the required factors for all indicators.

It is worth mentioning that certain data were not already in the correct form and needed to be converted to the right units. All the data from Jorge and Hertwich (2014) on grid technologies, were given as total sum for the whole network extension in Europe, and were simplified just divided by the planned capacity or energy use respectively. More detailed land use data for this technology was derived from DUH (2012). As for HVDC transmission lines, most of the data were coming from either Hess (2013) or May (2005). Life cycle data for hydrogen storage were derived from Spath et al. (2004), which additionally implied a calculation of the energy content from hydrogen to convert from *per kg hydrogen* to *per energy amount* (Winter and Nitsch, 1988). For further details it is referred to Appendix A.2. Finally, two technologies required the manual calculation of the capacity land use, similar to Section 4.2.3, as presented in Appendix A.3 - Table A.3.

4.3 Modelling of technology pathways (SEnSys)

The core of this thesis was the development of an indicator-based numeric model that can help to enhance sustainability of given energy technology pathways in Germany. This so-called Sustainable Energy Systems (SEnSys) model used a range of different sub-models and

Indicator	pump storage	H2 storage	grid conncetion	HVDC (overhead)
Capacity Credit	ELCALC	ELCALC	ELCALC	ELCALC
Life time	Nitsch et al. 2012	Nitsch et al. 2012	Jorge & Hertwich 2014	Hess 2013
Investment costs	Nitsch et al. 2012	Nitsch et al. 2012	ELCALC	Hess 2013
Fixed O&M costs	ELCALC	ELCALC	ELCALC	Hess 2013
Variable (fuel) costs	ELCALC	Nitsch et al. 2012	ELCALC	ELCALC
Depreciation	Nitsch et al. 2012	Nitsch et al. 2012	Jorge & Hertwich 2014	ELCALC
WACC	Nitsch et al. 2012	Nitsch et al. 2012	Nitsch et al. 2012	Nitsch et al. 2012
CO2eq	GEMIS	Spath et al. 2004	Jorge & Hertwich 2014	May 2005
SO2eq	GEMIS	Spath et al. 2004	Jorge & Hertwich 2014	May 2005
NOx	GEMIS	Spath et al. 2004	May 2005	May 2005
PM10	GEMIS	Spath et al. 2004	Jorge & Hertwich 2014	May 2005
CMR	GEMIS	Spath et al. 2004	Jorge & Hertwich 2014	May 2005
Capacity land use	Own estimate	Own estimate	DUH 2012	Hess 2013
Generation land use	Own estimate	Own estimate	Own estimate	Own estimate

Fig. 4.6. Overview on sources used for factor estimation for storage and transmission technologies

components as illustrated in Fig. 4.7. The different categories of capacity are defined as follows (see also Fig. 4.8):

- *Installed capacity*: is the capacity that is installed in the current year (both connected and shut-down)
- *Connected capacity*: is the capacity that should actually be connected for electricity generation in the current year (determined by the user)
- *Secured capacity*: is the capacity that can be secured at any time from the connected capacity in the current year (determined by capacity credit - see Section 4.2.1)
- *shut-down capacity*: is the capacity that is shut-down (but still installed), to achieve the desired connected capacity of the current year, starting with the oldest series first
- *Additional capacity*: is the capacity that needs to be installed additionally (starting in previous decade), to reach the desired connected capacity in the current year

In a nutshell, the user sets the desired connected capacity, and the SEnSys model internally calculates the resulting capacities and full load hours for the calculation of the indicators, which are subsequently processed by output files that the user can access. A more detailed description of the different steps follows in the next chapter.

4.3.1 SEnSys Tool

The SEnSys Tool is the main module in the overall SEnSys model, where all the operative Visual Basic for Applications (VBA) scripts are stored and running. With the help of the Graphic User interface (GUI), the user can determine the connected capacity in the different years of the model and gets a visual feedback (via update of the database) for parameters like secured, installed, connected, additional and shut-down capacity.

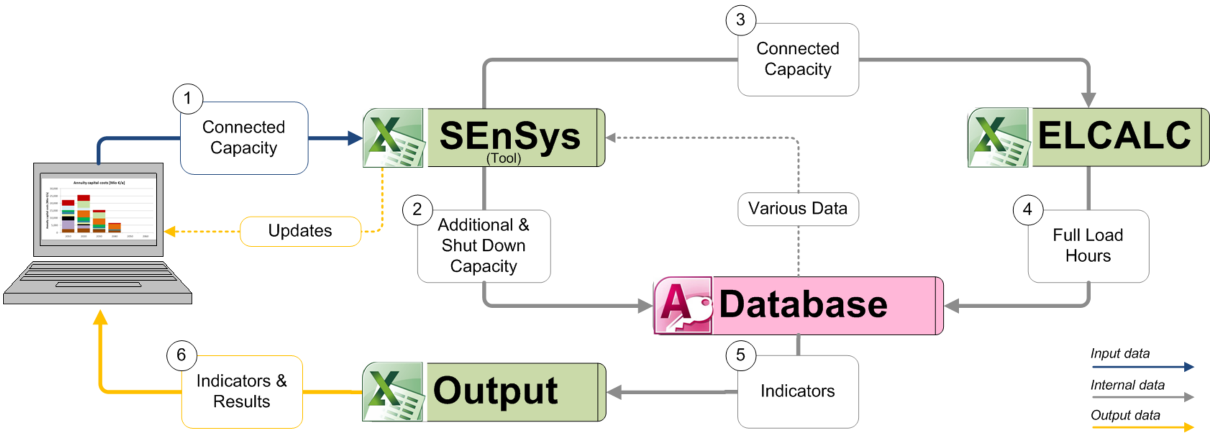

Fig. 4.7. Overview on the SEnSys model cycle. (1) User puts connected capacity into SEnSys Tool (2) Additional and shut-down capacity is calculated and inserted into database (3) Connected capacity is given to ELCALC model (4) Full load hours are calculated and inserted into database (5) Indicators are calculated inside database and given to Output tables (6) Indicators and integrated results are shown for the user

One important aspect of the SEnSys model was to include years of construction or so-called *series* for all the technologies that can be installed, to provide a more detailed picture of the technology pathway that would lead to the desired outcome. For this thesis, a series was defined as all plants of the same technology that have to be build up in the period of one decade. To give an example, all new build plants which would be put into operation from 2021 to 2030 would be submerged into the 2030-series respectively.

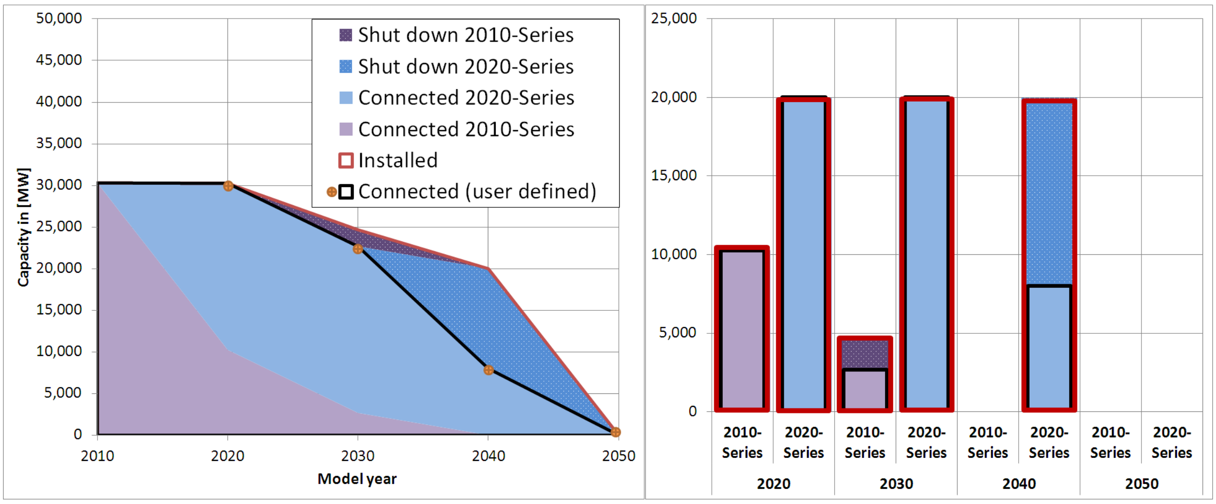

Fig. 4.8. Example for the calculation of installed, connected, additional and shut-down capacity

By dividing the installed capacity into different series, the model was able to reflect long term effects of different decisions in the future, which is a key aspect when it comes to SD, as stated by WCED (1987, p. 14). In practice this means that whenever new capacity of a certain technology is built in the model, it will be installed (but potentially not connected) for their assigned lifetime. Given that, the shut-down capacity can be an indicator for an oversized installation of energy technologies in the past years, in reference to future requirements.

Fig. 4.8 illustrates how the different capacities are connected to each other in an exemplary case. The black line is representing the desired connected capacity set by the user. In 2020, the connected capacity is bigger than the remaining installed capacity from the 2010 series, accordingly the model builds up 20,000 MW additional capacity (2020-series) in a linear manner from 2010 to 2020.[8] From 2030 on, the connected capacity (set by the user) is decreasing, so that too much installed capacity is available. Hence the model has to shut-down capacity before the end of its economic lifetime, starting with the oldest series, until reaching the desired 0 GW connected capacity in 2050 eventually.

4.3.2 ELCALC model

The second module of the SEnSys model is the so-called ELCALC tool developed by Trieb and Hess (2013), which is automatically connected to the SEnSys tool via VBA script. The ELCALC tool allows to run a simplified simulation of the electricity market of one year, taking into account demand and supply scenarios based on data from the Renewable Energy Mix for sustainable electricity supply (REMix) model developed by Scholz (2012). By running through every hour of a chosen year, the ELCALC tool can calculate the average workload of every energy technology and accordingly the resulting full load hours, in relation to the set capacity, with a fixed merit order. The model itself is not simulating a grid connection, as it is simplified to represent just one node.

In the SEnSys model, the connected capacity (set by the user) was given as an input for ELCALC, which then calculates the full load hours that are inserted into the SEnSys database for further use, as explained in the next chapter.

4.3.3 SEnSys database

The size of the model - due to the large range of technologies, technology series and indicators involved - required the development of an extensive database for storage and calculation purposes. For this task, a Microsoft Access database was created, which could be connected to the SEnSys tool via Structured Query Language (SQL) through the *Microsoft Jet Database engine* in the VBA environment.[9]

In general the database was filled with category-, data- and input-tables, as presented in Table 4.3. These basic tables could then be connected with each other through their specific key fields, such as for instance *Pathway-Load* with *Pathway-ConnectedCapacity* (trough *PathwayID*, *TechID* and *Year*) to get the produced energy from each technology series in every model year.[10] The

[8] In practice this means, that the model puts into operation 2,000 MW additional capacity of the 2020-series each year from 2011 on, until reaching the desired total additional capacity of 20,000 MW. Given an exemplary lifetime of 30 years, the first 2,000 MW of the 2020-series are de-constructed in 2041. Likewise the construction, the de-construction runs in a linear manner. Hence, the last plants of the 2020-series are de-constructed in 2049, leaving no plants for 2050.

[9] For more details it is referred to Microsoft (2014)

[10] The related SQL command would be: *SELECT Pathway-Load.PathwayID, Pathway-Load.TechID, Pathway-Load.BaseYear, Pathway-Load.Year, (Pathway-ConnectedCapacity.Capacity*Pathway-Load.Load) AS Generation FROM Pathway-Load INNER JOIN Pathway-ConnectedCapacity ON (Pathway-Load.PathwayID=Pathway-ConnectedCapacity.PathwayID) AND (Pathway-Load.TechID=Pathway-ConnectedCapacity.TechID) AND (Pathway-Load.BaseYear=Pathway-ConnectedCapacity.BaseYear) AND (Pathway-Load.Year=Pathway-ConnectedCapacity.Year);*

same procedure was applied to all other queries that were required to calculate the respective indicators.

Table 4.3
Overview on the created tables inside the SEnSys database, and their respective key fields

Type	Table	Key fields
Category	Factor	*FactorID*
	Indicators	*FactorID*
	Pathways	*PathwayID*
	Scenarios	*ScenarioID*
	Technologies	*TechID*
Data	Technology-Factor	*FactorsID, FactorID, TechID, SeriesID*
	HealthCost-Factor	*FactorsID, HCostID*
	Scenario-Demand	*DemandID, Year*
	Technology-DisparityFactor	*FactorsID, TechID1, TechID2, Year*
Input	Pathway-ConnectedCapacity	*PathwayID, TechID, Year*
	Pathway-InstalledCapacity	*PathwayID, TechID, SeriesID, Year*
	Pathway-ShutDownCapacity	*PathwayID, TechID, SeriesID, Year*
	Pathway-Load	*PathwayID, TechID, SeriesID, Year*
	Pathway-ExcessGeneration	*PathwayID, Year*

In the end, it was ensured that all the indicators can be summed up by series, technologies or years. In addition to that, the created database allowed to give results in three different types:

- *Annual indicators*: as indicators that are calculated only from impacts occuring in the respective year, to show absolute trends over the course of time.

- *Reference year indicators*: as annual indicators that are referred to a reference year, to show the future development in relative numbers (percentage).

- *Aggregated indicators*: as indicators that are summed up over the entire time span, to show the full impacts of energy technology pathways

All three types can be given in absolute numbers as well as in relation to either the produced energy in the respective time or the secured capacity. An overview on the different factors, indicators and possible outputs in the database is available in Appendix A.3 - Fig. A.4.

As for the calculation of aggregated indicators, a simplified approach with average values for indicator factors over a decade was chosen (Eq. (4.8)). Furthermore, the approach had to differentiate between indicators that are calculated for construction (per MW) or operation (per GWh) respectively.

$$Ind_{agg} = \sum_{i=m}^{n} \left(\overline{f}_i \cdot \underbrace{\overline{E}_i \cdot \Delta t_i}_{=1,\text{ if factor per MW}} \cdot \underbrace{C_{add,i}}_{=1,\text{ if factor per GWh}} \right) \tag{4.8}$$

with

Ind_{agg}: Aggregated Indicator (from decade m to n)

m: First decade (e.g. 2010)

n: Last decade (e.g. 2050)

$\overline{f}_i$: Average indicator factor in decade

$\overline{E}_i$: Average annual produced energy in decade [GWh/a]

Δt_i: Years in decade [a]

$C_{add,i}$: Total additional capacity in decade [MW]

A special case was the annuity capital costs, which were simply multiplied by their respective depreciation period in order to get the aggregated numbers. It is worth mentioning that the aggregated annuity costs were only calculated until the chosen decade, which in result omitted the capital costs that would have to be paid in the following decades, to finance the already existing energy technologies. The general implications of the simplified calculation of all aggregated indicators are discussed in Section 6.2.3.

4.4 Exemplary energy scenarios (case study)

In order to assess the feasibility of the SEnSys model to enhance sustainability of energy technology pathways in Germany, it was decided to compile a case study. The case study was based on the energy scenarios from the analysis of Trieb (2013a) and Trieb (2013b) as well as partly on Nitsch et al. (2012a). In the next chapter the different scenarios are described in more detail.

4.4.1 Demand and peak load scenario

The first step for the case study was to define a scenario on energy demand and peak load, as basic requirements to fulfil for the energy technology pathways. Nitsch et al. (2012a) provide a capacity retirement graph, which was used for defining the basic installed capacity for the 2010-Series.[11]

As for the scenario on future demand and peak load requirements, the numbers from Trieb (2013b) were used. From Fig. 4.9, it is obvious that a large gap between secured capacity and peak load occurs from 2010 on (if nothing else would be installed from this year on). To fill this gap is the goal of the technology scenarios that are presented in the next chapter.

4.4.2 Energy technology Scenarios (Trieb1 and Trieb2)

A countless number of different technology pathways could theoretically fulfil the basic load and energy requirements from the scenario presented in the previous chapter. As for this thesis, two quite controversial energy technology scenarios were chosen for further analysis. Data

[11] A capacity retirement graph is based on data of existing plants and their anticipated lifetime. The 2010-Series includes all the plants that were built until 2010, which is the chosen start year of the analysis.

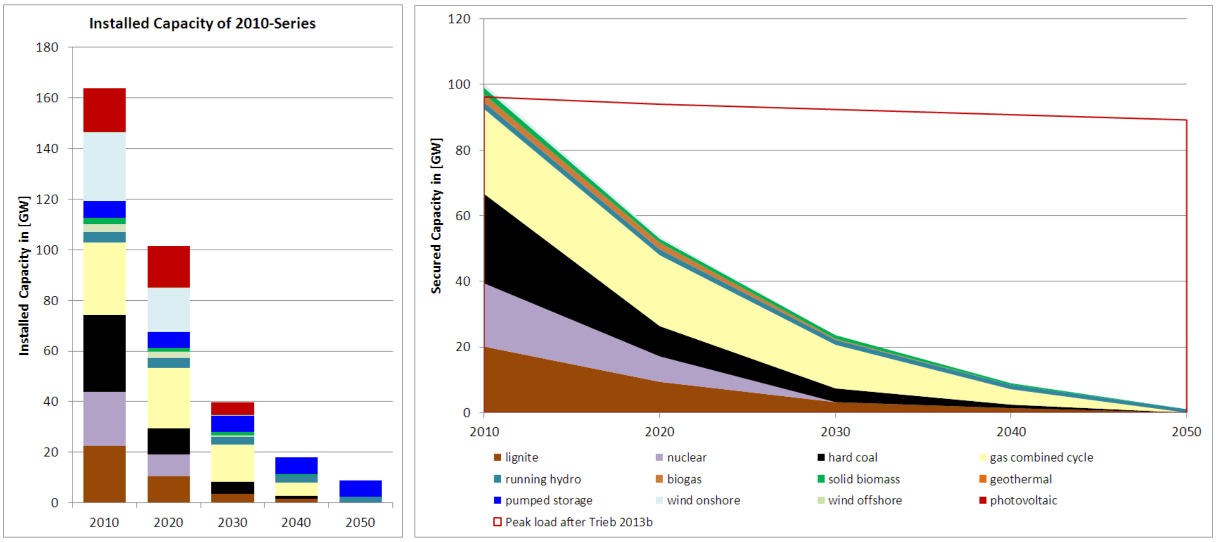

Fig. 4.9. Installed and secured capacity of the 2010-Series from Nitsch et al. (2012a) and the peak load scenario of Trieb (2013b), as used for the case study

for both energy technology scenarios where derived from Trieb (2013b), who presents two different technological configurations that would lead to the same share of renewable sources in Germany in the future.[12] Starting in 2010, the share rises to approximately 40% in 2020, until both scenarios reach a share of 90% in 2050 eventually. Fig. 4.10 shows the resulting connected capacities for *Trieb1* and *Trieb2*.[13]

While both technology scenarios for the future German energy mix plan to reach the same share of renewables in 2050, both scenarios feature some specific differences:

- *Trieb1*: high share of locally available fluctuating renewables and flexible gas turbines, resulting in high surplus capacities and a large demand for storage and network extension technology
- *Trieb2*: small share of flexible renewable imports (solar and hydro via intercontinental HVDC transmission lines), leading to smaller capacities and moderate requirements for storage and network extension.

The first scenario *Trieb1* is slowly replacing baseload power plants running on fossil fuels in Germany with locally available but mostly fluctuating renewables such as PV and wind (Trieb, 2013a). Due to the intermittent nature of supply from these sources, relatively large capacities of storage and backup power plants are required to ensure a secured supply at any time. In addition to that, the spatially and temporally fluctuating renewables demand for a significant network extension both inside Germany as well as to the neighbour countries in order to balance out production and export excess energy in times of high generation.

[12] A description of the scenarios in English can be found in Trieb (2013a, p. 21-24)

[13] As the scenarios were integrating biogas with solid biomass, it was decided to subtract the remaining biogas capacity (2010-Series) from the given biomass capacities in both scenarios, to get the same total connected capacity for biomass.

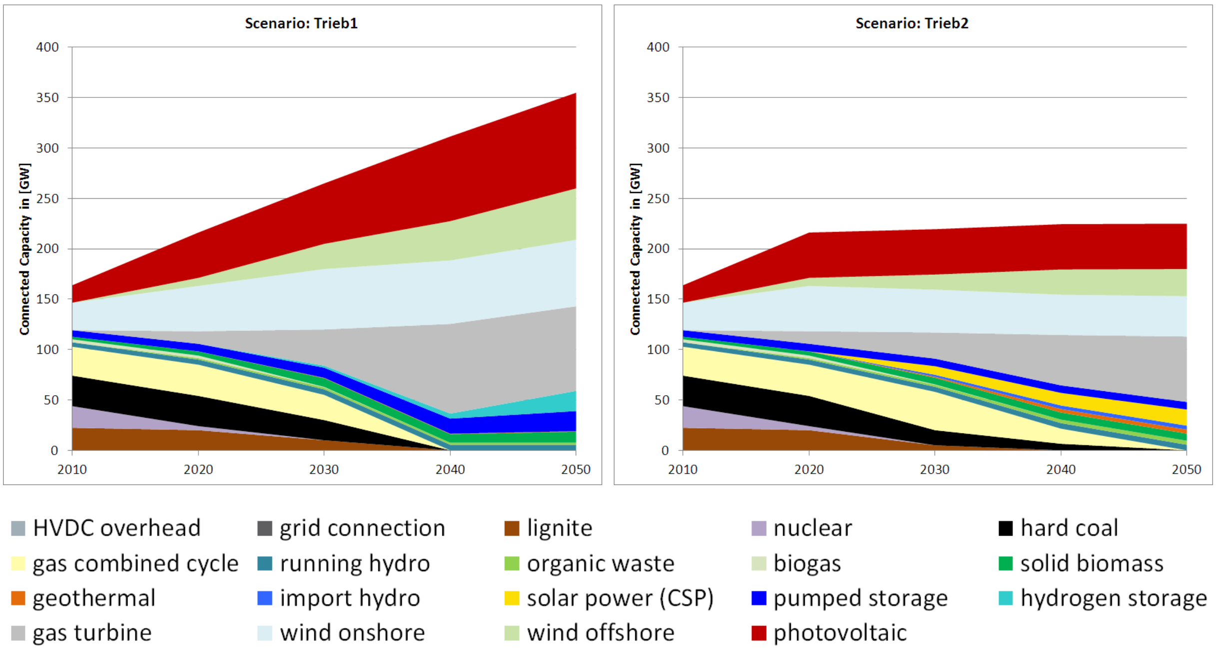

Fig. 4.10. Set connected capacity of *Trieb1* and *Trieb2* (data from Trieb (2013b)). Both scenarios cover the same annual electricity demand

Opposite to that, the second scenario *Trieb2* is balancing local renewables with means of relatively low shares of imports (up to 20% of the annual electricity production in 2050) from flexible renewable sources inside and outside Europe, while at the same time backing out from fossil power generation. Together with hydro power on demand from Norway, scenario *Trieb2* uses CSP technology for flexible electricity generation in North Africa, which can be transmitted on demand via HVDC in a point-to-point manner directly to the centres of demand.[14] This so called *point-to-point connection* would allow to integrate the solar power on demand, as if the plant was actually situated in the importing country itself. According to Trieb (2013a), these flexible imports allow to complement local renewable energy production and accordingly decrease the overall capacities of the total power park in Germany, as illustrated in Fig. 4.10. Along with that, no additional storage and network capacities are required

For further information on the CSP option, it is referred to Trieb et al. (2006), Trieb et al. (2012), Trieb (2013a) as well as Hess (2013).

[14] A brief introduction to CSP and HVDC technology can be found in Trieb (2013a, p. 30-35)

5. Results

Given the 19 available technologies as well as the 20 sub- and 6 main indicators in the SEnSys model, 494 datasets could be derived from the database for each energy technology scenario and decade. The case study in this thesis, with 2 technology scenarios over 5 decades and accordingly 5 main construction series, resulted therefore in 24,700 original data sets for comparison. As those datasets could be given as annual, aggregated or referenced values and furthermore in absolute numbers or in reference to either the used energy or secured capacity (see Section 4.3.3), a total amount of 222,300 datasets were resulting from the simulation of the technology scenarios in the SEnSys model.[1] From this vast amount of data, the most relevant numbers and results are presented in the following chapters. A more detailed collection of the results can be found in Appendix B.

5.1 Reference year 2020

In 2020, both energy technology scenarios of Trieb (2013b) feature the same technology mix. Therefore this year was chosen as the reference year for comparison. The simulation in ELCALC and SEnSys reveals a total annual electricity generation of around 599 Tera Watt hours (TWh). The share of all technologies in electricity generation is presented in Fig. 5.1. If the energy from storage and auxiliary systems as well as the excess production from renewables is subtracted, the remaining used energy is 595 TWh. Given these numbers, renewable sources feature a share of approximately 40% in the reference year 2020, which is therefore still dominated by fossil energy use.

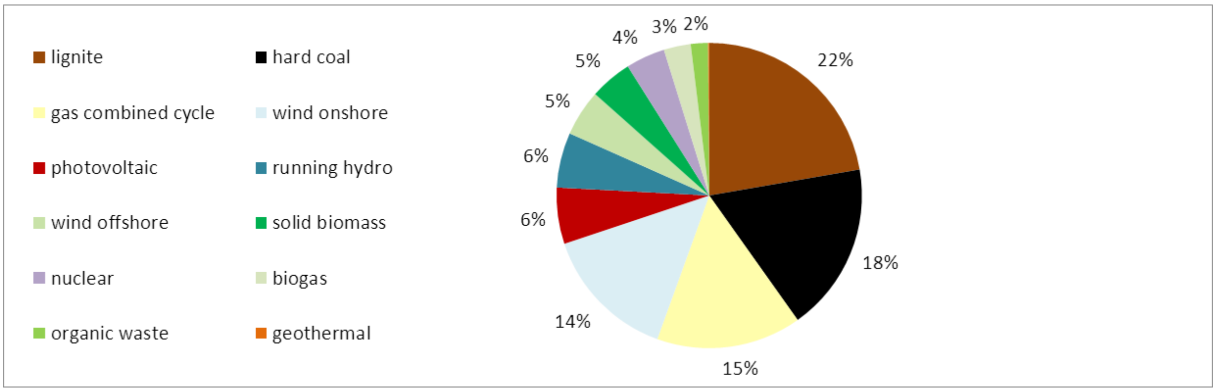

Fig. 5.1. Share of energy technologies in total electricity generation in reference year 2020 (599 TWh)

As for further results, the technical energy system mix accounts for approximately 99,144 MW secured capacity (after Eq. (4.1)). In relation to the estimated peak load of 93,999 MW from Trieb (2013b), a relative security margin of around 5.5% can therefore be accounted for in the year 2020. The diversity index of the electricity generation in 2020 - as defined in Section 4.2.1 - is 2.76, which is already an noticeable increase from 2010 (2.31).

[1] Not taking into account various other means of connecting or integrating the already existing datasets (e.g. relative share of total)

5.1.1 General Indicators

The results for the main indicator calculation for the reference year 2020 are presented in Table 5.1. Beside the absolute numbers for that year, relative numbers in terms of used energy and secured capacities are given additionally. A full list of all the indicators for the reference year 2020 can be found in Appendix B.1 - Table B.1.

Table 5.1
Resulting main indicators for the reference year 2020, given as annual numbers and normalized to energy production (per GWh) and secured capacity (per MW) in the same year

	Mio. €	**T€/GWh**	**T€/MW sec. capacity**
Annuity capital costs	16,201	27.2	163.4
Fixed operation&maintenance cost	9,631	16.2	97.1
Variable Cost	10,098	17.0	101.9
Total Costs	35,931	60.4	362.4
	Mt	**t/GWh**	**t/MW sec. capacity**
Summed CO2_eq Emissions	271	455.7	2,736.0
Summed CMR	15	24.6	147.7
	km^2	**ha/GWh**	**ha/MW sec. capacity**
Summed Land use	31,229	5.2	31.5
	t	**kg/GWh**	**kg/MW sec. capacity**
Summed SO2_eq Emissions	355,607	597.5	3,586.8
Summed Nox Emissions	213,188	358.2	2,150.3
Summed Particular matter Emissions (PM10)	15,084	25.3	152.1
	Mio.€	**T€/GWh**	**T€/MW sec. capacity**
Summed Health cost from air pollution	4,967	8.3	50.1

As for the total costs of electricity production, the resulting LCOE for the whole mix is around 6.0 €-cent/kWh. This is comparable with the results of Kost et al. (2013), who estimated LCOE ranging from 4 to 10 cent/kWh for a fossil dominated production.

5.1.2 Indicators by energy technologies

In order to identify the impacts from each technology individually, Fig. 5.2 shows the relative share of all used technologies in the main indicators. For absolute numbers of all indicators in the reference year 2020 it is referred to Appendix B.1 - Fig. B.1 and following.

As for *Summed health costs from air pollution*, *CO_2eq emissions* as well as *CMR*, more than the half of the impacts can be traced back to energy production from lignite and hard coal. Furthermore, over 60% up to 95% of all the emissions impacts and the respective material requirements for production in 2020 are due to fossil-based energy technologies. Only in *summed land use*, the impacts of renewables dominate conventional energy production by far. In

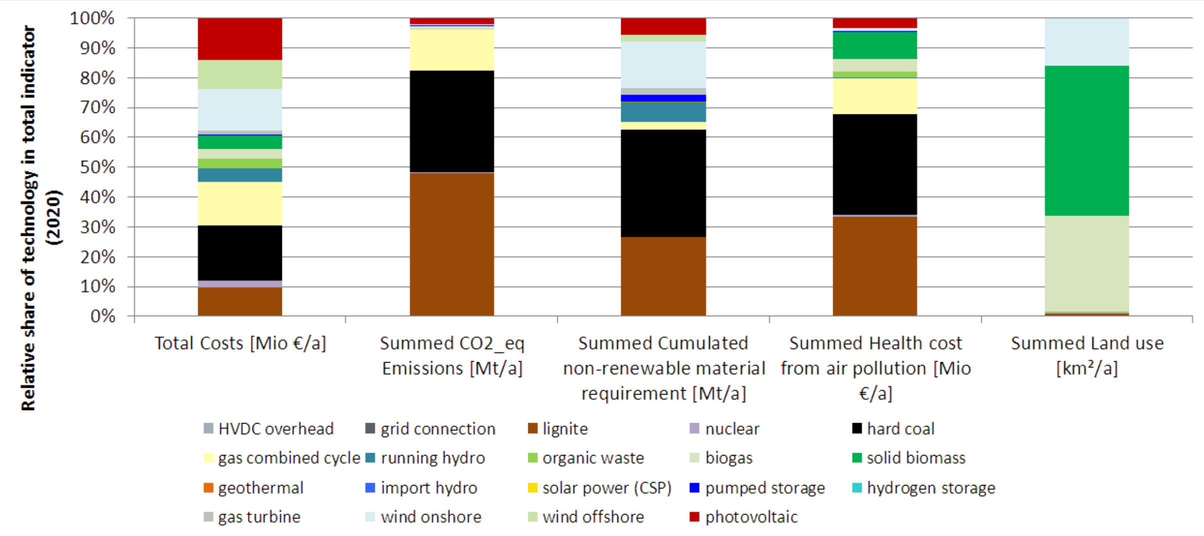

Fig. 5.2. Relative share of specific technologies in main indicators for reference year 2020

particular, energy derived from biomass shows a massive requirement for land in the reference year 2020, while only contributing 7% of the total generated power (see Fig. 5.1).

The total expenses for the expansion of renewables on one side and the conventional power plants on the other side are almost equal. As for the results of the SEnSys model, hard coal causes the highest *total costs* of all energy technologies with approximately 6.7 billion €. While hard coal is however contributing with around 18% to meet the energy demand, PV - being the second most expensive technology with around 5.1 billion €- is featuring only 6% of electricity generation in 2020. But, as mentioned before, the calculated *total costs* in Fig. 5.2 are only including all monetary costs that occur until 2020, and therefore neither reflect annuity capital costs in following years nor external costs such as health costs of the population caused by air pollution (see Section 6.2.1 and Section 6.2.3).

5.2 Comparison of scenarios with SEnSys

While in the reference year both technology scenarios from Trieb (2013b) feature the same technology mix and accordingly same results, after 2020 each scenario is following a different technology pathway. The domestic scenario *Trieb1* focuses on the expansion of local but fluctuating renewables, which requires storage and grid extension technologies to balance out the intermittent nature of the electricity production. Other than that, the import scenario *Trieb2* compensates the back out from conventional power technology by moderate share of flexible but remote renewable sources, such as CSP powered electricity generation and hydro power from Norway (see Section 4.4.2). The simulated implications of these two different approaches until 2050 are presented in this chapter.

5.2.1 Technical analysis

Table 5.2 shows the outcome of the SEnSys model in terms of resulting secured capacity, used and excess energy, share of renewable sources as well as the diversity index for both technology scenarios. It can be shown that after 2020, the technology scenario *Trieb1* requires slightly more energy production to meet the same demand (as *Trieb2*) due to the losses from storage operation and transmission of fluctuating renewables.

Table 5.2
Secured capacity (SC), used energy (UE), renewable excess energy (EE), share of renewable sources (SR) and diversity index (D) for both scenarios

	Year	SC [MW]	UE [GWh]	EE [GWh]	SR	D
Trieb1	2020	99,144	595,198	576	40.3%	2.76
	2030	98,080	599,653	3,827	62.0%	2.79
	2040	97,028	589,232	673	80.8%	2.39
	2050	95,530	605,963	157	92.1%	2.09
Trieb2	2020	99,144	595,198	576	40.3%	2.76
	2030	98,180	583,029	321	60.1%	2.94
	2040	96,040	572,872	371	79.9%	2.89
	2050	94,736	562,352	317	90.3%	2.76

Furthermore, the not usable excess energy in *Trieb1* is reaching almost 4,000 GWh in 2030, while *Trieb2* is reducing excess energy to around 320 GWh in the same year. The excess energy of *Trieb2* is oscillating around the same level, whereas *Trieb1* can decrease the not usable energy significantly due to its high storage and transmission capacities. Moreover, the model results indicate that after 2030, the estimated diversity of power supply is declining steadily in *Trieb1*, when the CSP-based scenario is coming back to the same diversity index than 2020, but with a significant increase in power production from renewable sources compared to the reference year.

The results of the SEnSys model show that the *Trieb1* scenario does not only require higher energy production to meet the same demand, but does also imply higher capacity requirements than the import scenario after 2020. Fig. 5.3 illustrates the total requirements of installed capacity, to reach the desired connected capacity for both technology scenarios. A full list of all different capacities for all technologies and respective years can be found in Appendix B.2 - Table B.2.

As for the capacity that needs to be shut down before reaching its respective lifetime, both technology scenarios do not differ substantially. The results in Fig. 5.4 indicate that from 2030 on high excess capacity from fossil-based power plants occur in both scenarios, which results in early retirement of up to 45 Giga Watt (GW) before the end of the respective economic lifetime.

Compared with the additionally added capacities in the same figure, it is obvious that the new built hard coal and lignite power plants from 2011 to 2020 are not in accordance with the desired back out of fossil fuels from 2030 on in both scenarios. Likewise, the additional construction of over 15 GW gas combined cycle plants from 2021 until 2030 in *Trieb2* is resulting in more than 13 GW excess capacity (only from that technology) that needs to be disconnected after just one decade before reaching its respective lifetime.

Other than that, the results of the SEnSys model show that scenario *Trieb1* requires significantly more additional capacities to meet the estimated demand from 2030 on. Besides higher capacities of wind plants, this can be traced back to an increased expansion of storage and network

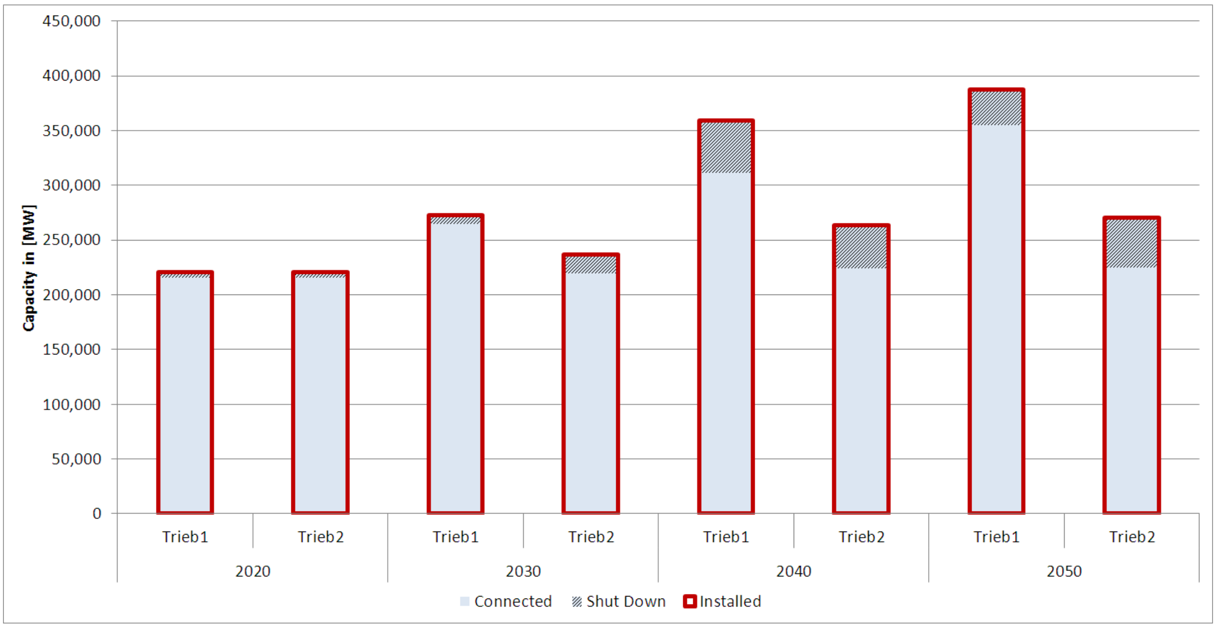

Fig. 5.3. Total installed, connected and shut down capacities of all power plants (incl. storage) for both scenarios

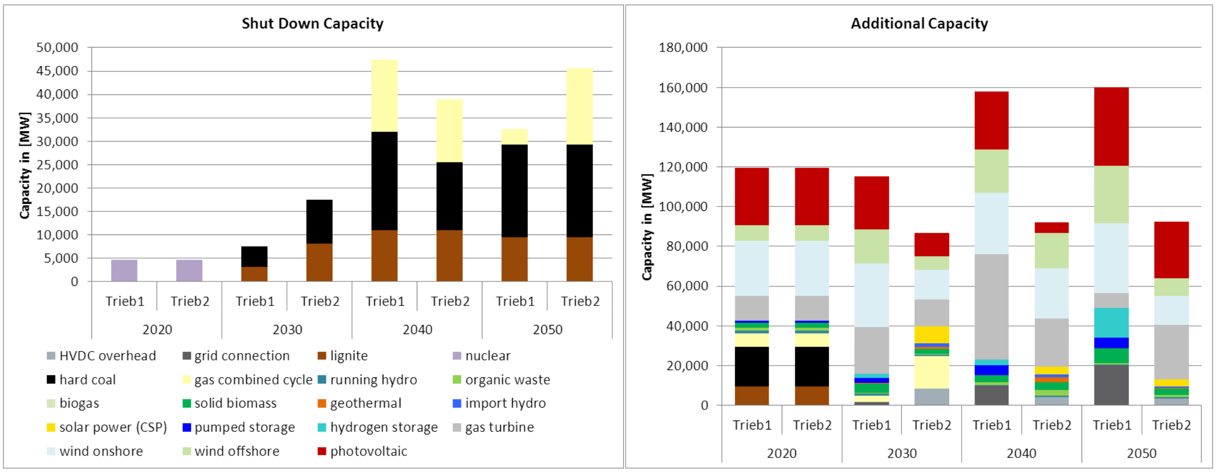

Fig. 5.4. Additional required and shut down capacity by technologies in both scenarios

technologies as well as a significant additional installation of gas turbines until 2040, to balance out the high share of fluctuating renewable sources (see Fig. 5.4).

5.2.2 General Indicators

Apart from the technical implications of the two different energy scenarios in the previous chapter, the SEnSys model provides also sustainability indicators for the comparison of the two different energy scenarios from Trieb (2013b).

The results of the main sustainability indicators from the SEnSys model for both technology scenarios are presented in Table 5.3. In order to fully access the impacts of electricity generation in the period after 2010 to 2050, the results are given as aggregated numbers (summed up over all respective years). While land use is considered as a main indicator, aggregation of this indicator is not feasible because land is mostly occupied by energy technologies and not consumed. Therefore, numbers for land use of the SEnSys model are shown as annual indicators in Section 5.2.3 and Section 5.2.4. Datasets of all relevant aggregated indicators for both scenarios are presented in detail in Appendix B.2 - Table B.3.

Table 5.3
Aggregated indicators for both scenarios from 2011 to 2050

Main Indicators	Trieb1	Trieb2	Δ Trieb1 to Trieb2
Total Costs in [Mio €]	1,914,413	1,762,439	7.9%
Investment Costs in [Mio €]	658,257	518,634	21.2%
Summed CO2_eq Emissions in [Mt]	7,127	6,713	5.8%
Summed CMR in [Mt]	375	320	14.7%
Summed Health cost from air pollution in [Mio €]	152,780	145,593	4.7%

One of the major findings from the comparison of the two energy scenarios with the SEnSys model is that, in every aggregated indicator, the scenario *Trieb1* has noticeable higher negative impacts then *Trieb2*. The almost twofold additional capacity of the domestic *Trieb1* scenario after 2020 (Fig. 5.4) is in particular reflected in the increased cumulated non-renewable material requirement (CMR) as well as the estimated investment costs, which are around 15% and 21% higher than *Trieb2* respectively. In that way, the difference for the aggregated *CO_2eq emissions*, as well as both *total costs* and *health costs*, are less significant but still noticeable with around 5-8% higher numbers for *Trieb1*.

It is worth mentioning again that the total costs in Table 5.3 are only including all the costs that would have to be paid from the year 2011 to 2050 and accordingly do not reflect costs occurring in later years.

5.2.3 Indicator in comparison with reference year 2020

Another way to present the results of the SEnSys model is in relation to the reference year 2020. As illustrated in Fig. 5.5, both scenarios reduce their annual negative impacts until 2050 in three of the five main indicators. Only *total costs* and *land use* are rising in relation to the reference year 2020.

When comparing both scenarios in Fig. 5.5, the indicators show the same general trends in most of the presented indicators until 2050. Yet, *Trieb2* is reducing its respective *CO_2eq emissions* and *health costs* in a earlier state, thus resulting in smaller aggregated impacts over the entire period, as mentioned before. Likewise, the significant higher CMR numbers of *Trieb1* are well reflected in the relative numbers to 2020 too. After a clear decrease from 2020 to 2030, the requirement of non-renewable material for construction is rising again steadily. For the same indicator, the results of the SEnSys model show that scenario *Trieb2* is reducing material demand for electricity generation until 2050.

Moreover, the results of the *SEnSys* model show that the *total costs* in *Trieb1* increase by over 55% in 2040, whereas in scenario *Trieb2* the increase in *total costs* is around 33% in the same

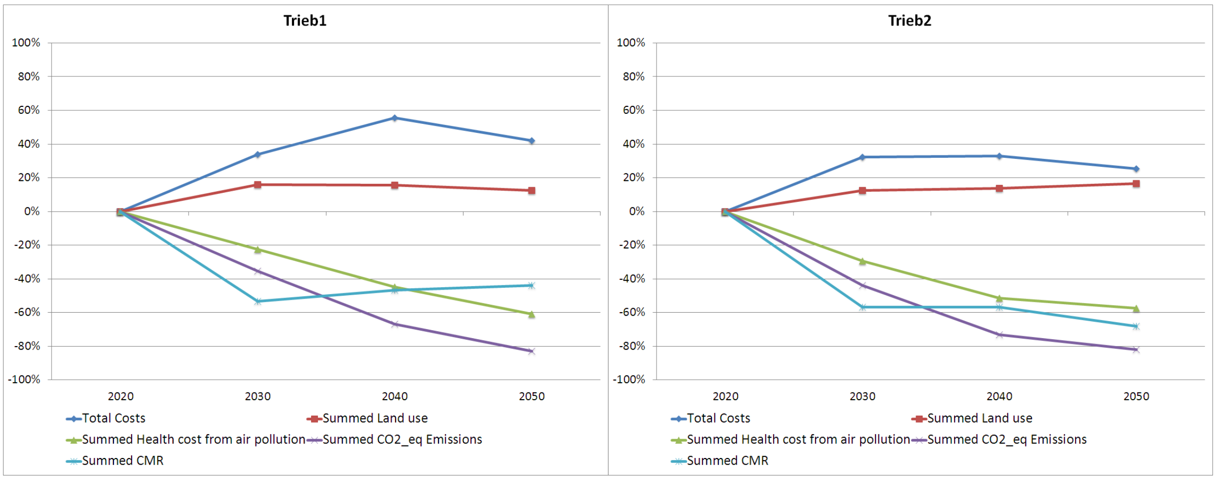

Fig. 5.5. Relative difference of total annual indicators to reference year 2020

year. One decade later, the high *total costs* of energy production in *Trieb1* are declining again to a 42% increase in reference to 2020. Likewise *total costs* in *Trieb2* are also declining, yet to a comparably lower number of approximately 25%. As for *land use*, scenario *Trieb1* shows a slight decreasing trend from 2030 on, while in the *Trieb2* option *land use* is steadily increasing up to 16% more than in 2020 respectively. In that way, *land use* is the only indicator from the results presented so far, in which the import scenario *Trieb2* is performing worse than the domestic counterpart.

A full list of all indicators in relation to the reference year 2020 for both scenarios can be found in Appendix B.2 - Table B.4.

5.2.4 Indicators by energy technologies

By looking at the share of the different technologies in the annual indicators, the different implications of both scenarios due to the choice of key technologies become even clearer. While the share of technologies for all SEnSys indicators can be found in Appendix B.2 - Fig. B.6, Fig. 5.6 illustrates exemplarily the implications for *material requirement*, *investment costs* and *total costs* resulting from the two different energy technology configurations.

The significantly higher CMR of *Trieb1* in comparison to *Trieb2* can be explained by steadily increasing additional wind power and storage capacity, which in 2050 account for almost 75% of the total CMR. This higher capacity requirement is even more reflected in the annual *investment costs* of the energy technology mix. Given the numbers of the SEnSys model, the grid extension due to high transmission capacity requirements in *Trieb1* accounts for approximately 20% of the total *investment costs* in 2050. In that way, only the *investment costs* for the additional network and storage capacities from *Trieb1* in 2050 would already pay half of the estimated *investment costs* for all technologies from *Trieb2* in the same year.

The picture is however changing when looking at the resulting *total costs* in the respective years (Fig. 5.6). Even while the mix and share of technologies in the figure are quite different in the two energy technology scenarios, the annual *total cost* do not differ more than 17% (2040) between

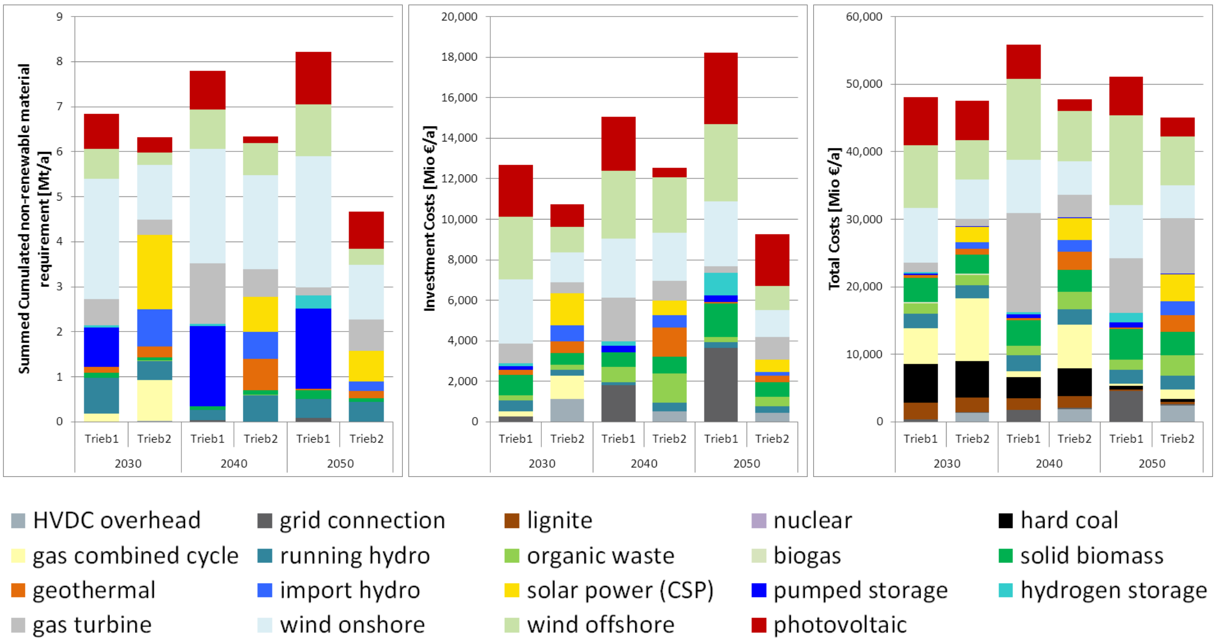

Fig. 5.6. Share of technologies in annual CMR, investment costs and total costs for both scenarios

Trieb1 and *Trieb2*. Moreover, in 2050, the summed up *total costs* of grid and storage technologies from *Trieb1* are almost equal to the summed spendings on CSP power generation and HVDC transmission lines. This shows that even scenarios with significant differences in technological solutions might still get comparable results in certain indicators due to compensation of impacts from different technologies.

Another result that can be derived from the simulation of the two Trieb (2013b) scenarios with the SEnSys model is the difference between impacts occurring from construction of energy technology and power generation. As explained in Section 4.2.3, the life cycle impacts of fuel-free (renewable) energies were assigned only to the construction phase, while fuel-driven technologies were assigned only to impacts resulting from power generation. Except for *particulate matter*, the SEnSys model indicates that only a small percentage of the total life cycle impacts is derived from construction of power plants. This is true for both scenarios, as exemplary illustrated for aggregated air pollution indicators in Fig. 5.7. A full list of all indicators is available in Appendix B.2 - Fig. B.7.

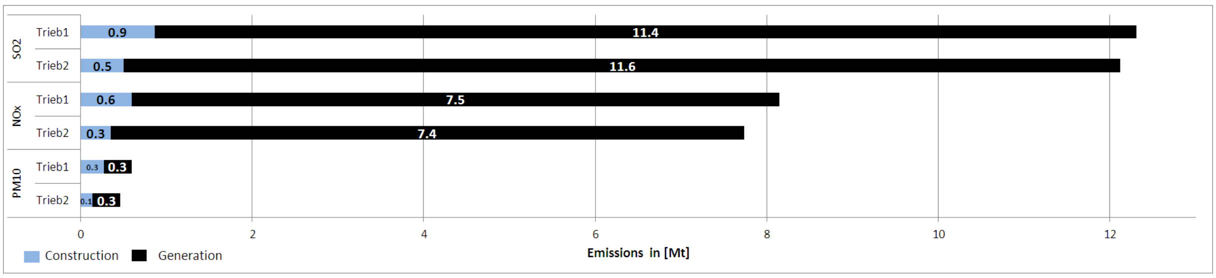

Fig. 5.7. Absolute share of construction and generation in air pollution indicators, in aggregated numbers from 2011 to 2050

When looking in more detail at the life cycle impacts of energy technology construction, the results of the SEnSys model show a clear trend for higher numbers for scenario *Trieb1* then *Trieb2* (see Appendix B.2 - Fig. B.8). In particular, indicators related to air pollution caused by construction work are rising significantly over the model period for *Trieb1*, as illustrated in Fig. 5.8.

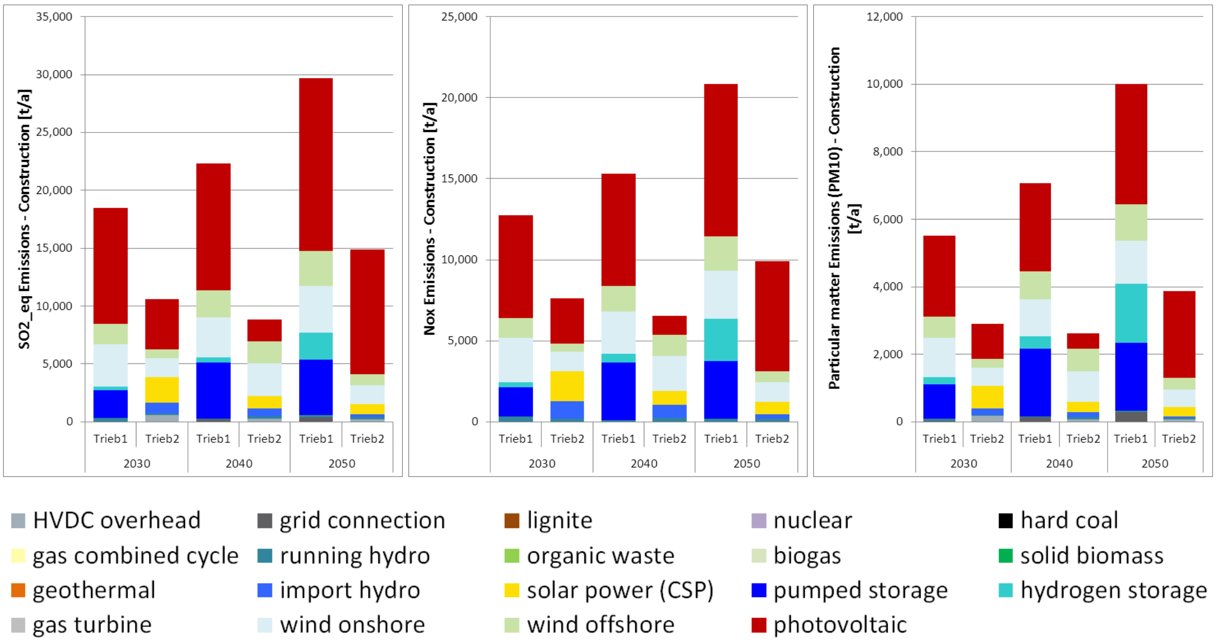

Fig. 5.8. Share of technologies in annual air pollution from construction for both scenarios

As for the technologies with the highest share in construction impacts, the model results show a clear dominance of PV followed by storage technologies and wind power. In that way, construction impacts related to CSP technology from the *Trieb2* scenario are comparably small. Other than that, the life cycle impacts from the extension of both transmission technologies seem almost negligible in both scenarios.

The implications and consequences of the presented results for this case study in relation to sustainable energy systems will be discussed in more detail in the following chapter.

6. Discussion

The case study results of the SEnSys model from the previous parts are discussed in more detail in this chapter. Beside a interpretation of the results in the light of sustainable energy systems, a detailed comparison with a previous study on the Trieb (2013a) scenarios is given. Moreover, the significant strengths and weaknesses of the SEnSys model approach are discussed, and along with that recommendations for further research are presented.

6.1 Case study results

This chapter has a look at the results of the case study from the previous parts in terms of sustainable energy systems. Beside a brief interpretation of the results for both analysed scenarios, new insights from this thesis in comparison with previous studies are discussed.

As the following discussion is based on the results from the SEnSys model approach, all the identified limitations and uncertainties from Section 6.2 apply also to the findings of the case study and accordingly to the comparison of both technology scenarios from Trieb (2013a).

It is worth mentioning that in order to give an overall statement on sustainability of the different energy technology scenarios examined in this study, various integration methods for multi-criteria analysis could have been applied to the resulting indicators. For instance Zolfani and Saparauskas (2013) propose a so-called *Step-wise Weight Assessment Ratio Analysis*, which consists of a ranking of priorities by an expert committee. However, as most multi-criteria methods require a high manual and personal effort and bare the risk of bias, the results of the SEnSys model are not processed further, but presented as independent indicators. In that way, a possible weighting and integrated evaluation of different indicators in relation to SD is a matter for the individual reader or possibly a challenge for further research.

6.1.1 Interpretation of the results

From the comparison of both energy technology scenarios from Trieb (2013a) with the SEnSys model, it can be stated that scenario *Trieb2* performs better in all chosen sustainability indicators than *Trieb1*, with small exceptions for *land use* and *health costs*. This is true for both the trends in annual numbers as well as for the aggregated impacts over the whole simulation period from 2010 to 2050. Given the numbers of the SEnSys model from Table 5.3, it can be stated that scenario *Trieb2* is reaching the same share of renewables and meeting the same demand as *Trieb1* in 2050 with significant lower costs and material requirements as well as slightly less environmental impacts. In addition to that, the development of technology pathway *Trieb1* requires significantly higher additionally constructed capacities and, according to the SEnSys model, results in a less diversified and hence supposedly more unstable power supply in Germany in the long run (Pisano, 2012).

In order to assess the implications of each energy technology scenario, it is useful to have a look at the three basic aspects (pillars) of SD in more detail (Rogers et al., 2008). As for the economic pillar, the main indicator used for this study is the *total costs of electricity generation*, including *annuity capital costs*, *fixed operation&maintenance costs* and *variable costs*. The results of the SEnSys model show a clear advantage for *Trieb2* over scenario *Trieb1*, with around 8% lower aggregated *total costs*. This can be explained by the significant higher additional capacities in *Trieb1* (see Fig. 5.4) after 2020, resulting in higher *annuity capital* and *fixed operation&maintenance* costs accordingly. From Fig. 6.1, it can be stated that the comparably stronger expansion of fluctuating renewables, network and storage technology is causing higher costs than the additional import from distant flexible energy sources via HVDC. While *total costs* are including only the costs that have to be paid until the respective year (see Section 6.2.1), a comparison of *investment costs* shows a clear advantage of the import scenario *Trieb2* over *Trieb1* in terms of expenses. As mentioned before, the *total costs* in this study do neither reflect the *health costs* nor any other external costs. For further studies it is recommended to include external costs from Krewitt (2007) or other relevant sources.

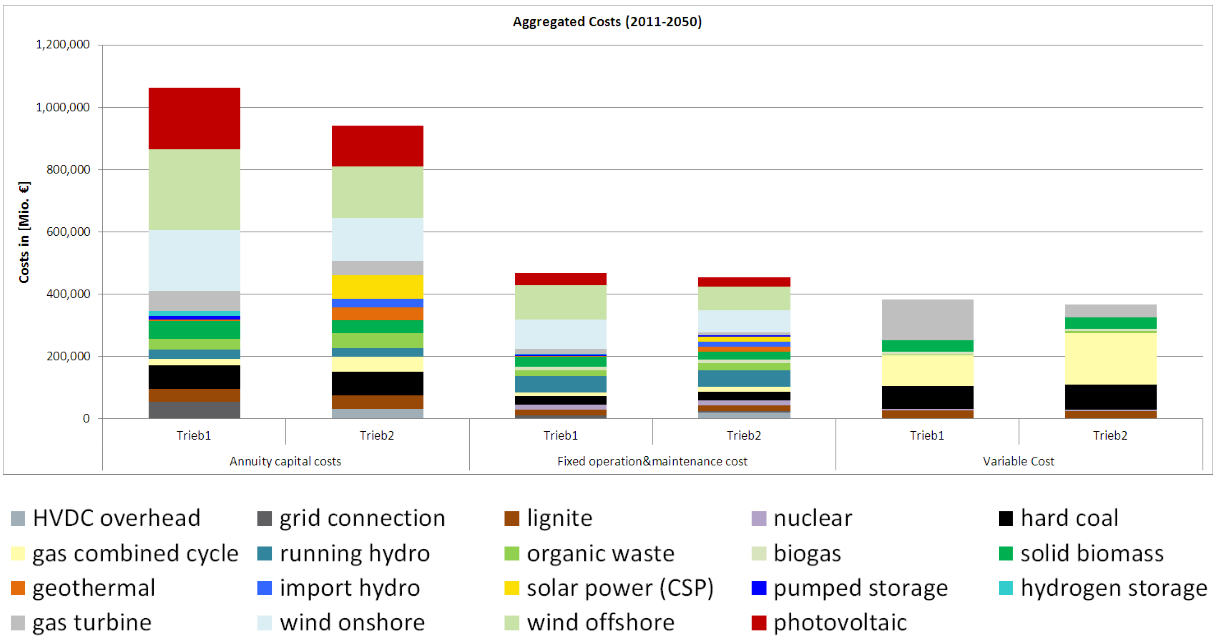

Fig. 6.1. Aggregated annuity capital, fixed operation&maintenance and variable costs (2011-2050) by technologies

Beside a clear advantage of scenario *Trieb2* in economic terms, the results of the SEnSys model indicate also an overall better performance in environmental aspects for the flexible imports scenario. Given the numbers in Table B.3, it can be stated that the domestic renewables scenario *Trieb1* shows a significant higher CMR as well as slightly higher emission values in aggregated numbers than *Trieb2*. Only in 2050, *Trieb2* is requiring slightly more land for its respective power generation than *Trieb1*. This can be explained by the then higher numbers for electricity generation from solid biomass and CSP in scenario *Trieb2*, as illustrated in Fig. 6.2.

However, according to Droste-Franke et al. (2012), land use changes should be evaluated in terms of previous land type respectively. In that way, both power generation from hydro power and in particular CSP from technology scenario *Trieb2* are situated outside Germany, in countries (Norway and Morocco) with significant lower population densities and accordingly less stress on land resources (World Bank Group, 2013). Moreover, as CSP technology is performing best at sites with high solar irradiation and arid climate, CSP plants can be constructed in desert areas,

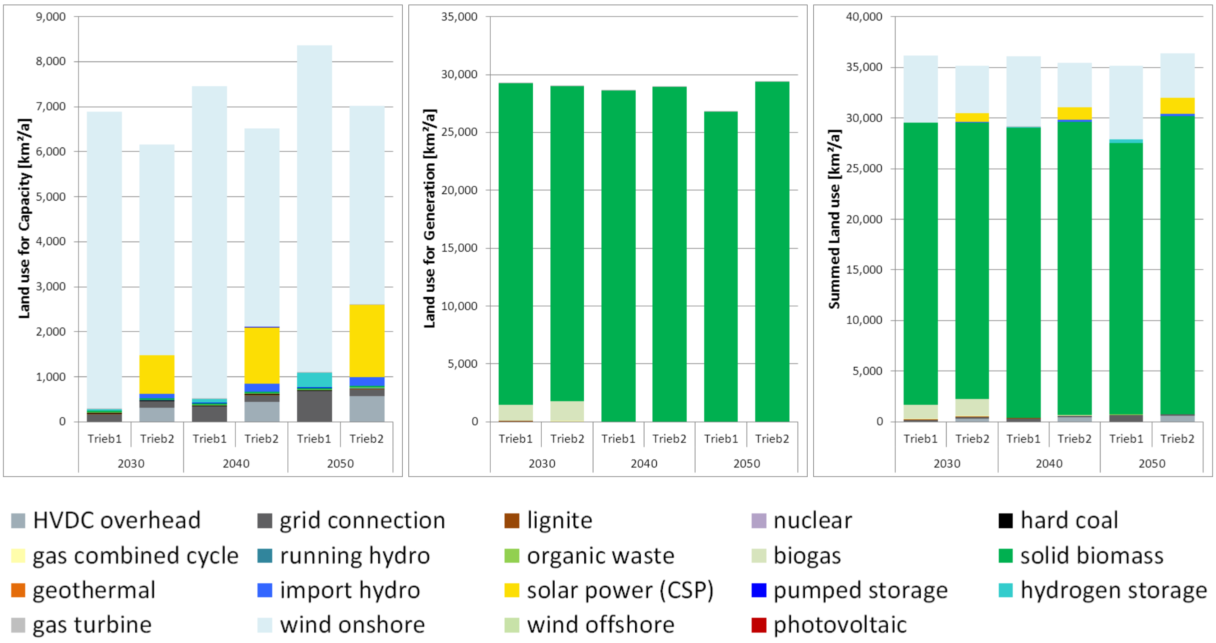

Fig. 6.2. Annual land use of both scenarios by capacity and generation requirement

resulting in no land use competition with urban or agricultural land (Trieb et al., 2006). Quite the contrary, sea water desalination and shadowing from CSP technology can enable agriculture in the first place and accordingly expand usable land rather than consuming it (Hitchin, 2014; Trieb et al., 2007). Given that, land use from Norwegian hydro power and CSP plants in North Africa should be accounted for differently. Accordingly, it can be stated that *Trieb2* is featuring less or almost equal land use than the domestic scenario *Trieb1*, even if *Trieb2* shows an increasing trend of land use throughout the SEnSys model time (Fig. 6.2).

In terms of social implications, the findings of the SEnSys model can only be seen as a preparatory study due to the limited indicators in that field (see discussion in Section 6.2.1). Nevertheless, when taking estimated *health costs* of the SEnSys model as an indicator for social implications of power generation in Germany, the picture is not as clear as for the economic and environmental aspects presented earlier.

On one hand, technology scenario *Trieb1* is starting with relative higher numbers for *health costs* in 2030, while the annual numbers in Fig. 6.3 show a strong downward trend, which results in relatively lower *health costs* in 2050 for *Trieb1* compared to *Trieb2*. This can be explained by the combustion of more solid biomass and organic waste in scenario *Trieb2*, resulting in higher numbers for NOx and SO_2 emissions in 2050.

But on the other hand, taking into account the full impacts over the whole model period, energy technology scenario *Trieb1* is causing slightly more aggregated *health costs* than the import scenario *Trieb2* (see Table 5.3). It is therefore hard to assess which technology option would have an greater impact on the population from the results of the SEnSys model.

One of the key aspects when it comes to assessing social aspects of technology pathways is the acceptance and support of the social framework for necessary changes and burdens related with

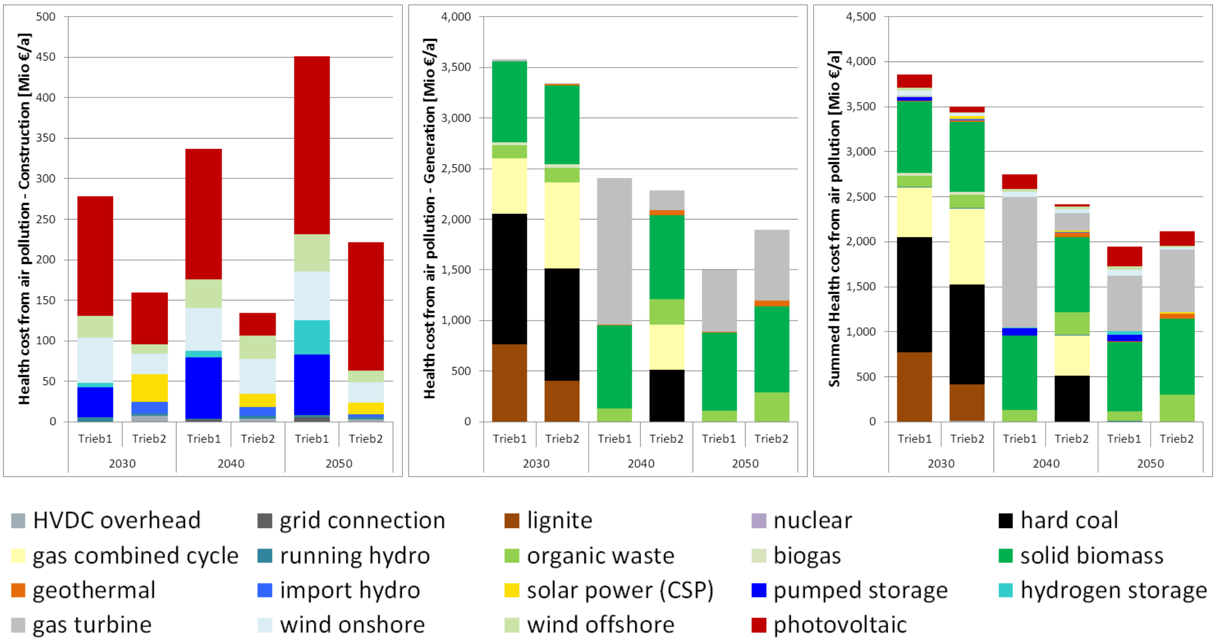

Fig. 6.3. Annual health costs of both scenarios by capacity and generation requirement

it (IEA, 2012a). In that way, the higher total costs and environmental burdens of scenario *Trieb1* due to higher generation, storage and grid capacities - as estimated by the SEnSys model - could indicate more restrictions towards the development of this technology pathway.

However, opposite to that, plans of ostensible centralized, high tech and large scale CSP plants in remote deserts might lead to reservations among advocates of a decentralized and grassroot-based transformation on the German energy system. Moreover, the construction of intercontinental HVDC transmission lines would of course not only require acceptance from the German society, but would need extensive international support from industries over politicians to affected citizens.[1] In terms of supply guarantee and security risks, the public opinion towards scenario *Trieb2*, with power generation that is to some extend depending on imports from foreign countries, might be sceptical as well. However, to be fair, the current and the designated power production of scenario *Trieb1* is also requiring significant resource imports from fossil fuels such as natural gas, although less perceived in public (Trieb, 2013a).

Given these contradictory opinions, it is hard to provide a final statement for the social sector, just by the resulting indicators of the SEnSys model. It is therefore recommended to address the limitations and weaknesses of the SEnSys approach, as discussed in Section 6.2, and accordingly compile a more detailed study on the sustainability implications of both energy technology scenarios from Trieb (2013a) with the new model parameters, as well as a qualitative social study on the acceptance of certain technology options in Germany.

[1] While the import scenario of Trieb (2013a) is based on citizen participation (in all affected countries) - both for investment and operation of the CSP plants and HVDC transmission lines - and is designed to not replace but rather complement local renewables, this message might not be enough communicated to the public. For a detailed description (in German) of an exemplary integration of CSP technology in the state of Baden-Württemberg it is referred to Hess (2013).

6.1.2 Comparison with previous study

This chapter compares the results of the SEnSys model with a previous study in order to identify which findings are matching or contradictory, as well as new findings the analysis did provide. The case study in this thesis is based on the data provided by Trieb (2013b), who was also assessing the implications of the both scenarios in Germany until 2050. The full data set used for this comparison can be found in Appendix C.1 - Table C.1.

Other than the SEnSys model approach, the study of Trieb (2013b) used a *greenfield site* approach, which simplified constructed all power plants and related infrastructure each decade completely new.[2] Furthermore, the analysis of Trieb (2013b) presents only annual numbers, while not taking into account the full impact of the indicator as in the aggregated numbers of the SEnSys model. Both analyses have in common that the full load hours of each technology and , accordingly, the share of generated energy were calculated with the ELCALC model and that data for the economic analysis were mostly derived from Nitsch et al. (2012a).

The reflection of technology series together with their respective economic lifetimes was resulting in higher numbers for the SEnSys model in terms of installed capacity, whereas the analysis of Trieb (2013b) was setting the connected capacity equal to the installed capacity. This is in particular noticeable by the high shut down capacities of both energy technology scenarios, as presented in Fig. 5.4. In that way, the SEnSys model shows that the back out from fossil energy technologies in both scenarios is not in balance with the high connected capacities required earlier. The results of the SEnSys model do further allow identifying which technology series are shut down how many years after construction or before reaching its respective economic lifetime. For future studies, it is therefore recommended to use these findings of the SEnSys model to decrease unnecessary shut down capacities in the scenarios in order to prevent avoidable impacts such as in Fig. 6.4.

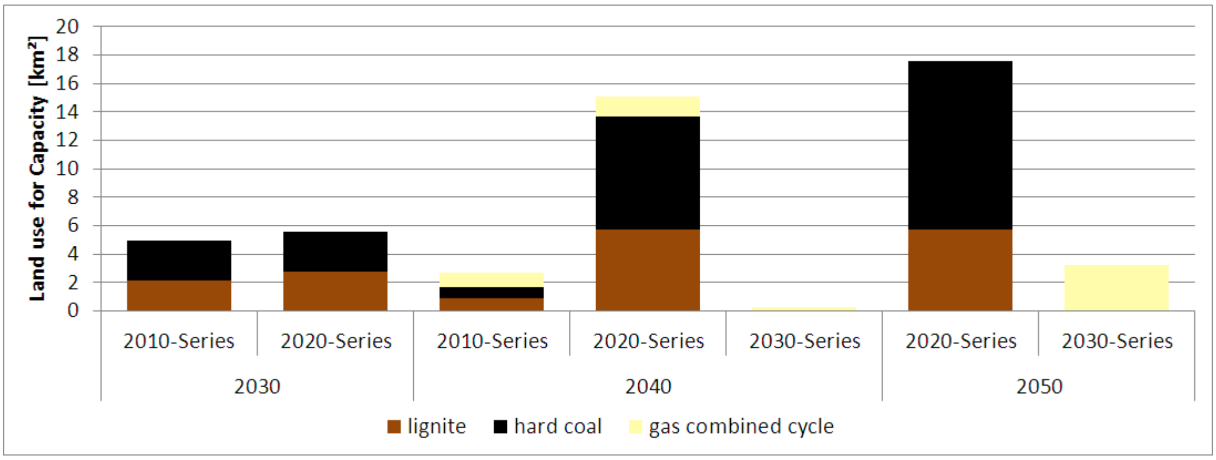

Fig. 6.4. Land use of shut down plants in scenario Trieb2 as exemplary impacts from high shut down capacities

[2]The SEnSys model approach was estimating the real additional capacities (by series) that would be required in each decade to reach the desired connected capacity of the technology scenarios, as explained in more detail in Section 4.3.1.

Plants that are shut down before reaching their lifetime in the SEnSys model do still cause *land use*, *annuity capital costs* (if still inside the depreciation period) and *fixed operation&maintenance costs*. These additional requirements were not reflected in the analysis of Trieb (2013b).

When compared in absolute numbers, the results of Trieb (2013b) and the SEnSys model, in the available environmental impacts, do not differ substantially from each other. In Fig. 6.5, the CO_2 *emissions* show a clear downward trend both for the SEnSys and the Trieb (2013b) results. The additional land use from shut down capacities does not explain the higher annual land use in the SEnSys simulation, as the impacts are negligible (compare numbers in Fig. 6.4 with Fig. 6.5).

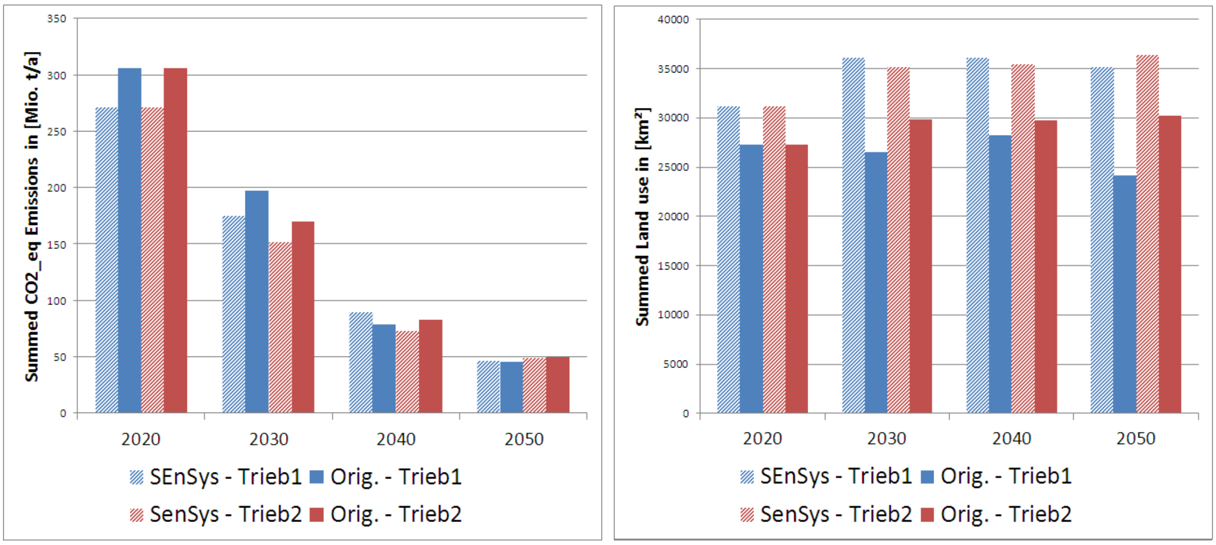

Fig. 6.5. Direct comparison of annual results for environmental impacts from Trieb (2013b) (=Orig.) and SEnSys model

As for economic indicators, the results of the study from Trieb (2013b) and the results in this thesis are totally different, due to the different approaches for installed capacity as mentioned earlier. Naturally, the investment costs of Trieb (2013b) are way higher than in this study, as the whole capacity was rebuild every presented year. In that way, the difference to the SEnSys model does reflect the share of technologies that were already installed in previous decades (Fig. 6.6). This difference is of course also noticeable in the LCOE, although less significant.

Beside absolute numbers, the results of the SEnSys model and the original results of Trieb (2013b) can also be compared in relative trends of both energy technology scenarios. In that way, the difference in the installed and additional capacity approaches should be less distinctive for the comparison. The relative differences between scenario *Trieb1* and *Trieb2* from both studies in Fig. 6.7 do not show a clear trend inside the indicators. While some indicators show almost equal relative differences from *Trieb1* to *Trieb2* - such as CO_2 and *Investment costs* in 2030 - other differences are contradictory to each other (e.g. CO_2 in 2040). However, in general terms, it can be stated that the comparison of the two energy technology scenarios with the SEnSys model approach does affirm the basic findings of Trieb (2013b).

Another result of this thesis that can be compared to the study of Trieb (2013b) is the development of indicators in relation to the reference year 2020 (see Section 5.1). For the reduction in

Fig. 6.6. Direct comparison of annual results for economical impacts from Trieb (2013b) (=Orig.) and SEnSys model

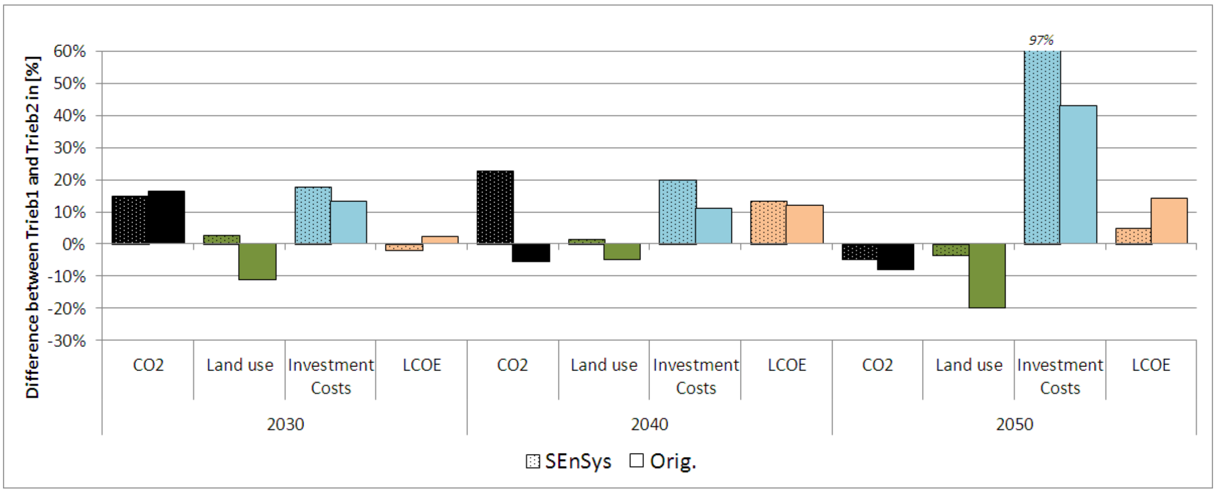

Fig. 6.7. Relative difference of annual numbers between scenario Trieb1 and Trieb2 from Trieb (2013b) (=Orig.) and SEnSys model

CO2 from 2020 on, both model approaches show almost identical matches in both technology scenarios (see Fig. 6.8). While land use in scenario *Trieb2* gets similar results from the two model approaches, the numbers for land use in *Trieb1* show some clear deviations between SEnSys and the original study.

The match between the different model approaches in terms of economic indicators (in reference to 2020) does not provide a clear picture, as illustrated in Fig. 6.9. Whereas the *investment costs* in *Trieb1* and, to some extent, in *Trieb2* show at least a similar trend, the two models are showing significant differences for the development of the LCOE after 2020. The SEnSys model indicate that the LCOE are rising in respect to the reference year, while the findings of Trieb (2013b) show identical costs for *Trieb1* and even declining costs for *Trieb2*. The results for that

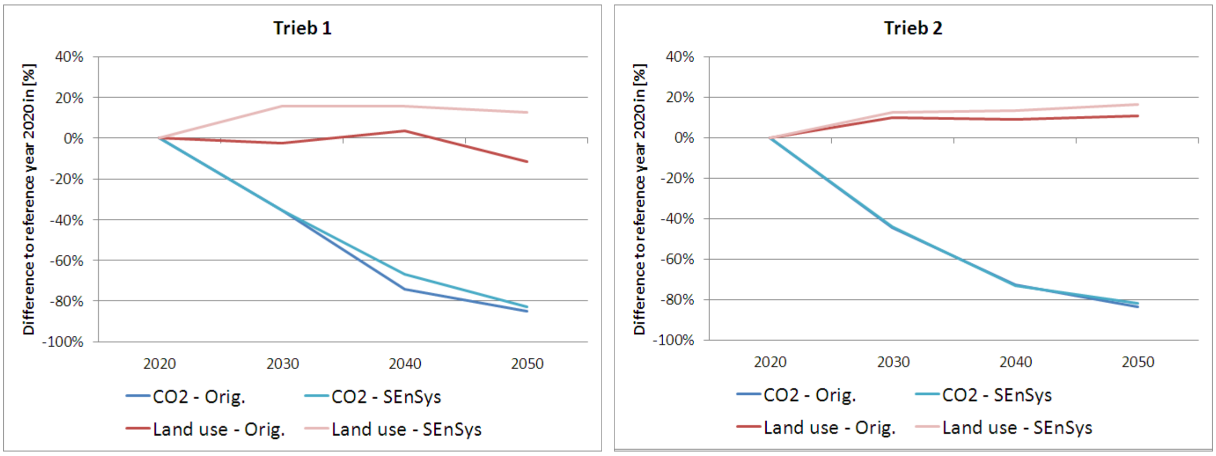

Fig. 6.8. Development of environmental indicators in reference to 2020 from Trieb (2013b) (=Orig.) and SEnSys model

particular indicator indicate that the more complex approach of the SEnSys model does provide new findings in comparison to the previous estimations of Trieb (2013b).

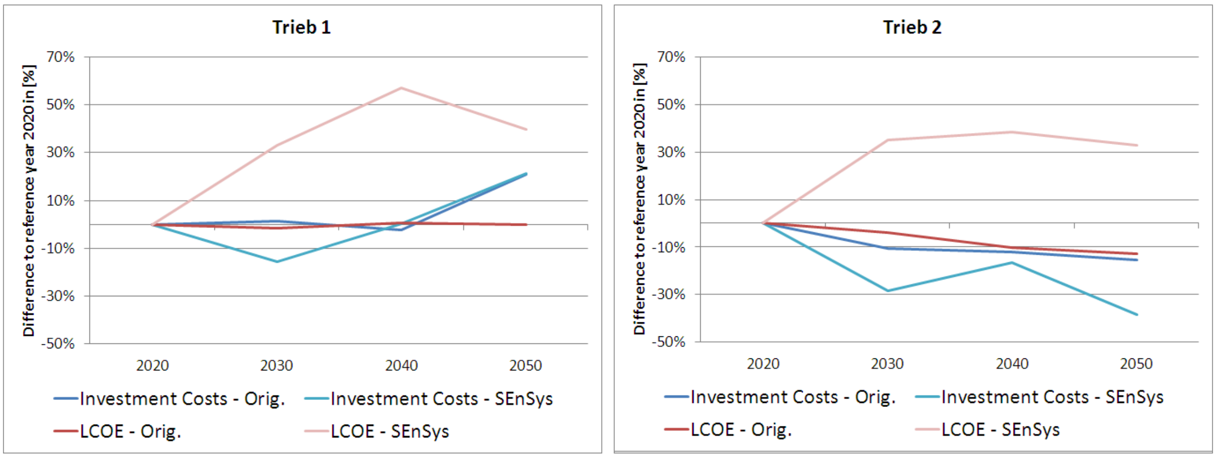

Fig. 6.9. Development of economical indicators in reference to 2020 from Trieb (2013b) (=Orig.) and SEnSys model

A majority of the general findings of Trieb (2013b) could be affirmed by the results from this thesis. For instance, the comparably higher material requirement and costs for *Trieb1* to *Trieb2* from Trieb (2013b) could be second by various results of the SEnSys model. Moreover, the reduction of CO_2 *emissions* from 2020 on is well reflected in both studies. As for land use, the results of this thesis indicate higher numbers and show no significant reduction after 2040 for *Trieb1*. It is thus recommended to compare the two model approaches in more detail for this particular indicator. The results for costs did naturally not match due to the different approach of Trieb (2013b) (annual rebuilding of all plants). In that way, the SEnSys model showed clear differences and accordingly provided new insights in reference to the comparison of the two different energy technology scenarios for power supply in Germany.

6.2 Assessment of the SEnSys approach

This chapter features a discussion of the strengths and weaknesses of the overall model approach, and provides specific suggestions and recommendations for further improvements of the SEnSys model.

To begin with, the development of the SEnSys model required the input and handling of large amount of data inside various applications. While the results of this thesis were reviewed several times - also by other scholars - it cannot be assured that no typing or converting occurred during the process. Moreover, as any other study that has set time restrictions, the development of the SEnSys model required certain simplifications and limitations to stay inside the scope of this thesis. This can in certain cases result in high uncertainties and misinterpretation of the results. Among other model development steps, this applies in particular to the choice and data acquisition of indicators as well as the actual modelling of energy systems. The resulting implications for these model elements are discussed in more detail in the following chapters.

6.2.1 Choice of indicators

The final choice of indicators for the SEnSys model was based on relevance and workload for data acquisition of the specific indicators (see Table 4.1 in Section 4.1.2). Whereas the relevance of the indicator was determined by the frequency of the respective indicator from the literature review described in Section 4.1.1, the workload was based on own estimations. This simplified approach allowed to compile the data acquisition in a reasonable time span while still featuring a meaningful set of indicators. However, it stays uncertain whether the frequency of an indicator in multiple sources is truly representing the relevance or importance or rather just a widespread agreement on scientific hot spots in the sustainability discussion. To make things even more complicated, *relevance* can be seen as a subjective term that only gets a meaning when applied to a certain point of departure and specific interests. Furthermore, from a science-and-technology studies perspective, the agreement on scientific and, in particular, political papers can be seen as a social process, which is accordingly subject to social frameworks and power relations (Heiskanen, 1997). In this regard, a somehow biased choice of indicators cannot be completely ruled out by any means.

Given these uncertainties, it seems feasible to define relevance by the frequency of indicators mentioned in various sources from different political and scientific fields, knowing and taking into account the limitations and drawbacks of this simplified approach. This applies in particular to the social sector, as discussed later in this chapter.

As for the economic sector, the SEnSys model could be criticized for providing only a macroeconomic perspective of the different energy technology scenarios. In that way, the model cannot assess whether the operation of the plants would generate enough income to, at least, compensate the expenses from a business perspective.[3] This would, however, require an elaborate modelling of demand and supply scenarios, coupled with price and market development including new ways of financing such as capacity markets or demand side management schemes (Droste-Franke et al.,

[3] In particular, the decreasing full load hours or early retirement (shut down) of conventional power plants - as seen in the results of this case study - might lead to unprofitable situations for power plant operator, if no additional market mechanism are set up.

2012). It is therefore questionable whether the effort to implement a comprehensive business perspective into the SEnSys model would be feasible.

Another aspect of the used economic evaluation that could be criticized is the exclusion of external costs from the total costs calculation. As stated by Trieb et al. (2006), the European Commission assumes that each kWh produced energy in the current mix, accounts for around 5€-cents of external costs, ranging from climate change over acid rain to actual health costs for the population. This would for instance almost double the LCOE from 2020 in the case study (see Fig. 6.6). Given this numbers, it is highly recommendable to implement an external costs option into the calculation of the total costs inside the SEnSys model. As proposed by Droste-Franke et al. (2012), the database from *ExternE* and following projects could be used as a comprehensive data source for this task (IER, 2014).

In terms of environmental indicators, it can be stated that the SEnSys model provides already a sound collection, which could naturally be extended. From the environmental indicators of Table 4.1 that were omitted from this analysis, indicators concerning waste and water treatment, as well as biodiversity and habitat fragmentation, could be added for further studies. Along with that, a more detailed analysis of specific material requirements - possibly supplemented by a rough estimation of resource availability - would help to strengthen the significance of the SEnSys model in terms of environmental indicators.

One of the major drawbacks of the SEnSys model so far, is the under-representation of social indicators in the analysis. In this study only health costs caused by air pollution were considered as social implications of the examined energy technology scenarios, as described in Section 4.2.4. However, according to a social study on citizen preferences towards energy scenarios from 1985 by Renn et al. (1985), the almost 500 participants ranked *environmental impacts* and *health and safety* as the highest priorities, followed by security of supply. In that way, it could be argued that the SEnSys model, developed in this thesis, already featured a part of the most relevant indicators when it comes to public acceptance and support of energy options. While the study of Renn et al. (1985) was conducted almost 30 years ago, a more recent paper by Gallego Carrera and Mack (2009) lists a more detailed set of possible social indicators. Compared with the list of Gallego Carrera and Mack (2009, p. 6), only 3 out of 20 social sub-indicators are included in the SEnSys model. An extension of social criteria seems therefore crucial for further studies. In particular, the assessment of participative decision making is highly recommendable from the findings of Gallego Carrera and Mack (2009), together with two additional technological parameters concerning visual impacts and noise pollution of the respective plant.

However, the acquisition of data for social indicators can be rather difficult as no common theory or model exists in this field (Gallego Carrera and Mack, 2009). Furthermore, the natural subjectivity of social indicators does not always allow a pure quantitative assessment, and must therefore be supplemented by qualitative data too. Further research is required to identify feasible ways to include qualitative data into a numerical model, such as the SEnSys approach.

In summary, it can be argued that the choice of indicators for the SEnSys model was done in a simplified but feasible manner, concerning the scope of this study. A more detailed analysis of the indicators reveals however that the range of indicators should be extended for further studies, first and foremost in terms of the social sector.

6.2.2 Data selection and calculation of indicators

As shown in the previous chapter, the choice of indicators can have significant effects on the results. The same is of course true for the selection of factors and approaches to actually calculate the final indicators inside the model. Therefore, this chapter presents the main uncertainties in the factor calculation of the SEnSys model and compares input and output parameters with other relevant studies in the respective fields where applicable. This helps to assess the significance of the results of this thesis in the different indicators or sectors. It is worth mentioning that the range of factors used among different studies can be huge. This is due to either regional differences or varying basic assumptions such as the economic lifetime or average full load hours of energy technologies.

In terms of economic factors, the calculation of the SEnSys model required *investment costs*, *fixed operation&maintenance costs* and *variable costs* (see Section 4.2.2). The economic factors of this thesis can be compared to the OpenEI (2012) *Transparent Costs Database*, which provides a wide range of global historical numbers from highest to lowest (as well as a median value) for each energy technology. Another source for comparison is the *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants* published by the U.S. Department of Energy (EIA, 2013), together with estimations of IEA (2012b) for Europe as well as Kost et al. (2013) and the IINAS (2014) GEMIS database for specific numbers of Germany.

Fig. 6.10 shows the range of *investment costs* estimates from these sources in comparison with the factors used in this thesis for the main technologies. Beside running hydro power and geothermal power generation, it can be stated that the *investment costs* used for the SEnSys approach are on a relatively low scale in a global ranking. In particular the numbers for fossil power generation were estimated quite low, which should be considered when looking at the results of the SEnSys model.

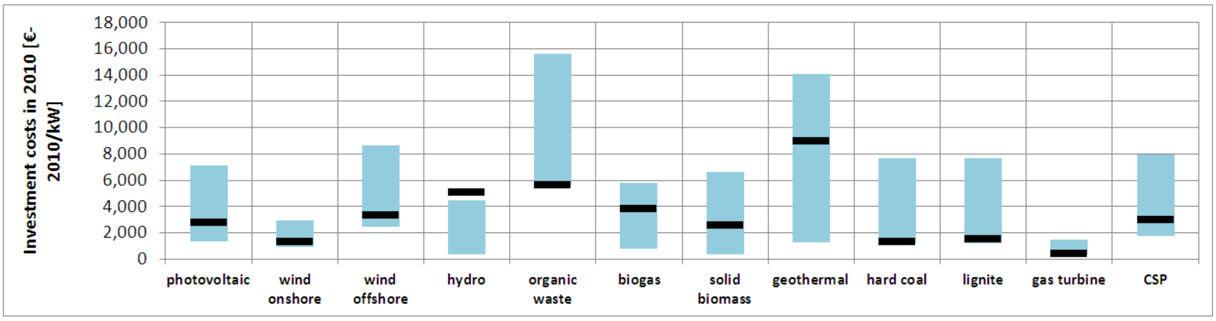

Fig. 6.10. Range of investment costs (blue bar) of main energy technologies compared with SEnSys factors (black line). Numbers are given for the 2010-series, in real monetary values of 2010. (data from OpenEI (2012), EIA (2013), IEA (2012b), Kost et al. (2013), IINAS (2014))

As for *fixed operation&maintenance costs*, the factors of the SEnSys model for wind offshore, hydro, biogas and geothermal power generation are significantly higher than the ranges given by other scholars, as illustrated in Fig. 6.11.

The comparison of *variable costs* from the SEnSys factors with other studies is difficult, as some studies differentiate between the costs of generation of energy and the extra costs for fuel consumption. In the case of the SEnSys model, only the fuel costs were assigned to the

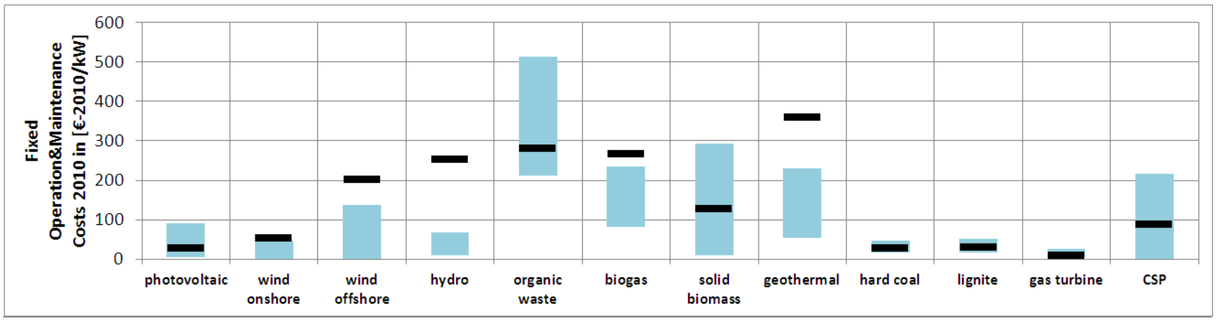

Fig. 6.11. Range of fixed operation&maintenance costs (blue bar) of main energy technologies compared with SEnSys factors (black line). Numbers are given for the 2010-series, in real monetary values of 2010. (data from OpenEI (2012), EIA (2013), IEA (2012b), Kost et al. (2013))

variable costs (see Section 4.2.2). This explains the too high numbers for fossil power generation in Fig. 6.12 and might therefore not be interpreted as an overestimation. Or on the contrary, the variable costs of around 5 €/MWh of coal plants just for operation are not reflected in the SEnSys numbers.

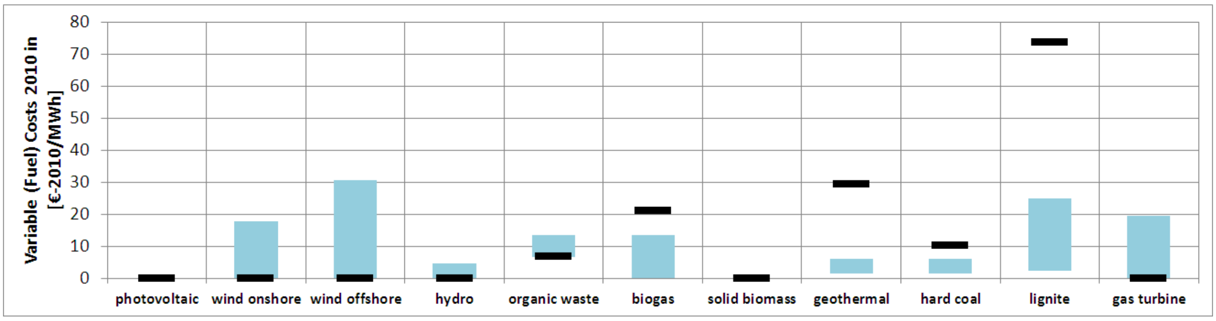

Fig. 6.12. Range of variable costs (blue bar) of main energy technologies compared with SEnSys factors (black line). Numbers are given for the 2010-series, in real monetary values of 2010. (data from OpenEI (2012), EIA (2013))

In addition to that, it is noticeable that the simplified approach of the SEnSys model to assign no variable costs for fuel free (renewable) power generation is not shared among all scholars. According to EIA (2013) and OpenEI (2012), advanced power generation technologies like CSP and offshore wind turbines can cause extra costs related to their respective energy generation. It is therefore recommendable to differentiate in further studies between pure variable costs and fuel costs, to ensure a better representation of the different energy technologies.

When taking into account all the differences between the economic SEnSys factors and other scholars, the results for costs estimates for certain technologies seem to be disputable. In that way, the high estimates in Fig. 6.10 and Fig. 6.11 indicate that the overall costs factors for geothermal and, in particular, hydro power in Germany inside the SEnSys model are most probably too high. Opposite to that, the comparison with other studies reveals that costs associated to fossil power generation might be estimated too low in the SEnSys model.

To get a more holistic assessment of the economic sector inside the SEnSys model, it is useful to have a look at the resulting LCOE from the case study with the ranges given by other studies.

The LCOE of the two energy technology scenarios are given as average numbers over the whole model period. From the comparison in Fig. 6.13, it can be stated that the majority of the SEnSys LCOE results are in a low range, but still in accordance with the findings of OpenEI (2012), Maxim (2014) and Kost et al. (2013). Only the total cost of power generation from biogas seems to be comparably too low in the results of this case study. The high average total costs of gas turbine power plants can be explained by the decreasing full load hours in both scenarios for fossil power generation.

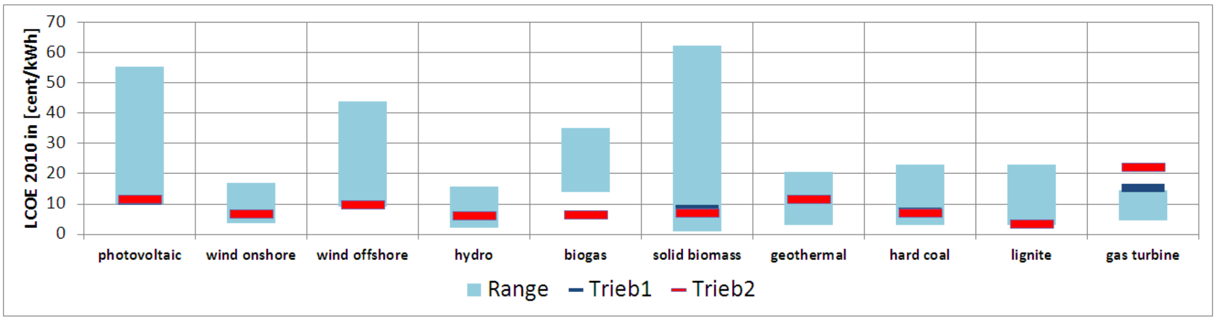

Fig. 6.13. Range of LCOE of main energy technologies compared with SEnSys results. Numbers are given for the whole model period, in real monetary values of 2010. (data from OpenEI (2012), Maxim (2014), Kost et al. (2013))

In a nutshell, given the comparison with other studies, it can be stated that the economic results of the SEnSys model can be interpreted as low estimates, but within a feasible range. In that way, the resulting total costs of the case study in this thesis might be higher in reality.

As for the selection of factors for life cycle impacts in the SEnSys model, false estimation could have occurred due to the standard generic technology parameters inside the GEMIS database. In particular, the set lifetime and average full load hours of the plants can have a big influence on the resulting LCA factors. This was already alleviated by assigning all the life cycle impacts of fuel-free rewewables, storage and transmission technologies only to the construction of the plants respectively. However, it is recommended for further studies to differentiate in more detail which impacts occur in which phase of the lifetime. Similar to May (2005), the impacts of each indicator could be differentiated for at least the construction, operation and decommissioning phase. This would allow more scenario specific results, less dependent on generic lifetime and full load hours parameters.

In Fig. 6.14, resulting CO_2 emissions from the case study in this thesis are exemplary compared to LCA estimations of Masanet et al. (2013), Turconi et al. (2013), Varun et al. (2009) and European Environment Agency (2009). As for most renewable energies, the resulting numbers of the SEnSys approach are relatively low in comparison with the range given by other studies in the field. Further research is required to evaluate whether in this case the SEnSys input factors are too low, or if the resulting full load hours (from ELCALC) are exceptional high due to large shares of renewables in both scenarios of Trieb (2013a). Compared with the range given in Fig. 6.14, CO2 emission factors in the SEnSys model used for fossil fuels can be seen as low but feasible estimates. Again, a breakdown of emission values in construction, operation and decommissioning for all technologies could enhance the LCA results for specific scenarios.

Another indicator of the SEnSys model that features some uncertainties is *land use*. To begin with,

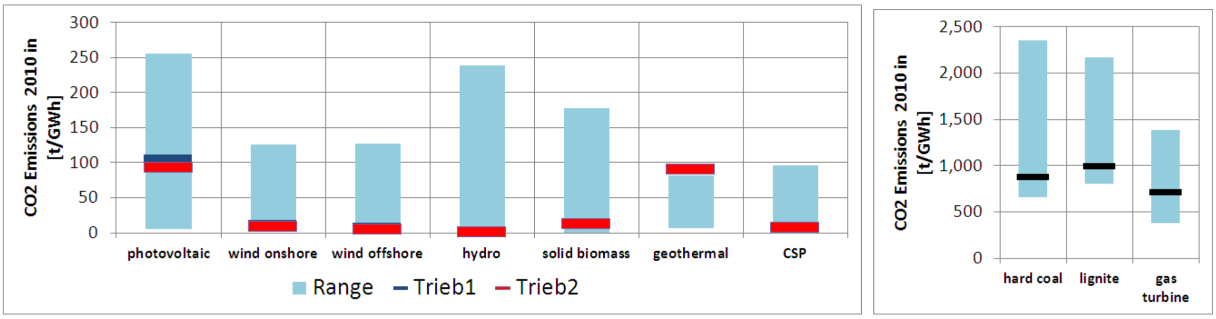

Fig. 6.14. Range of CO_2 emissions of main energy technologies compared with SEnSys results. Numbers are given for the whole model period. (data from Masanet et al. (2013), Turconi et al. (2013), Varun et al. (2009), European Environment Agency (2009))

the estimation of land use assigned to the respective capacity included the manual measurement of area requirements where no generic data was available (see Section 4.2.3 and Appendix A.3 - Table A.3). This simplification ignores land use of related infrastructure, such as a possible railway construction for transporting coal from the mining district to the actual power plant (Sims, 2014). The only technology in the SEnSys model that reflects additional infrastructure to some extend is CSP with its respective HVDC transmission lines from North Africa to the centres of demand in Germany. In that way, the resulting land use estimates might be biased in favour of conventional power generation compared to CSP.

Moreover, the magnitude of land use impact is varying depending on the affected terrain. According to Droste-Franke et al. (2012), assessments of land use should always be related to the previous use of the area. In addition to that, '*recovery costs, losses of utility, as well as other (non-use) values (e.g., option value, loss of originality, are particularly important for the evaluation of land use changes*' (Droste-Franke et al., 2012, p. 15). This applies in particular to CSP technology, which can be constructed on arid land in desert areas (Hitchin, 2014). It is therefore recommended to revise the land use estimates in the SEnSys model for further studies and implement land use categories.

Another important aspect of the SEnSys model is that only economic factors were considered to change over time. This is reasonable as so-called learning or experience curves are usually applied in terms of costs development (IEA, 2000). The basic theory of learning curves assumes that '*each time a unit of a particular technology (e.g. a wind turbine) is produced, some learning accumulates which leads to cheaper production of the next unit of that technology*' (Wiesenthal et al., 2012, p. 5). In that sense, learning curves are usually based on global production capacity of a certain technology.[4] However, this makes it difficult to implement specific learning rates for factors in the SEnSys model, in particular when the learning rate should reflect the respective capacity development of certain energy technology scenarios inside a single country. While Wiesenthal et al. (2012) mention regional effects in learning curves, they still strongly recommend to apply learning curves only on a global scale.

As mentioned earlier, most scholars use learning curves as a tool for political consulting, to

[4]For instance, a doubling of global production capacity for CSP technology might lead to costs reductions from 10% up to 50%, as presented by Neij (2008)

estimate global costs developments and assess the potential for technology change in certain scenarios (Wiesenthal et al., 2012). However, given the flexibility of the approach, learning curves could also be used to estimate changes in technology specific parameters inside the SEnSys model. With increasing efficiency of the producing industry and the power plants themselves, not only the monetary costs are decreasing but - it seems reasonable to argue - also environmental burdens related to the construction and operation of the plant. For instance, the higher the capacity of a single wind turbine is, the lower gets the specific land use per capacity. Future studies could therefore integrate global learning curves not only in economic terms but also concerning environmental burdens and specific technology development.

To summarize, the factors and accordingly results of the SEnSys model are comparable to other relevant studies, even though a revision of certain technology factors or calculation approaches is recommendable for further studies. This could also include a more detailed review on technology learning curves for certain parameters.

6.2.3 SEnSys model

One of the strengths of the SEnSys approach is the subdivision of specific technologies into series or construction years respectively. As explained in Section 4.3.1, each additional required technology was classified in model ranges of ten years and kept installed throughout its respective economic lifetime. This allowed tracking impacts of certain technologies down to their series and accordingly the point in time - in the scenarios - that did lead to them. Furthermore, this ensured that the major economic, environmental and, to some extent, social consequences of each constructed power plant (or rather its equivalent in capacity) in the model were reflected over its entire economic lifetime. Even more by providing aggregated numbers for indicators in addition to annual trends. In that way, the general principle of taking responsibility for actions in the future in accordance with WCED (1987) and a long term perspective for energy technology systems in line with IEA (2004) was taken into account for the SEnSys model approach.

Nevertheless, it is worth mentioning that the case study in this thesis included only all impacts until the end of the simulation period, namely year 2050. In that way, the impacts and consequences after 2050 are accordingly omitted, which might bias the results of the comparison from the two Trieb (2013a) scenarios. It is therefore recommended to compile a *beyond 2050* study on the two energy technology scenarios, by either increasing renewable generation to 100% or keeping the status quo of 2050 respectively. This should be coupled with the suggested breakdown of life cycle impacts - in at least construction, operation and decommissioning phases - from the previous chapter.

Another improvement that could be done to the SEnSys model is a more detailed reflection of feedback mechanism inside the energy system. For instance, the IEA (2012a) is stating that a combination of different fluctuating renewable energy sources can enhance the capacity factor and, in certain cases, the capacity credit of the overall renewable mix. While a yearly simulation of the full load hours in ELCALC is already considering the first aspects (see Section 4.3.2), it is worth mentioning that a feedback mechanism for the capacity credit in respect to the development of certain technologies is missing in the SEnSys model. Furthermore, the model does not reflect that an increased share of renewables in the energy mix would lead to lower emissions concerning the construction of renewable energies.[5] To implement this feedback mechanism into the SEnSys model, it would be required to estimate the part of the life cycle impacts that is resulting from electricity consumption and to subtract this from the other life cycle impacts.

An alternative way to present the results of the indicators in the SEnSys model would have been in relation to their respective thresholds or critical loads. In that way, the resilience of the energy system, as part of the SD approach, could be measured by the distance from thresholds of critical system change (Pisano, 2012). However, while the assessment of indicator sets in regard to set thresholds would allow a natural weighting, the IEA (2004) consider it as quite challenging to define long term targets - such as emission pledges - due to the (scientific) uncertainties surrounding the topic. Moreover, Rockström et al. (2009a) points out, that thresholds do not existing separately, but can influence each other. Along with that, the crossing of one threshold might reduce the critical threshold of another process, such as major deforestation will have an influence on green-house gas limits. Hence, a comprehensive implementation of thresholds in the SEnSys approach would require extended research on resilience and dynamics of social and natural systems.

Finally, the SEnSys approach could be coupled with a computer-based optimization routine, to identify pathways with considerably low impacts in certain indicators or on a more holistic scale. One possibility would be to implement the SEnSys model of this thesis inside an already existing optimization tool for renewable energy mixes (Scholz, 2012), or to create a customized optimization routine.

[5] Fthenakis et al. (2008) for instance estimated that the life cycle green-house gas emissions of photovoltaic modules could be reduced by half, if not the conventional electricity mix was considered but a mix only consisting of photovoltaic power generation.

7. Conclusion

Despite the drawbacks of the method discussed in the previous chapter, it can be stated that both the development as well as the application of the SEnSys model in an exemplary case study were providing new valuable insights to the sustainability discussion in terms of the energy transformation in Germany. By not only focusing on the implications of certain energy technology scenarios in future years, but by also assessing the technological pathways (based on previous installations) that would lead to a desired configuration, the SEnSys model allowed to identify hidden weak-spots of technology scenarios. This new approach, coupled with the simplified simulation of the resulting energy mix in an exemplary year - to get a realistic workload of the respective plants - , provided a broad appraisal of the chosen energy technology scenario in terms of technical, economic, environmental and to some extends social aspects. Together with the possibility of assessing annual as well as aggregated impacts - also in relation to their respective energy generation or secured capacity - it can be stated that the SEnSys model approach bears the potential for studying a wide range of research questions concerning future sustainable energy systems.

As for the particular case study in this thesis, the SEnSys model could affirm a majority of the general findings by Trieb (2013b) concerning the development and comparison of indicators in both energy technology scenarios. Notwithstanding, the results did also show that some indicators, such as costs and land use, behave differently when analysed by the more complex SEnSys approach (see Section 6.1.2).

In terms of comparison between a future power supply in Germany dominated by only local but mostly fluctuating renewables and an option including imports from remote but flexible renewable sources, the results of the SEnSys model indicate a clear advantage for the import option in respect to economic and environmental aspects (see Section 6.1.1). Further research is required to improve the assessment of social implications of both energy technology scenarios.

However, when talking about the results of this thesis, the identified limitations and uncertainties of the model in Section 6.2 should not be ignored. As every modelling and scenario approach features some uncertainties and limitations that are coupled to the method and therefore always persistent (Olsson and Sjöstedt, 2004), it is crucial to always challenge and interpret the results in the light of these uncertainties and necessary simplifications.

Other than that, specific limitations of this thesis, as presented in Section 6.2, can be taken as a basis for further development and improvement of the SEnSys approach. In particular, the lack of social indicators and a less generic LCA approach should be addressed in future research. It is further recommended to couple this with a revision of certain input factors and a more holistic economic calculation including an external costs option. In the long term perspective, a more advanced modelling of technology learning and feedback mechanism, consideration of social and natural thresholds, as well as the possibility to implement computer-based optimization routines would allow new research questions to be analysed.

In that way, the improvement of the model with the given recommendations could enhance the feasibility of the SEnSys model approach to assess and potentially improve the sustainability of energy technology scenarios for energy transformation in Germany and other countries.

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A. Methods

A.1 SD Indicators

Fig. A.1. Full list of sustainability Indicators from DESA (2007)

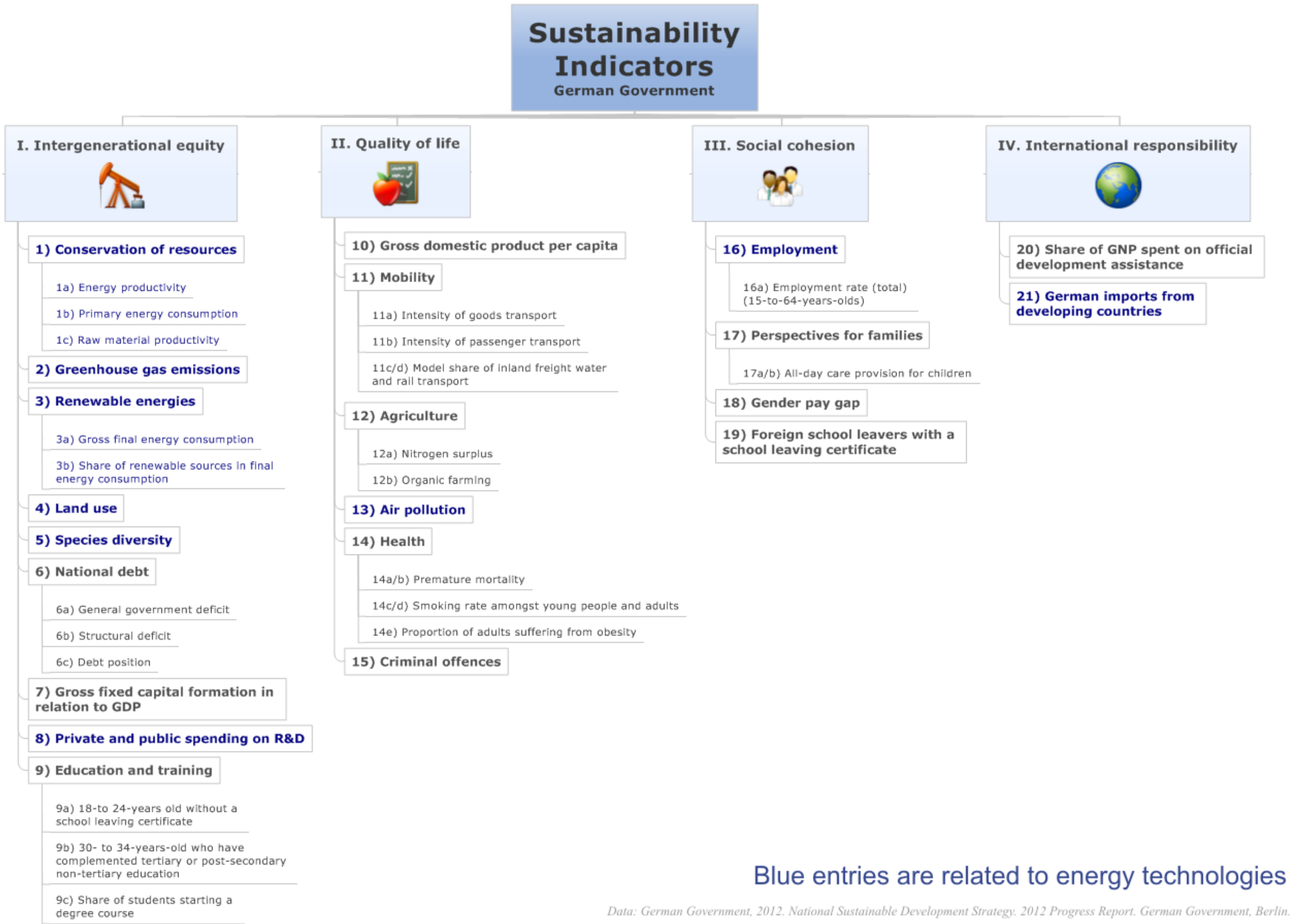


Fig. A.2. Full list of sustainability Indicators from German Federal Government (2012)

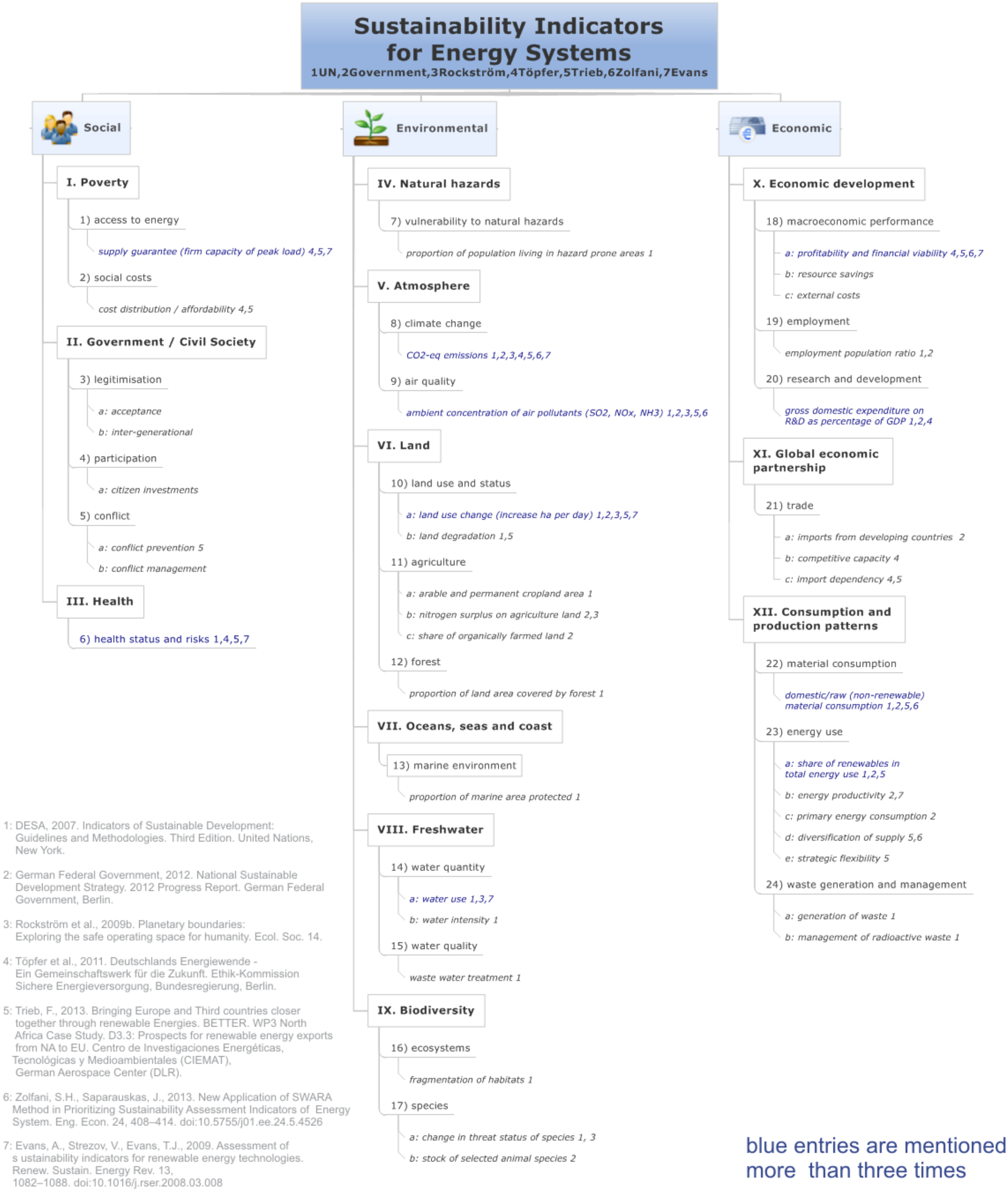


Fig. A.3. Full list of sustainability Indicators from literature review for SEnSys model

A.2 Data Collection

Table A.1
Overview on factors for sustainability indicators of the SEnSys model

FactorID	FactorName	SumFactorID	MW	Invest	GWh	Unit
CC	Capacity Credit		x			%
LT	Life time					a
IC	Investment Costs			x		T€/MW
FOM_C	Fixed O&M Costs	TC				% Invest./a
VC	Variable Costs	TC			x	T€/GWh
DP	Depreciation Period					a
WACC	Weighted average costs of capital					%
CO2_C	CO2_eq Emissions - Construction	CO2		x		t/MW
CO2_G	CO2_eq Emissions - Generation	CO2			x	t/GWh
SO2_C	SO2_eq Emissions - Construction	SO2		x		kg/GWh
SO2_G	SO2_eq Emissions - Generation	SO2			x	kg/GWh
NOx_C	Nox Emissions - Construction	NOx			x	kg/GWh
NOx_G	Nox Emissions - Generation	NOx			x	kg/GWh
PM10_C	Particular matter Emissions - Construction	PM10		x		kg/GWh
PM10_G	Particular matter Emissions - Generation	PM10			x	kg/GWh
CMR_C	Cumulated non-renewable material requirement - Con	CMR		x		t/GWh
CMR_G	Cumulated non-renewable material requirement - Gen	CMR			x	t/GWh
LU_C	Land use for Capacity		x			ha/MW
LU_G	Land use for Generation				x	ha/GWh

CAPACITY CREDIT in [%]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	CC	PV	2010		0		Trieb 2006	
			CC	PV	2020		0			
			CC	PV	2030		0			
			CC	PV	2040		0			
			CC	PV	2050		0			
			CC	PV	2060		0			
		photovoltaic utility	CC	PV_U	2010		0		Trieb 2006	
			CC	PV_U	2020		0			
			CC	PV_U	2030		0			
			CC	PV_U	2040		0			
			CC	PV_U	2050		0			
			CC	PV_U	2060		0			
	wind	wind onshore	CC	W_On	2010	0.01	0.042	0.08	Nitsch 2012a	
			CC	W_On	2020	0.01	0.042	0.08		
			CC	W_On	2030	0.01	0.042	0.08		
			CC	W_On	2040	0.01	0.042	0.08		
			CC	W_On	2050	0.01	0.042	0.08		
			CC	W_On	2060	0.01	0.042	0.08		
		wind offshore	CC	W_Off	2010	0.063	0.073	0.091	Nitsch 2012a	
			CC	W_Off	2020	0.063	0.073	0.091		
			CC	W_Off	2030	0.063	0.073	0.091		
			CC	W_Off	2040	0.063	0.073	0.091		
			CC	W_Off	2050	0.063	0.073	0.091		
			CC	W_Off	2060	0.063	0.073	0.091		
	hydro	small hydro (<1MW)	CC	H_S	2010		0.25		Winkler 2013	
			CC	H_S	2020		0.25			
			CC	H_S	2030		0.25			
			CC	H_S	2040		0.25			
			CC	H_S	2050		0.25			
			CC	H_S	2060		0.25			
		large hydro (>1MW)	CC	H_L	2010	0.463	0.47	0.486	Nitsch 2012a	
			CC	H_L	2020	0.463	0.47	0.486		
			CC	H_L	2030	0.463	0.47	0.486		
			CC	H_L	2040	0.463	0.47	0.486		
			CC	H_L	2050	0.463	0.47	0.486		
			CC	H_L	2060	0.463	0.47	0.486		
		organic waste	CC	OW	2010		0.8		Winkler 2013	
			CC	OW	2020		0.8			
			CC	OW	2030		0.8			
			CC	OW	2040		0.8			
			CC	OW	2050		0.8			
			CC	OW	2060		0.8			
	biomass	biogas	CC	BG	2010		0.8		Winkler 2013	
			CC	BG	2020		0.8			
			CC	BG	2030		0.8			
			CC	BG	2040		0.8			
			CC	BG	2050		0.8			
			CC	BG	2060		0.8			
		solid biomass	CC	SB	2010	0.5	0.8	0.9	Winkler 2013	
			CC	SB	2020	0.5	0.8	0.9		
			CC	SB	2030	0.5	0.8	0.9		
			CC	SB	2040	0.5	0.8	0.9		
			CC	SB	2050	0.5	0.8	0.9		
			CC	SB	2060	0.5	0.8	0.9		
		geothermal	CC	GEO	2010		0.9		Trieb 2006	
			CC	GEO	2020		0.9			
			CC	GEO	2030		0.9			
			CC	GEO	2040		0.9			
			CC	GEO	2050		0.9			
			CC	GEO	2060		0.9			
	coal	hard coal	CC	HC	2010		0.9		Trieb 2006	
			CC	HC	2020		0.9			
			CC	HC	2030		0.9			
			CC	HC	2040		0.9			
			CC	HC	2050		0.9			
			CC	HC	2060		0.9			
		lignite	CC	LG	2010		0.9		Trieb 2006	
			CC	LG	2020		0.9			
			CC	LG	2030		0.9			
			CC	LG	2040		0.9			
			CC	LG	2050		0.9			
			CC	LG	2060		0.9			

CAPACITY CREDIT in [%]

Category	Subcategory	Technology	FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		nuclear	CC	NC	2010		0.9		Trieb 2006	
			CC	NC	2020		0.9			
			CC	NC	2030		0.9			
			CC	NC	2040		0.9			
			CC	NC	2050		0.9			
			CC	NC	2060		0.9			
		gas turbine	CC	GT	2010		0.9		Trieb 2006	
			CC	GT	2020		0.9			
			CC	GT	2030		0.9			
			CC	GT	2040		0.9			
			CC	GT	2050		0.9			
			CC	GT	2060		0.9			
		gas combined cycle	CC	GCC	2010		0.9		Trieb 2006	
			CC	GCC	2020		0.9			
			CC	GCC	2030		0.9			
			CC	GCC	2040		0.9			
			CC	GCC	2050		0.9			
			CC	GCC	2060		0.9			
import		hydro power	CC	HP	2010		0.8		Winkler (2013)	
			CC	HP	2020		0.8			
			CC	HP	2030		0.8			
			CC	HP	2040		0.8			
			CC	HP	2050		0.8			
			CC	HP	2060		0.8			
		solar power (CSP)	CC	CSP	2010		0.9		Trieb 2006	
			CC	CSP	2020		0.9			
			CC	CSP	2030		0.9			
			CC	CSP	2040		0.9			
			CC	CSP	2050		0.9			
			CC	CSP	2060		0.9			
storage and grid	storage	pump storage	CC	PS	2010		0		ELMOD	
			CC	PS	2020		0		Own Estimate	
			CC	PS	2030		0			
			CC	PS	2040		0			
			CC	PS	2050		0			
			CC	PS	2060		0			
		H2 storage	CC	H2	2010		0		ELMOD	
			CC	H2	2020		0		Own Estimate	
			CC	H2	2030		0			
			CC	H2	2040		0			
			CC	H2	2050		0			
			CC	H2	2060		0			
	grid	national power supply system	CC	NTC	2010		0		ELMOD	
			CC	NTC	2020		0		Own Estimate	
			CC	NTC	2030		0			
			CC	NTC	2040		0			
			CC	NTC	2050		0			
			CC	NTC	2060		0			
		high voltage, direct current	CC	HVDC	2010		0		ELMOD	
			CC	HVDC	2020		0		Own Estimate	
			CC	HVDC	2030		0			
			CC	HVDC	2040		0			
			CC	HVDC	2050		0			
			CC	HVDC	2060		0			

LIFE TIME in [a]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	LT	PV	2010		30		Nitsch 2012a	
			LT	PV	2020		30		SZEN11-A	
			LT	PV	2030		30			
			LT	PV	2040		30			
			LT	PV	2050		30			
			LT	PV	2060		30			
		photovoltaic utility	LT	PV_U	2010		30		Nitsch 2012a	
			LT	PV_U	2020		30		SZEN11-A	
			LT	PV_U	2030		30			
			LT	PV_U	2040		30			
			LT	PV_U	2050		30			
			LT	PV_U	2060		30			
	wind	wind onshore	LT	W_On	2010		20		Nitsch 2012a	
			LT	W_On	2020		20		SZEN11-A	
			LT	W_On	2030		20			
			LT	W_On	2040		20			
			LT	W_On	2050		20			
			LT	W_On	2060		20			
		wind offshore	LT	W_Off	2010		20		Nitsch 2012a	
			LT	W_Off	2020		20		SZEN11-A	
			LT	W_Off	2030		20			
			LT	W_Off	2040		20			
			LT	W_Off	2050		20			
			LT	W_Off	2060		20			
	hydro	small hydro (<1MW)	LT	H_S	2010		50		Trieb 2006	
			LT	H_S	2020		50			
			LT	H_S	2030		50			
			LT	H_S	2040		50			
			LT	H_S	2050		50			
			LT	H_S	2060		50			
		large hydro (>1MW)	LT	H_L	2010		50		Trieb 2006	
			LT	H_L	2020		50			
			LT	H_L	2030		50			
			LT	H_L	2040		50			
			LT	H_L	2050		50			
			LT	H_L	2060		50			
		organic waste	LT	OW	2010		20		Nitsch 2012a	
			LT	OW	2020		20		SZEN11-A	
			LT	OW	2030		20			
			LT	OW	2040		20			
			LT	OW	2050		20			
			LT	OW	2060		20			
	biomass	biogas	LT	BG	2010		20		Nitsch 2012a	
			LT	BG	2020		20		SZEN11-A	
			LT	BG	2030		20			
			LT	BG	2040		20			
			LT	BG	2050		20			
			LT	BG	2060		20			
		solid biomass	LT	SB	2010		20		Nitsch 2012a	
			LT	SB	2020		20		SZEN11-A	
			LT	SB	2030		20			
			LT	SB	2040		20			
			LT	SB	2050		20			
			LT	SB	2060		20			
		geothermal	LT	GEO	2010		30		Trieb 2006	
			LT	GEO	2020		30			
			LT	GEO	2030		30			
			LT	GEO	2040		30			
			LT	GEO	2050		30			
			LT	GEO	2060		30			
	coal	hard coal	LT	HC	2010		40		Nitsch 2012a	
			LT	HC	2020		40		SZEN11-A	
			LT	HC	2030		40			
			LT	HC	2040		40			
			LT	HC	2050		40			
			LT	HC	2060		40			
		lignite	LT	LG	2010		40		Nitsch 2012a	
			LT	LG	2020		40		SZEN11-A	
			LT	LG	2030		40			
			LT	LG	2040		40			
			LT	LG	2050		40			
			LT	LG	2060		40			

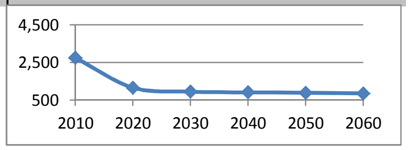
LIFE TIME in [a]

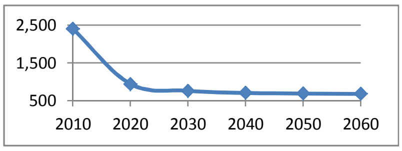
			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		nuclear	LT	NC	2010		40		Nitsch 2012a	
			LT	NC	2020		40		SZEN11-A	
			LT	NC	2025		40			
			LT	NC	2030		40			
			LT	NC	2040		40			
			LT	NC	2050		40			
			LT	NC	2060		40			
		gas turbine	LT	GT	2010		30		OECD 2010	
			LT	GT	2020		30			
			LT	GT	2030		30			
			LT	GT	2040		30			
			LT	GT	2050		30			
			LT	GT	2060		30			
		gas combined cycle	LT	GCC	2010		30		Trieb 2006	
			LT	GCC	2020		30			
			LT	GCC	2030		30			
			LT	GCC	2040		30			
			LT	GCC	2050		30			
			LT	GCC	2060		30			
import		hydro power	LT	HP	2010		50		Trieb 2006	
			LT	HP	2020		50			
			LT	HP	2030		50			
			LT	HP	2040		50			
			LT	HP	2050		50			
			LT	HP	2060		50			
		solar power (CSP)	LT	CSP	2010		40		Trieb 2006	
			LT	CSP	2020		40			
			LT	CSP	2030		40			
			LT	CSP	2040		40			
			LT	CSP	2050		40			
			LT	CSP	2060		40			
storage and grid	storage	pump storage	LT	PS	2010		60		Nitsch 2012a	
			LT	PS	2020		60		Appendix II	
			LT	PS	2030		60		Tab 1-46	
			LT	PS	2040		60			
			LT	PS	2050		60			
			LT	PS	2060		60			
		H2 storage	LT	H2	2010		30		Nitsch 2012a	
			LT	H2	2020		30		Appendix II	
			LT	H2	2030		30		Tab 1-50	
			LT	H2	2040		30			
			LT	H2	2050		30			
			LT	H2	2060		30			
	grid	national power supply system	LT	NTC	2010		40		Jorge & Hertwich	
			LT	NTC	2020		40		2014	
			LT	NTC	2030		40			
			LT	NTC	2040		40			
			LT	NTC	2050		40			
			LT	NTC	2060		40			
		high voltage, direct current (underground)	LT	HVDC	2010		40		Hess 2013	
			LT	HVDC	2020		40		Table 48	
			LT	HVDC	2030		40		(p. 152)	
			LT	HVDC	2040		40			
			LT	HVDC	2050		40			
			LT	HVDC	2060		40			
		high voltage, direct current (overhead)	LT	HVDC_O	2010		40		Hess 2013	
			LT	HVDC_O	2020		40		Table 48	
			LT	HVDC_O	2030		40		(p. 152)	
			LT	HVDC_O	2040		40			
			LT	HVDC_O	2050		40			
			LT	HVDC_O	2060		40			

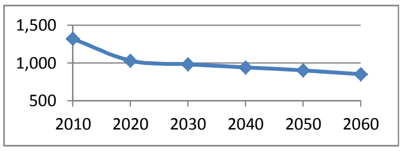
INVESTMENT COSTS in [T€/MW]

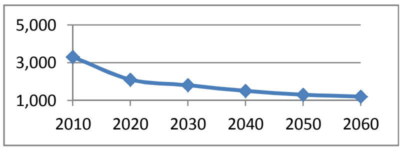
			FactorID	TechID	Year	Min	Mid	Max	SOURCE
renewables		photovoltaic (building integrated)	IC	PV	2010		2,750		Nitsch 2012a Appendix II Tab 1-2
			IC	PV	2020		1,160		
			IC	PV	2030		950		
			IC	PV	2040		910		
			IC	PV	2050		890		
			IC	PV	2060		850		
		photovoltaic utility	IC	PV_U	2010		2,400		Nitsch 2012a Appendix II Tab 1-5
			IC	PV_U	2020		940		
			IC	PV_U	2030		760		
			IC	PV_U	2040		705		
			IC	PV_U	2050		690		
			IC	PV_U	2060		680		
	wind	wind onshore	IC	W_On	2010		1,320		Nitsch 2012a Appendix II Tab 1-6
			IC	W_On	2020		1,030		
			IC	W_On	2030		980		
			IC	W_On	2040		940		
			IC	W_On	2050		900		
			IC	W_On	2060		850		
		wind offshore	IC	W_Off	2010		3,300		Nitsch 2012a Appendix II Tab 1-7
			IC	W_Off	2020		2,100		
			IC	W_Off	2030		1,800		
			IC	W_Off	2040		1,500		
			IC	W_Off	2050		1,300		
			IC	W_Off	2060		1,200		
	hydro	small hydro (<1MW)	IC	H_S	2010		5,800		Nitsch 2012a Appendix II Tab 1-27
			IC	H_S	2020		6,150		
			IC	H_S	2030		6,450		
			IC	H_S	2040		6,750		
			IC	H_S	2050		7,000		
			IC	H_S	2060		7,250		
		large hydro (>1MW)	IC	H_L	2010		5,000		Nitsch 2012a Appendix II Tab 1-28
			IC	H_L	2020		5,000		
			IC	H_L	2030		5,000		
			IC	H_L	2040		5,000		
			IC	H_L	2050		5,000		
			IC	H_L	2060		5,000		
		organic waste	IC	OW	2010		5,556		IEA 2012b Europe 2010
			IC	OW	2020		4,978		
			IC	OW	2030		4,889		Learn curve from Solid Biomass
			IC	OW	2040		4,823		
			IC	OW	2050		4,778		
			IC	OW	2060		4,756		
	biomass	biogas	IC	BG	2010		3,760		Nitsch 2012a Appendix II Tab 1-15
			IC	BG	2020		3,520		
			IC	BG	2030		3,480		
			IC	BG	2040		3,400		
			IC	BG	2050		3,350		
			IC	BG	2060		3,320		
		solid biomass	IC	SB	2010		2,500		Nitsch 2012a Appendix II Tab 1-12
			IC	SB	2020		2,240		
			IC	SB	2030		2,200		
			IC	SB	2040		2,170		
			IC	SB	2050		2,150		
			IC	SB	2060		2,140		
		geothermal	IC	GEO	2010		8,850		Nitsch 2012a Appendix II Tab 1-23
			IC	GEO	2020		6,820		
			IC	GEO	2030		6,100		
			IC	GEO	2040		5,700		
			IC	GEO	2050		5,500		
			IC	GEO	2060		5,400		
	coal	hard coal	IC	HC	2010		1,300		Nitsch 2012a Appendix II Tab 1-34
			IC	HC	2020		1,300		
			IC	HC	2030		1,300		
			IC	HC	2040		1,300		
			IC	HC	2050		1,300		
			IC	HC	2060		1,300		
		lignite	IC	LG	2010		1,500		Nitsch 2012a Appendix II Tab 1-37
			IC	LG	2020		1,500		
			IC	LG	2030		1,500		
			IC	LG	2040		1,500		
			IC	LG	2050		1,500		
			IC	LG	2060		1,500		

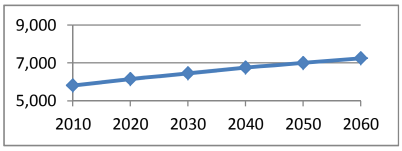
Learning curve

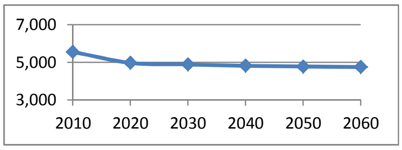


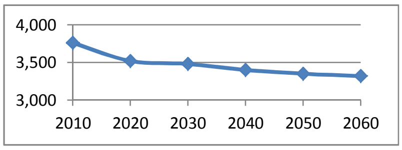


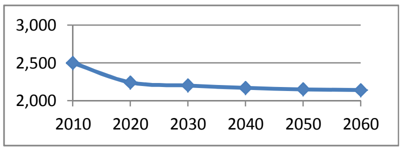


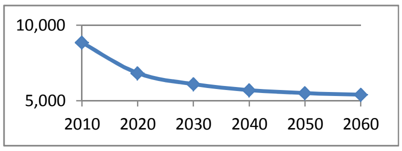






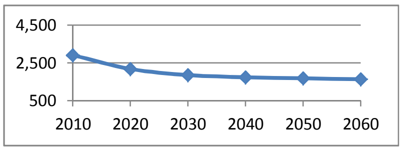


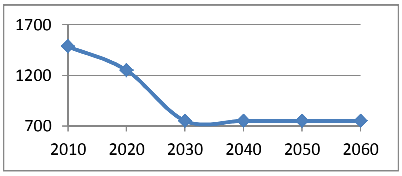




INVESTMENT COSTS in [T€/MW]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		nuclear	IC	NC	2010		4,254		EIA 2013	
fossil		nuclear	IC	NC	2020		4,254			
fossil		nuclear	IC	NC	2025		4,254			
fossil		nuclear	IC	NC	2030		4,254			
fossil		nuclear	IC	NC	2040		4,254			
fossil		nuclear	IC	NC	2050		4,254			
fossil		nuclear	IC	NC	2060		4,254			
fossil		gas turbine	IC	GT	2010		400		Nitsch 2012a	
fossil		gas turbine	IC	GT	2020		400		Appendix II	
fossil		gas turbine	IC	GT	2030		400		Tab 1-33	
fossil		gas turbine	IC	GT	2040		400			
fossil		gas turbine	IC	GT	2050		400			
fossil		gas turbine	IC	GT	2060		400			
fossil		gas combined cycle	IC	GCC	2010		700		Nitsch 2012a	
fossil		gas combined cycle	IC	GCC	2020		700		Appendix II	
fossil		gas combined cycle	IC	GCC	2030		700		Tab 1-31	
fossil		gas combined cycle	IC	GCC	2040		700			
fossil		gas combined cycle	IC	GCC	2050		700			
fossil		gas combined cycle	IC	GCC	2060		700			
import		hydro power	IC	HP	2010		4000		Nitsch 2012a	
import		hydro power	IC	HP	2020		4000		Appendix II	
import		hydro power	IC	HP	2030		4000		Tab 1-29	
import		hydro power	IC	HP	2040		4000			
import		hydro power	IC	HP	2050		4000			
import		hydro power	IC	HP	2060		4000			
import		solar power (CSP)	IC	CSP	2010		2,905		Nitsch 2012a	
import		solar power (CSP)	IC	CSP	2020		2,176		Appendix II	
import		solar power (CSP)	IC	CSP	2030		1,852		Tab 1-30	
import		solar power (CSP)	IC	CSP	2040		1,737			
import		solar power (CSP)	IC	CSP	2050		1,677		Assumption??	
import		solar power (CSP)	IC	CSP	2060		1,630			
storage and grid	storage	pump storage	IC	PS	2010		640		Nitsch 2012a	
storage and grid	storage	pump storage	IC	PS	2020		640		Appendix II	
storage and grid	storage	pump storage	IC	PS	2030		640		Tab 1-46	
storage and grid	storage	pump storage	IC	PS	2040		640			
storage and grid	storage	pump storage	IC	PS	2050		640			
storage and grid	storage	pump storage	IC	PS	2060		640			
storage and grid	storage	H2 storage	IC	H2	2010		1485			
storage and grid	storage	H2 storage	IC	H2	2020		1250		Nitsch 2012a	
storage and grid	storage	H2 storage	IC	H2	2030		750		Appendix II	
storage and grid	storage	H2 storage	IC	H2	2040		750		Tab 1-50	
storage and grid	storage	H2 storage	IC	H2	2050		750			
storage and grid	storage	H2 storage	IC	H2	2060		750			
storage and grid	grid	national power supply system	IC	NTC	2010		1800		ELMOD	
storage and grid	grid	national power supply system	IC	NTC	2020		1800		Own Estimate	
storage and grid	grid	national power supply system	IC	NTC	2030		1800			
storage and grid	grid	national power supply system	IC	NTC	2040		1800			
storage and grid	grid	national power supply system	IC	NTC	2050		1800			
storage and grid	grid	national power supply system	IC	NTC	2060		1800			
storage and grid	grid	high voltage, direct current (underground)	IC	HVDC	2010		3300		Hess 2013	
storage and grid	grid	high voltage, direct current (underground)	IC	HVDC	2020		3300		Table 49	
storage and grid	grid	high voltage, direct current (underground)	IC	HVDC	2030		3300		(p. 154)	
storage and grid	grid	high voltage, direct current (underground)	IC	HVDC	2040		3300			
storage and grid	grid	high voltage, direct current (underground)	IC	HVDC	2050		3300			
storage and grid	grid	high voltage, direct current (underground)	IC	HVDC	2060		3300			
		high voltage, direct current (overhead)	IC	HVDC_O	2010		1300		Hess 2013	
		high voltage, direct current (overhead)	IC	HVDC_O	2020		1300		Table 49	
		high voltage, direct current (overhead)	IC	HVDC_O	2030		1300		(p. 154)	
		high voltage, direct current (overhead)	IC	HVDC_O	2040		1300			
		high voltage, direct current (overhead)	IC	HVDC_O	2050		1300			
		high voltage, direct current (overhead)	IC	HVDC_O	2060		1300			





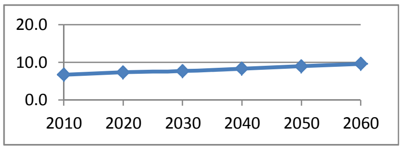
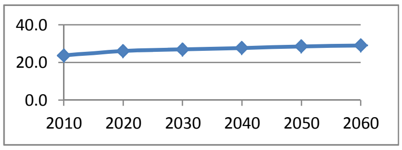
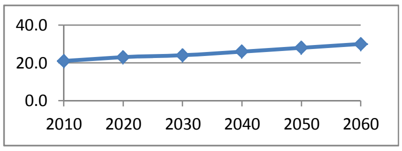
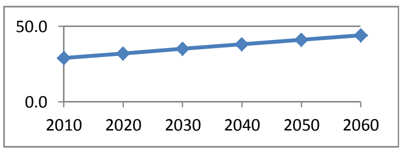
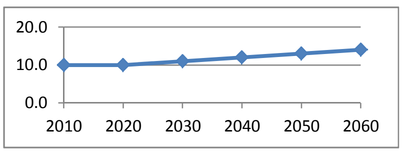
FIXED OPERATION&MAINTENANCE COSTS in [% Invest./a]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	FOM_C	PV	2010		0.01		Nitsch 2012a	
			FOM_C	PV	2020		0.01		Appendix II	
			FOM_C	PV	2030		0.01		Tab 1-2	
			FOM_C	PV	2040		0.01			
			FOM_C	PV	2050		0.01			
			FOM_C	PV	2060		0.01			
		photovoltaic utility	FOM_C	PV_U	2010		0.01		Nitsch 2012a	
			FOM_C	PV_U	2020		0.01		Appendix II	
			FOM_C	PV_U	2030		0.01		Tab 1-5	
			FOM_C	PV_U	2040		0.01			
			FOM_C	PV_U	2050		0.01			
			FOM_C	PV_U	2060		0.01			
	wind	wind onshore	FOM_C	W_On	2010		0.04		Nitsch 2012a	
			FOM_C	W_On	2020		0.04		Appendix II	
			FOM_C	W_On	2030		0.04		Tab 1-6	
			FOM_C	W_On	2040		0.04			
			FOM_C	W_On	2050		0.04			
			FOM_C	W_On	2060		0.04			
		wind offshore	FOM_C	W_Off	2010		0.06		Nitsch 2012a	
			FOM_C	W_Off	2020		0.06		Appendix II	
			FOM_C	W_Off	2030		0.06		Tab 1-7	
			FOM_C	W_Off	2040		0.06			
			FOM_C	W_Off	2050		0.06			
			FOM_C	W_Off	2060		0.06			
	hydro	small hydro (<1MW)	FOM_C	H_S	2010		0.05		Nitsch 2012a	
			FOM_C	H_S	2020		0.05		Appendix II	
			FOM_C	H_S	2030		0.05		Tab 1-27	
			FOM_C	H_S	2040		0.05			
			FOM_C	H_S	2050		0.05			
			FOM_C	H_S	2060		0.05			
		large hydro (>1MW)	FOM_C	H_L	2010		0.05		Nitsch 2012a	
			FOM_C	H_L	2020		0.05		Appendix II	
			FOM_C	H_L	2030		0.05		Tab 1-28	
			FOM_C	H_L	2040		0.05			
			FOM_C	H_L	2050		0.05			
			FOM_C	H_L	2060		0.05			
		organic waste	FOM_C	OW	2010		0.05		Nitsch 2012a	
			FOM_C	OW	2020		0.05		Appendix II	
			FOM_C	OW	2030		0.05		Tab 1-12	
			FOM_C	OW	2040		0.05			
			FOM_C	OW	2050		0.05			
			FOM_C	OW	2060		0.05			
	biomass	biogas	FOM_C	BG	2010		0.07		Nitsch 2012a	
			FOM_C	BG	2020		0.07		Appendix II	
			FOM_C	BG	2030		0.07		Tab 1-15	
			FOM_C	BG	2040		0.07			
			FOM_C	BG	2050		0.07			
			FOM_C	BG	2060		0.07			
		solid biomass	FOM_C	SB	2010		0.05		Nitsch 2012a	
			FOM_C	SB	2020		0.05		Appendix II	
			FOM_C	SB	2030		0.05		Tab 1-12	
			FOM_C	SB	2040		0.05			
			FOM_C	SB	2050		0.05			
			FOM_C	SB	2060		0.05			
		geothermal	FOM_C	GEO	2010		0.04		Nitsch 2012a	
			FOM_C	GEO	2020		0.04		Appendix II	
			FOM_C	GEO	2030		0.04		Tab 1-23	
			FOM_C	GEO	2040		0.04			
			FOM_C	GEO	2050		0.04			
			FOM_C	GEO	2060		0.04			
	coal	hard coal	FOM_C	HC	2010		0.02		Nitsch 2012a	
			FOM_C	HC	2020		0.02		Appendix II	
			FOM_C	HC	2030		0.02		Tab 1-34	
			FOM_C	HC	2040		0.02			
			FOM_C	HC	2050		0.02			
			FOM_C	HC	2060		0.02			
		lignite	FOM_C	LG	2010		0.02		Nitsch 2012a	
			FOM_C	LG	2020		0.02		Appendix II	
			FOM_C	LG	2030		0.02		Tab 1-37	
			FOM_C	LG	2040		0.02			
			FOM_C	LG	2050		0.02			
			FOM_C	LG	2060		0.02			

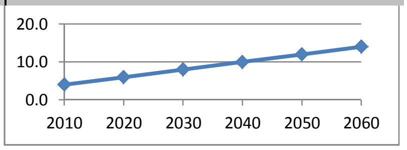
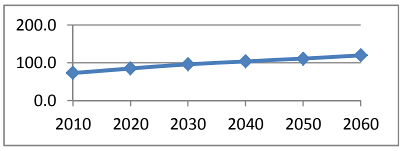
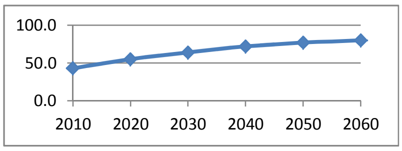
FIXED OPERATION&MAINTENANCE COSTS in [% Invest./a]

		FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil	nuclear	FOM_C	NC	2010		0.02		Own Estimate	
		FOM_C	NC	2020		0.02			
		FOM_C	NC	2025		0.02			
		FOM_C	NC	2030		0.02			
		FOM_C	NC	2040		0.02			
		FOM_C	NC	2050		0.02			
		FOM_C	NC	2060		0.02			
	gas turbine	FOM_C	GT	2010		0.02		Nitsch 2012a	
		FOM_C	GT	2020		0.02		Appendix II	
		FOM_C	GT	2030		0.02		Tab 1-33	
		FOM_C	GT	2040		0.02			
		FOM_C	GT	2050		0.02			
		FOM_C	GT	2060		0.02			
	gas combined cycle	FOM_C	GCC	2010		0.02		Nitsch 2012a	
		FOM_C	GCC	2020		0.02		Appendix II	
		FOM_C	GCC	2030		0.02		Tab 1-31	
		FOM_C	GCC	2040		0.02			
		FOM_C	GCC	2050		0.02			
		FOM_C	GCC	2060		0.02			
import	hydro power	FOM_C	HP	2010		0.05		Nitsch 2012a	
		FOM_C	HP	2020		0.05		Appendix II	
		FOM_C	HP	2030		0.05		Tab 1-29	
		FOM_C	HP	2040		0.05			
		FOM_C	HP	2050		0.05			
		FOM_C	HP	2060		0.05			
	solar power (CSP)	FOM_C	CSP	2010		0.03		Nitsch 2012a	
		FOM_C	CSP	2020		0.03		Appendix II	
		FOM_C	CSP	2030		0.03		Tab 1-30	
		FOM_C	CSP	2040		0.03			
		FOM_C	CSP	2050		0.03		Assumption??	
		FOM_C	CSP	2060		0.03			
storage and grid / storage	pump storage	FOM_C	PS	2010		0.015		ELMOD	
		FOM_C	PS	2020		0.015		Own Estimate	
		FOM_C	PS	2030		0.015			
		FOM_C	PS	2040		0.015			
		FOM_C	PS	2050		0.015			
		FOM_C	PS	2060		0.015			
	H2 storage	FOM_C	H2	2010		0.02		ELMOD	
		FOM_C	H2	2020		0.02		Own Estimate	
		FOM_C	H2	2030		0.02			
		FOM_C	H2	2040		0.02			
		FOM_C	H2	2050		0.02			
		FOM_C	H2	2060		0.02			
grid	national power supply system	FOM_C	NTC	2010		0.01		ELMOD	
		FOM_C	NTC	2020		0.01		Own Estimate	
		FOM_C	NTC	2030		0.01			
		FOM_C	NTC	2040		0.01			
		FOM_C	NTC	2050		0.01			
		FOM_C	NTC	2060		0.01			
	high voltage, direct current (underground)	FOM_C	HVDC	2010		0.033		Hess 2013	
		FOM_C	HVDC	2020		0.033		Table 50	
		FOM_C	HVDC	2030		0.033		(p. 155)	
		FOM_C	HVDC	2040		0.033			
		FOM_C	HVDC	2050		0.033			
		FOM_C	HVDC	2060		0.033			
	high voltage, direct current (overhead)	FOM_C	HVDC_O	2010		0.05		Hess 2013	
		FOM_C	HVDC_O	2020		0.05		Table 50	
		FOM_C	HVDC_O	2030		0.05		(p. 155)	
		FOM_C	HVDC_O	2040		0.05			
		FOM_C	HVDC_O	2050		0.05			
		FOM_C	HVDC_O	2060		0.05			

VARIABLE (fuel) COSTS in [T€/GWh]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	VC	PV	2010		0.0		Nitsch 2012a Appendix II Tab 1-2	
			VC	PV	2020		0.0			
			VC	PV	2030		0.0			
			VC	PV	2040		0.0			
			VC	PV	2050		0.0			
			VC	PV	2060		0.0			
		photovoltaic utility	VC	PV_U	2010		0.0		Nitsch 2012a Appendix II Tab 1-5	
			VC	PV_U	2020		0.0			
			VC	PV_U	2030		0.0			
			VC	PV_U	2040		0.0			
			VC	PV_U	2050		0.0			
			VC	PV_U	2060		0.0			
	wind	wind onshore	VC	W_On	2010		0.0		Nitsch 2012a Appendix II Tab 1-6	
			VC	W_On	2020		0.0			
			VC	W_On	2030		0.0			
			VC	W_On	2040		0.0			
			VC	W_On	2050		0.0			
			VC	W_On	2060		0.0			
		wind offshore	VC	W_Off	2010		0.0		Nitsch 2012a Appendix II Tab 1-7	
			VC	W_Off	2020		0.0			
			VC	W_Off	2030		0.0			
			VC	W_Off	2040		0.0			
			VC	W_Off	2050		0.0			
			VC	W_Off	2060		0.0			
	hydro	small hydro (<1MW)	VC	H_S	2010		0.0		Nitsch 2012a Appendix II Tab 1-27	
			VC	H_S	2020		0.0			
			VC	H_S	2030		0.0			
			VC	H_S	2040		0.0			
			VC	H_S	2050		0.0			
			VC	H_S	2060		0.0			
		large hydro (>1MW)	VC	H_L	2010		0.0		Nitsch 2012a Appendix II Tab 1-28	
			VC	H_L	2020		0.0			
			VC	H_L	2030		0.0			
			VC	H_L	2040		0.0			
			VC	H_L	2050		0.0			
			VC	H_L	2060		0.0			
		organic waste	VC	OW	2010		6.7		EIA 2013	
			VC	OW	2020		7.4			
			VC	OW	2030		7.7		Learning curve from solid biomass	
			VC	OW	2040		8.3			
			VC	OW	2050		9.0			
			VC	OW	2060		9.6			
	biomass	biogas	VC	BG	2010		23.7		Nitsch 2012a Appendix II Tab 1-15	
			VC	BG	2020		26.1			
			VC	BG	2030		26.9			
			VC	BG	2040		27.7			
			VC	BG	2050		28.5			
			VC	BG	2060		29.0			
		solid biomass	VC	SB	2010		21.0		Nitsch 2012a Appendix II Tab 1-12	
			VC	SB	2020		23.0			
			VC	SB	2030		24.0			
			VC	SB	2040		26.0			
			VC	SB	2050		28.0			
			VC	SB	2060		30.0			
		geothermal	VC	GEO	2010		0.0		Nitsch 2012a Appendix II Tab 1-23	
			VC	GEO	2020		0.0			
			VC	GEO	2030		0.0			
			VC	GEO	2040		0.0			
			VC	GEO	2050		0.0			
			VC	GEO	2060		0.0			
	coal	hard coal	VC	HC	2010		29.0		Nitsch 2012a Appendix II Tab 1-34 Path B moderate	
			VC	HC	2020		32.0			
			VC	HC	2030		35.0			
			VC	HC	2040		38.0			
			VC	HC	2050		41.0			
			VC	HC	2060		44.0			
		lignite	VC	LG	2010		10.0		Nitsch 2012a Appendix II Tab 1-37 Path B moderate	
			VC	LG	2020		10.0			
			VC	LG	2030		11.0			
			VC	LG	2040		12.0			
			VC	LG	2050		13.0			
			VC	LG	2060		14.0			

VARIABLE (fuel) COSTS in [T€/GWh]

		FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil	nuclear	VC	NC	2010		4.0		Nitsch 2012a Appendix II Tab 1-40 moderate	
		VC	NC	2020		6.0			
		VC	NC	2030		8.0			
		VC	NC	2040		10.0			
		VC	NC	2050		12.0			
		VC	NC	2060		14.0			
	gas turbine	VC	GT	2010		73.0		Nitsch 2012a Appendix II Tab 1-33 Path B moderate	
		VC	GT	2020		85.0			
		VC	GT	2030		96.0			
		VC	GT	2040		104.0			
		VC	GT	2050		111.0			
		VC	GT	2060		120.0			
	gas combined cycle	VC	GCC	2010		43.0		Nitsch 2012a Appendix II Tab 1-31 Path B moderate	
		VC	GCC	2020		55.0			
		VC	GCC	2030		64.0			
		VC	GCC	2040		72.0			
		VC	GCC	2050		77.0			
		VC	GCC	2060		80.0			
import	hydro power	VC	HP	2010		0.0		Nitsch 2012a Appendix II Tab 1-29	
		VC	HP	2020		0.0			
		VC	HP	2030		0.0			
		VC	HP	2040		0.0			
		VC	HP	2050		0.0			
		VC	HP	2060		0.0			
	solar power (CSP)	VC	CSP	2010		0.0		Nitsch 2012a Appendix II Tab 1-30	
		VC	CSP	2020		0.0			
		VC	CSP	2030		0.0			
		VC	CSP	2040		0.0			
		VC	CSP	2050		0.0			
		VC	CSP	2060		0.0			
storage and grid – storage	pump storage	VC	PS	2010		0		ELMOD Own Estimate	
		VC	PS	2020		0			
		VC	PS	2030		0			
		VC	PS	2040		0			
		VC	PS	2050		0			
		VC	PS	2060		0			
	H2 storage	VC	H2	2010		0		Nitsch 2012a Appendix II Tab 1-50	
		VC	H2	2020		0			
		VC	H2	2030		0			
		VC	H2	2040		0			
		VC	H2	2050		0			
		VC	H2	2060		0			
storage and grid – grid	national power supply system	VC	NTC	2010		0		ELMOD Own Estimate	
		VC	NTC	2020		0			
		VC	NTC	2030		0			
		VC	NTC	2040		0			
		VC	NTC	2050		0			
		VC	NTC	2060		0			
	high voltage, direct current (underground)	VC	HVDC	2010		0		ELMOD Own Estimate	
		VC	HVDC	2020		0			
		VC	HVDC	2030		0			
		VC	HVDC	2040		0			
		VC	HVDC	2050		0			
		VC	HVDC	2060		0			
	high voltage, direct current (overhead)	VC	HVDC_O	2010		0		ELMOD Own Estimate	
		VC	HVDC_O	2020		0			
		VC	HVDC_O	2030		0			
		VC	HVDC_O	2040		0			
		VC	HVDC_O	2050		0			
		VC	HVDC_O	2060		0			

DEPRECIATION PERIOD in [a]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	DP	PV	2010		20		Nitsch 2012a Appendix II Tab 1-2	
			DP	PV	2020		20			
			DP	PV	2030		20			
			DP	PV	2040		20			
			DP	PV	2050		20			
			DP	PV	2060		20			
		photovoltaic utility	DP	PV_U	2010		20		Nitsch 2012a Appendix II Tab 1-5	
			DP	PV_U	2020		20			
			DP	PV_U	2030		20			
			DP	PV_U	2040		20			
			DP	PV_U	2050		20			
			DP	PV_U	2060		20			
	wind	wind onshore	DP	W_On	2010		20		Nitsch 2012a Appendix II Tab 1-6	
			DP	W_On	2020		20			
			DP	W_On	2030		20			
			DP	W_On	2040		20			
			DP	W_On	2050		20			
			DP	W_On	2060		20			
		wind offshore	DP	W_Off	2010		20		Nitsch 2012a Appendix II Tab 1-7	
			DP	W_Off	2020		20			
			DP	W_Off	2030		20			
			DP	W_Off	2040		20			
			DP	W_Off	2050		20			
			DP	W_Off	2060		20			
	hydro	small hydro (<1MW)	DP	H_S	2010		30		Nitsch 2012a Appendix II Tab 1-27	
			DP	H_S	2020		30			
			DP	H_S	2030		30			
			DP	H_S	2040		30			
			DP	H_S	2050		30			
			DP	H_S	2060		30			
		large hydro (>1MW)	DP	H_L	2010		30		Nitsch 2012a Appendix II Tab 1-28	
			DP	H_L	2020		30			
			DP	H_L	2030		30			
			DP	H_L	2040		30			
			DP	H_L	2050		30			
			DP	H_L	2060		30			
		organic waste	DP	OW	2010		20		Nitsch 2012a ARES11-A Tab 6a	
			DP	OW	2020		20			
			DP	OW	2030		20			
			DP	OW	2040		20			
			DP	OW	2050		20			
			DP	OW	2060		20			
	biomass	biogas	DP	BG	2010		20		Nitsch 2012a Appendix II Tab 1-15	
			DP	BG	2020		20			
			DP	BG	2030		20			
			DP	BG	2040		20			
			DP	BG	2050		20			
			DP	BG	2060		20			
		solid biomass	DP	SB	2010		20		Nitsch 2012a Appendix II Tab 1-12	
			DP	SB	2020		20			
			DP	SB	2030		20			
			DP	SB	2040		20			
			DP	SB	2050		20			
			DP	SB	2060		20			
		geothermal	DP	GEO	2010		20		Nitsch 2012a Appendix II Tab 1-23	
			DP	GEO	2020		20			
			DP	GEO	2030		20			
			DP	GEO	2040		20			
			DP	GEO	2050		20			
			DP	GEO	2060		20			
	coal	hard coal	DP	HC	2010		30		Nitsch 2012a Appendix II Tab 1-34	
			DP	HC	2020		30			
			DP	HC	2030		30			
			DP	HC	2040		30			
			DP	HC	2050		30			
			DP	HC	2060		30			
		lignite	DP	LG	2010		30		Nitsch 2012a Appendix II Tab 1-37	
			DP	LG	2020		30			
			DP	LG	2030		30			
			DP	LG	2040		30			
			DP	LG	2050		30			
			DP	LG	2060		30			

DEPRECIATION PERIOD in [a]

		FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil	nuclear	DP	NC	2010		30			
		DP	NC	2020		30			
		DP	NC	2030		30			
		DP	NC	2040		30			
		DP	NC	2050		30			
		DP	NC	2060		30			
	gas turbine	DP	GT	2010		30		Nitsch 2012a Appendix II Tab 1-33	
		DP	GT	2020		30			
		DP	GT	2030		30			
		DP	GT	2040		30			
		DP	GT	2050		30			
		DP	GT	2060		30			
	gas combined cycle	DP	GCC	2010		30		Nitsch 2012a Appendix II Tab 1-31	
		DP	GCC	2020		30			
		DP	GCC	2030		30			
		DP	GCC	2040		30			
		DP	GCC	2050		30			
		DP	GCC	2060		30			
import	hydro power	DP	HP	2010		30		Nitsch 2012a Appendix II Tab 1-29	
		DP	HP	2020		30			
		DP	HP	2030		30			
		DP	HP	2040		30			
		DP	HP	2050		30			
		DP	HP	2060		30			
	solar power (CSP)	DP	CSP	2010		30		Nitsch 2012a Appendix II Tab 1-30	
		DP	CSP	2020		30			
		DP	CSP	2030		30			
		DP	CSP	2040		30			
		DP	CSP	2050		30		Assumption??	
		DP	CSP	2060		30			
storage and grid / storage	pump storage	DP	PS	2010		60		Nitsch 2012a Appendix II Tab 1-46	
		DP	PS	2020		60			
		DP	PS	2030		60			
		DP	PS	2040		60			
		DP	PS	2050		60			
		DP	PS	2060		60			
	H2 storage	DP	H2	2010		30		Nitsch 2012a Appendix II Tab 1-50	
		DP	H2	2020		30			
		DP	H2	2030		30			
		DP	H2	2040		30			
		DP	H2	2050		30			
		DP	H2	2060		30			
storage and grid / grid	national power supply system	DP	NTC	2010		40		Jorge & Hertwich 2014	
		DP	NTC	2020		40			
		DP	NTC	2030		40			
		DP	NTC	2040		40			
		DP	NTC	2050		40			
		DP	NTC	2060		40			
	high voltage, direct current (underground)	DP	HVDC	2010		40		ELMOD Own Estimate	
		DP	HVDC	2020		40			
		DP	HVDC	2030		40			
		DP	HVDC	2040		40			
		DP	HVDC	2050		40			
		DP	HVDC	2060		40			
	high voltage, direct current (overhead)	DP	HVDC_O	2010		40		ELMOD Own Estimate	
		DP	HVDC_O	2020		40			
		DP	HVDC_O	2030		40			
		DP	HVDC_O	2040		40			
		DP	HVDC_O	2050		40			
		DP	HVDC_O	2060		40			

WEIGHTED AVERAGE COSTS OF CAPITAL (WACC) in [%]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	WACC	PV	2010		1.044		Kost et al 2013	
			WACC	PV	2020		1.044		Table 2	
			WACC	PV	2030		1.044		WACC nominal	
			WACC	PV	2040		1.044			
			WACC	PV	2050		1.044			
			WACC	PV	2060		1.044			
		photovoltaic utility	WACC	PV_U	2010		1.048		Kost et al 2013	
			WACC	PV_U	2020		1.048		Table 2	
			WACC	PV_U	2030		1.048		WACC nominal	
			WACC	PV_U	2040		1.048			
			WACC	PV_U	2050		1.048			
			WACC	PV_U	2060		1.048			
	wind	wind onshore	WACC	W_On	2010		1.059		Kost et al 2013	
			WACC	W_On	2020		1.059		Table 2	
			WACC	W_On	2030		1.059		WACC nominal	
			WACC	W_On	2040		1.059			
			WACC	W_On	2050		1.059			
			WACC	W_On	2060		1.059			
		wind offshore	WACC	W_Off	2010		1.098		Kost et al 2013	
			WACC	W_Off	2020		1.098		Table 2	
			WACC	W_Off	2030		1.098		WACC nominal	
			WACC	W_Off	2040		1.098			
			WACC	W_Off	2050		1.098			
			WACC	W_Off	2060		1.098			
	hydro	small hydro (<1MW)	WACC	H_S	2010		1.060		Nitsch 2012a	
			WACC	H_S	2020		1.060		Appendix II	
			WACC	H_S	2030		1.060		Tab 1-27	
			WACC	H_S	2040		1.060			
			WACC	H_S	2050		1.060			
			WACC	H_S	2060		1.060			
		large hydro (>1MW)	WACC	H_L	2010		1.060		Nitsch 2012a	
			WACC	H_L	2020		1.060		Appendix II	
			WACC	H_L	2030		1.060		Tab 1-28	
			WACC	H_L	2040		1.060			
			WACC	H_L	2050		1.060			
			WACC	H_L	2060		1.060			
		organic waste	WACC	OW	2010		1.060		Nitsch 2012a	
			WACC	OW	2020		1.060		ARES11-A	
			WACC	OW	2030		1.060		Tab 6a	
			WACC	OW	2040		1.060			
			WACC	OW	2050		1.060			
			WACC	OW	2060		1.060			
	biomass	biogas	WACC	BG	2010		1.060		Nitsch 2012a	
			WACC	BG	2020		1.060		Appendix II	
			WACC	BG	2030		1.060		Tab 1-15	
			WACC	BG	2040		1.060			
			WACC	BG	2050		1.060			
			WACC	BG	2060		1.060			
		solid biomass	WACC	SB	2010		1.062		Kost et al 2013	
			WACC	SB	2020		1.062		Table 2	
			WACC	SB	2030		1.062		WACC nominal	
			WACC	SB	2040		1.062			
			WACC	SB	2050		1.062			
			WACC	SB	2060		1.062			
		geothermal	WACC	GEO	2010		1.060		Nitsch 2012a	
			WACC	GEO	2020		1.060		Appendix II	
			WACC	GEO	2030		1.060		Tab 1-23	
			WACC	GEO	2040		1.060			
			WACC	GEO	2050		1.060			
			WACC	GEO	2060		1.060			
	coal	hard coal	WACC	HC	2010		1.090		Kost et al 2013	
			WACC	HC	2020		1.090		Table 2	
			WACC	HC	2030		1.090		WACC nominal	
			WACC	HC	2040		1.090			
			WACC	HC	2050		1.090			
			WACC	HC	2060		1.090			
		lignite	WACC	LG	2010		1.090		Kost et al 2013	
			WACC	LG	2020		1.090		Table 2	
			WACC	LG	2030		1.090		WACC nominal	
			WACC	LG	2040		1.090			
			WACC	LG	2050		1.090			
			WACC	LG	2060		1.090			

WEIGHTED AVERAGE COSTS OF CAPITAL (WACC) in [%]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		nuclear	WACC	NC	2010		1.060			
			WACC	NC	2020		1.060			
			WACC	NC	2030		1.060			
			WACC	NC	2040		1.060			
			WACC	NC	2050		1.060			
			WACC	NC	2060		1.060			
		gas turbine	WACC	GT	2010		1.060		Nitsch 2012a	
			WACC	GT	2020		1.060		Appendix II	
			WACC	GT	2030		1.060		Tab 1-33	
			WACC	GT	2040		1.060			
			WACC	GT	2050		1.060			
			WACC	GT	2060		1.060			
		gas combined cycle	WACC	GCC	2010		1.090		Kost et al 2013	
			WACC	GCC	2020		1.090		Table 2	
			WACC	GCC	2030		1.090		WACC nominal	
			WACC	GCC	2040		1.090			
			WACC	GCC	2050		1.090			
			WACC	GCC	2060		1.090			
import		hydro power	WACC	HP	2010		1.060		Nitsch 2012a	
			WACC	HP	2020		1.060		Appendix II	
			WACC	HP	2030		1.060		Tab 1-29	
			WACC	HP	2040		1.060			
			WACC	HP	2050		1.060			
			WACC	HP	2060		1.060			
		solar power (CSP)	WACC	CSP	2010		1.097		Kost et al 2013	
			WACC	CSP	2020		1.097		Table 2	
			WACC	CSP	2030		1.097		WACC nominal	
			WACC	CSP	2040		1.097			
			WACC	CSP	2050		1.097			
			WACC	CSP	2060		1.097			
storage and grid	storage	pump storage	WACC	PS	2010		1.060			
			WACC	PS	2020		1.060			
			WACC	PS	2030		1.060			
			WACC	PS	2040		1.060			
			WACC	PS	2050		1.060			
			WACC	PS	2060		1.060			
		H2 storage	WACC	H2	2010		1.060			
			WACC	H2	2020		1.060			
			WACC	H2	2030		1.060			
			WACC	H2	2040		1.060			
			WACC	H2	2050		1.060			
			WACC	H2	2060		1.060			
	grid	national power supply system	WACC	NTC	2010		1.060			
			WACC	NTC	2020		1.060			
			WACC	NTC	2030		1.060			
			WACC	NTC	2040		1.060			
			WACC	NTC	2050		1.060			
			WACC	NTC	2060		1.060			
		high voltage, direct current	WACC	HVDC_O	2010		1.060			
			WACC	HVDC_O	2020		1.060			
			WACC	HVDC_O	2030		1.060			
			WACC	HVDC_O	2040		1.060			
			WACC	HVDC_O	2050		1.060			
			WACC	HVDC_O	2060		1.060			

CO_2eq EMISSIONS in [t/GWh]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	CO2	PV	2010		68.3		GEMIS	
			CO2	PV	2020		68.3		solar-PV-multi-framed-with-rack-DE-2010	
			CO2	PV	2030		68.3			
			CO2	PV	2040		68.3			
			CO2	PV	2050		68.3			
			CO2	PV	2060		68.3			
		photovoltaic utility	CO2	PV_U	2010		134.3		GEMIS	
			CO2	PV_U	2020		134.3		Solar-PV-mono-Rahmen-mit-Rack-DE-2010	
			CO2	PV_U	2030		134.3			
			CO2	PV_U	2040		134.3			
			CO2	PV_U	2050		134.3			
			CO2	PV_U	2060		134.3			
	wind	wind onshore	CO2	W_On	2010		9.2		GEMIS	
			CO2	W_On	2020		9.2		wind-turbine-DE-2010-inland	
			CO2	W_On	2030		9.2			
			CO2	W_On	2040		9.2			
			CO2	W_On	2050		9.2			
			CO2	W_On	2060		9.2			
		wind offshore	CO2	W_Off	2010		5.9		GEMIS	
			CO2	W_Off	2020		5.9		wind-turbine-DE-2010-offshore	
			CO2	W_Off	2030		5.9			
			CO2	W_Off	2040		5.9			
			CO2	W_Off	2050		5.9			
			CO2	W_Off	2060		5.9			
	hydro	small hydro (<1MW)	CO2	H_S	2010		6.4		GEMIS	
			CO2	H_S	2020		6.4		hydro-ROR-small-DE-2010-standalone	
			CO2	H_S	2030		6.4			
			CO2	H_S	2040		6.4			
			CO2	H_S	2050		6.4			
			CO2	H_S	2060		6.4			
		large hydro (>1MW)	CO2	H_L	2010		2.8		GEMIS	
			CO2	H_L	2020		2.8		hydro-ROR-big-DE-2010 (update)	
			CO2	H_L	2030		2.8			
			CO2	H_L	2040		2.8			
			CO2	H_L	2050		2.8			
			CO2	H_L	2060		2.8			
		organic waste	CO2	OW	2010		11.5		GEMIS	
			CO2	OW	2020		11.5		bio-waste-cogen-ST-DE-2010	
			CO2	OW	2030		11.5			
			CO2	OW	2040		11.5			
			CO2	OW	2050		11.5			
			CO2	OW	2060		11.5			
	biomass	biogas	CO2	BG	2010		188.1		GEMIS	
			CO2	BG	2020		188.1		biogas-manure-ICE-500-DE-2010/en	
			CO2	BG	2030		188.1			
			CO2	BG	2040		188.1			
			CO2	BG	2050		188.1			
			CO2	BG	2060		188.1			
		solid biomass	CO2	SB	2010		13.6		GEMIS	
			CO2	SB	2020		13.6		wood-wastes-A1-4-cogen-ST-DE_2010	
			CO2	SB	2030		13.6			
			CO2	SB	2040		13.6			
			CO2	SB	2050		13.6			
			CO2	SB	2060		13.6			
		geothermal	CO2	GEO	2010		91.8		GEMIS	
			CO2	GEO	2020		91.8		geothermal-ST-ORC-DE-2010	
			CO2	GEO	2030		91.8			
			CO2	GEO	2040		91.8			
			CO2	GEO	2050		91.8			
			CO2	GEO	2060		91.8			
	coal	hard coal	CO2	HC	2010		867.0		GEMIS	
			CO2	HC	2020		867.0		coal-ST-DE-2010	
			CO2	HC	2030		867.0			
			CO2	HC	2040		867.0			
			CO2	HC	2050		867.0			
			CO2	HC	2060		867.0			
		lignite	CO2	LG	2010		982.0		GEMIS	
			CO2	LG	2020		982.0		lignite-ST-DE-2010-Lausitz	
			CO2	LG	2030		982.0			
			CO2	LG	2040		982.0			

CO2eq EMISSIONS in [t/GWh]

Category	Technology	FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		CO2	LG	2050		982.0			
fossil		CO2	LG	2060		982.0			
fossil	nuclear	CO2	NC	2010		21.9		GEMIS	
fossil	nuclear	CO2	NC	2020		21.9		nuclear-powerplant-PWR-DE-2010	
fossil	nuclear	CO2	NC	2030		21.9			
fossil	nuclear	CO2	NC	2040		21.9			
fossil	nuclear	CO2	NC	2050		21.9			
fossil	nuclear	CO2	NC	2060		21.9			
fossil	gas turbine	CO2	GT	2010		701.3		GEMIS	
fossil	gas turbine	CO2	GT	2020		701.3		gas-GT-DE-2010	
fossil	gas turbine	CO2	GT	2030		701.3			
fossil	gas turbine	CO2	GT	2040		701.3			
fossil	gas turbine	CO2	GT	2050		701.3			
fossil	gas turbine	CO2	GT	2060		701.3			
fossil	gas combined cycle	CO2	GCC	2010		405.2		GEMIS	
fossil	gas combined cycle	CO2	GCC	2020		405.2		gas-CC-DE-2010	
fossil	gas combined cycle	CO2	GCC	2030		405.2			
fossil	gas combined cycle	CO2	GCC	2040		405.2			
fossil	gas combined cycle	CO2	GCC	2050		405.2			
fossil	gas combined cycle	CO2	GCC	2060		405.2			
import	hydro power	CO2	HP	2010		10.3		GEMIS	
import	hydro power	CO2	HP	2020		10.3		hydro-dam-big-NO-2000	
import	hydro power	CO2	HP	2030		10.3			
import	hydro power	CO2	HP	2040		10.3			
import	hydro power	CO2	HP	2050		10.3			
import	hydro power	CO2	HP	2060		10.3			
import	solar power (CSP)	CO2	CSP	2010		11.8		GEMIS	
import	solar power (CSP)	CO2	CSP	2020		11.8		solar-CSP-ES-2020;	
import	solar power (CSP)	CO2	CSP	2030		11.8			
import	solar power (CSP)	CO2	CSP	2040		11.8			
import	solar power (CSP)	CO2	CSP	2050		11.8			
import	solar power (CSP)	CO2	CSP	2060		11.8			
storage and grid / storage	pump storage	CO2	PS	2010		14.1		GEMIS	
storage and grid / storage	pump storage	CO2	PS	2020		14.1		hydro-dam-big-generic-2000	
storage and grid / storage	pump storage	CO2	PS	2030		14.1			
storage and grid / storage	pump storage	CO2	PS	2040		14.1			
storage and grid / storage	pump storage	CO2	PS	2050		14.1			
storage and grid / storage	pump storage	CO2	PS	2060		14.1			
storage and grid / storage	H2 storage	CO2	H2	2010		6.5		Spath et al 2004 Table 4 p. 3	
storage and grid / storage	H2 storage	CO2	H2	2020		6.5			
storage and grid / storage	H2 storage	CO2	H2	2030		6.5			
storage and grid / storage	H2 storage	CO2	H2	2040		6.5			
storage and grid / storage	H2 storage	CO2	H2	2050		6.5			
storage and grid / storage	H2 storage	CO2	H2	2060		6.5			
storage and grid / grid	national power supply system	CO2	NTC	2010		1		Jorge & Hertwich 2014 Table10 Own Calculation	
storage and grid / grid	national power supply system	CO2	NTC	2020		1			
storage and grid / grid	national power supply system	CO2	NTC	2030		1			
storage and grid / grid	national power supply system	CO2	NTC	2040		1			
storage and grid / grid	national power supply system	CO2	NTC	2050		1			
storage and grid / grid	national power supply system	CO2	NTC	2060		1			
storage and grid / grid	high voltage, direct current (underground)	CO2	HVDC	2010					
storage and grid / grid	high voltage, direct current (underground)	CO2	HVDC	2020					
storage and grid / grid	high voltage, direct current (underground)	CO2	HVDC	2030					
storage and grid / grid	high voltage, direct current (underground)	CO2	HVDC	2040					
storage and grid / grid	high voltage, direct current (underground)	CO2	HVDC	2050					
storage and grid / grid	high voltage, direct current (underground)	CO2	HVDC	2060					
	high voltage, direct current (overhead)	CO2	HVDC_O	2010		0.1		May-05 Table 61 (p. 172)	
	high voltage, direct current (overhead)	CO2	HVDC_O	2020		0.1			
	high voltage, direct current (overhead)	CO2	HVDC_O	2030		0.1			
	high voltage, direct current (overhead)	CO2	HVDC_O	2040		0.1			
	high voltage, direct current (overhead)	CO2	HVDC_O	2050		0.1			
	high voltage, direct current (overhead)	CO2	HVDC_O	2060		0.1			

SO2eq EMISSIONS in [kg/GWh]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	SO2	PV	2010		140.1		GEMIS	
			SO2	PV	2020		140.1		solar-PV-multi-framed-with-rack-DE-2010	
			SO2	PV	2030		140.1			
			SO2	PV	2040		140.1			
			SO2	PV	2050		140.1			
			SO2	PV	2060		140.1			
		photovoltaic utility	SO2	PV_U	2010		258.5		GEMIS	
			SO2	PV_U	2020		258.5			
			SO2	PV_U	2030		258.5		Solar-PV-mono-Rahmen-mit-Rack-DE-2010	
			SO2	PV_U	2040		258.5			
			SO2	PV_U	2050		258.5			
			SO2	PV_U	2060		258.5			
	wind	wind onshore	SO2	W_On	2010		25.7		GEMIS	
			SO2	W_On	2020		25.7			
			SO2	W_On	2030		25.7		wind-turbine-DE-2010-inland	
			SO2	W_On	2040		25.7			
			SO2	W_On	2050		25.7			
			SO2	W_On	2060		25.7			
		wind offshore	SO2	W_Off	2010		17.4		GEMIS	
			SO2	W_Off	2020		17.4			
			SO2	W_Off	2030		17.4		wind-turbine-DE-2010-offshore	
			SO2	W_Off	2040		17.4			
			SO2	W_Off	2050		17.4			
			SO2	W_Off	2060		17.4			
	hydro	small hydro (<1MW)	SO2	H_S	2010		20.1		GEMIS	
			SO2	H_S	2020		20.1		hydro-ROR-small-DE-2010-standalone	
			SO2	H_S	2030		20.1			
			SO2	H_S	2040		20.1			
			SO2	H_S	2050		20.1			
			SO2	H_S	2060		20.1			
		large hydro (>1MW)	SO2	H_L	2010		6.9		GEMIS	
			SO2	H_L	2020		6.9			
			SO2	H_L	2030		6.9		hydro-ROR-big-DE-2010 (update)	
			SO2	H_L	2040		6.9			
			SO2	H_L	2050		6.9			
			SO2	H_L	2060		6.9			
		organic waste	SO2	OW	2010		595.6		GEMIS	
			SO2	OW	2020		595.6			
			SO2	OW	2030		595.6		bio-waste-cogen-ST-DE-2010	
			SO2	OW	2040		595.6			
			SO2	OW	2050		595.6			
			SO2	OW	2060		595.6			
	biomass	biogas	SO2	BG	2010		851.1		GEMIS	
			SO2	BG	2020		851.1		biogas-manure-ICE-500-DE-2010/en	
			SO2	BG	2030		851.1			
			SO2	BG	2040		851.1			
			SO2	BG	2050		851.1			
			SO2	BG	2060		851.1			
		solid biomass	SO2	SB	2010		1,028.5		GEMIS	
			SO2	SB	2020		1,028.5			
			SO2	SB	2030		1,028.5		wood-wastes-A1-4-cogen-ST-DE_2010	
			SO2	SB	2040		1,028.5			
			SO2	SB	2050		1,028.5			
			SO2	SB	2060		1,028.5			
		geothermal	SO2	GEO	2010		131.5		GEMIS	
			SO2	GEO	2020		131.5			
			SO2	GEO	2030		131.5		geothermal-ST-ORC-DE-2010	
			SO2	GEO	2040		131.5			
			SO2	GEO	2050		131.5			
			SO2	GEO	2060		131.5			
	coal	hard coal	SO2	HC	2010		600.5		GEMIS	
			SO2	HC	2020		600.5			
			SO2	HC	2030		600.5		coal-ST-DE-2010	
			SO2	HC	2040		600.5			
			SO2	HC	2050		600.5			
			SO2	HC	2060		600.5			
		lignite	SO2	LG	2010		942.0		GEMIS	
			SO2	LG	2020		942.0			
			SO2	LG	2030		942.0		lignite-ST-DE-2010-Lausitz	
			SO2	LG	2040		942.0			
			SO2	LG	2050		942.0			

SO2eq EMISSIONS in [kg/GWh]

		FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		SO2	LG	2060		942.0			
	nuclear	SO2	NC	2010		59.7		GEMIS	
		SO2	NC	2020		59.7		nuclear-powerplant-PWR-DE-2010	
		SO2	NC	2030		59.7			
		SO2	NC	2040		59.7			
		SO2	NC	2050		59.7			
		SO2	NC	2060		59.7			
	gas turbine	SO2	GT	2010		788.4		GEMIS	
		SO2	GT	2020		788.4		gas-GT-DE-2010	
		SO2	GT	2030		788.4			
		SO2	GT	2040		788.4			
		SO2	GT	2050		788.4			
		SO2	GT	2060		788.4			
	gas combined cycle	SO2	GCC	2010		399.5		GEMIS	
		SO2	GCC	2020		399.5		gas-CC-DE-2010	
		SO2	GCC	2030		399.5			
		SO2	GCC	2040		399.5			
		SO2	GCC	2050		399.5			
		SO2	GCC	2060		399.5			
import	hydro power	SO2	HP	2010		38.5		GEMIS	
		SO2	HP	2020		38.5		hydro-dam-big-NO-2000	
		SO2	HP	2030		38.5			
		SO2	HP	2040		38.5			
		SO2	HP	2050		38.5			
		SO2	HP	2060		38.5			
	solar power (CSP)	SO2	CSP	2010		34.4		GEMIS	
		SO2	CSP	2020		34.4		solar-CSP-ES-2020;	
		SO2	CSP	2030		34.4			
		SO2	CSP	2040		34.4			
		SO2	CSP	2050		34.4			
		SO2	CSP	2060		34.4			
storage and grid	storage: pump storage	SO2	PS	2010		18.2		GEMIS	
		SO2	PS	2020		18.2		hydro-dam-big-generic-2000	
		SO2	PS	2030		18.2			
		SO2	PS	2040		18.2			
		SO2	PS	2050		18.2			
		SO2	PS	2060		18.2			
	storage: H2 storage	SO2	H2	2010		69.5		Spath et al 2004 Table 4 p. 3	
		SO2	H2	2020		69.5			
		SO2	H2	2030		69.5			
		SO2	H2	2040		69.5			
		SO2	H2	2050		69.5			
		SO2	H2	2060		69.5			
	grid: national power supply system	SO2	NTC	2010		5		Jorge & Hertwich 2014 Table10 Own Calculation	
		SO2	NTC	2020		5			
		SO2	NTC	2030		5			
		SO2	NTC	2040		5			
		SO2	NTC	2050		5			
		SO2	NTC	2060		5			
	grid: high voltage, direct current (underground)	SO2	HVDC	2010					
		SO2	HVDC	2020					
		SO2	HVDC	2030					
		SO2	HVDC	2040					
		SO2	HVDC	2050					
		SO2	HVDC	2060					
	high voltage, direct current (overhead)	SO2	HVDC_O	2010		3.3		May-05 Table 60 (p. 172)	
		SO2	HVDC_O	2020		3.3			
		SO2	HVDC_O	2030		3.3			
		SO2	HVDC_O	2040		3.3			
		SO2	HVDC_O	2050		3.3			
		SO2	HVDC_O	2060		3.3			

NOx EMISSIONS in [kg/GWh]

		Technology	FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	NOx	PV	2010		88.5		GEMIS	
			NOx	PV	2020		88.5		solar-PV-multi-framed-with-rack-DE-2010	
			NOx	PV	2030		88.5			
			NOx	PV	2040		88.5			
			NOx	PV	2050		88.5			
			NOx	PV	2060		88.5			
		photovoltaic utility	NOx	PV_U	2010		173.3		GEMIS	
			NOx	PV_U	2020		173.3		Solar-PV-mono-Rahmen-mit-Rack-DE-2010	
			NOx	PV_U	2030		173.3			
			NOx	PV_U	2040		173.3			
			NOx	PV_U	2050		173.3			
			NOx	PV_U	2060		173.3			
	wind	wind onshore	NOx	W_On	2010		19.3		GEMIS	
			NOx	W_On	2020		19.3		wind-turbine-DE-2010-inland	
			NOx	W_On	2030		19.3			
			NOx	W_On	2040		19.3			
			NOx	W_On	2050		19.3			
			NOx	W_On	2060		19.3			
		wind offshore	NOx	W_Off	2010		12.0		GEMIS	
			NOx	W_Off	2020		12.0		wind-turbine-DE-2010-offshore	
			NOx	W_Off	2030		12.0			
			NOx	W_Off	2040		12.0			
			NOx	W_Off	2050		12.0			
			NOx	W_Off	2060		12.0			
	hydro	small hydro (<1MW)	NOx	H_S	2010		18.2		GEMIS	
			NOx	H_S	2020		18.2		hydro-ROR-small-DE-2010-standalone	
			NOx	H_S	2030		18.2			
			NOx	H_S	2040		18.2			
			NOx	H_S	2050		18.2			
			NOx	H_S	2060		18.2			
		large hydro (>1MW)	NOx	H_L	2010		7.5		GEMIS	
			NOx	H_L	2020		7.5		hydro-ROR-big-DE-2010 (update)	
			NOx	H_L	2030		7.5			
			NOx	H_L	2040		7.5			
			NOx	H_L	2050		7.5			
			NOx	H_L	2060		7.5			
		organic waste	NOx	OW	2010		854.6		GEMIS	
			NOx	OW	2020		854.6		bio-waste-cogen-ST-DE-2010	
			NOx	OW	2030		854.6			
			NOx	OW	2040		854.6			
			NOx	OW	2050		854.6			
			NOx	OW	2060		854.6			
	biomass	biogas	NOx	BG	2010		509.1		GEMIS	
			NOx	BG	2020		509.1		biogas-manure-ICE-500-DE-2010/en	
			NOx	BG	2030		509.1			
			NOx	BG	2040		509.1			
			NOx	BG	2050		509.1			
			NOx	BG	2060		509.1			
		solid biomass	NOx	SB	2010		1,423.1		GEMIS	
			NOx	SB	2020		1,423.1		wood-wastes-A1-4-cogen-ST-DE_2010	
			NOx	SB	2030		1,423.1			
			NOx	SB	2040		1,423.1			
			NOx	SB	2050		1,423.1			
			NOx	SB	2060		1,423.1			
		geothermal	NOx	GEO	2010		98.2		GEMIS	
			NOx	GEO	2020		98.2		geothermal-ST-ORC-DE-2010	
			NOx	GEO	2030		98.2			
			NOx	GEO	2040		98.2			
			NOx	GEO	2050		98.2			
			NOx	GEO	2060		98.2			
	coal	hard coal	NOx	HC	2010		429.7		GEMIS	
			NOx	HC	2020		429.7		coal-ST-DE-2010	
			NOx	HC	2030		429.7			
			NOx	HC	2040		429.7			
			NOx	HC	2050		429.7			
			NOx	HC	2060		429.7			
		lignite	NOx	LG	2010		364.4		GEMIS	
			NOx	LG	2020		364.4		lignite-ST-DE-2010-Lausitz	
			NOx	LG	2030		364.4			
			NOx	LG	2040		364.4			
			NOx	LG	2050		364.4			

NOx EMISSIONS in [kg/GWh]

		FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
		NOx	LG	2060		364.4			
fossil	nuclear	NOx	NC	2010		57.7		GEMIS	
		NOx	NC	2020		57.7		nuclear-powerplant-PWR-DE-2010	
		NOx	NC	2030		57.7			
		NOx	NC	2040		57.7			
		NOx	NC	2050		57.7			
		NOx	NC	2060		57.7			
	gas turbine	NOx	GT	2010		1,090.7		GEMIS	
		NOx	GT	2020		1,090.7		gas-GT-DE-2010	
		NOx	GT	2030		1,090.7			
		NOx	GT	2040		1,090.7			
		NOx	GT	2050		1,090.7			
		NOx	GT	2060		1,090.7			
	gas combined cycle	NOx	GCC	2010		555.1		GEMIS	
		NOx	GCC	2020		555.1		gas-CC-DE-2010	
		NOx	GCC	2030		555.1			
		NOx	GCC	2040		555.1			
		NOx	GCC	2050		555.1			
		NOx	GCC	2060		555.1			
import	hydro power	NOx	HP	2010		28.6		GEMIS	
		NOx	HP	2020		28.6		hydro-dam-big-NO-2000	
		NOx	HP	2030		28.6			
		NOx	HP	2040		28.6			
		NOx	HP	2050		28.6			
		NOx	HP	2060		28.6			
	solar power (CSP)	NOx	CSP	2010		28.7		GEMIS	
		NOx	CSP	2020		28.7		solar-CSP-ES-2020;	
		NOx	CSP	2030		28.7			
		NOx	CSP	2040		28.7			
		NOx	CSP	2050		28.7			
		NOx	CSP	2060		28.7			
storage and grid / storage	pump storage	NOx	PS	2010		21.4		GEMIS	
		NOx	PS	2020		21.4		hydro-dam-big-generic-2000	
		NOx	PS	2030		21.4			
		NOx	PS	2040		21.4			
		NOx	PS	2050		21.4			
		NOx	PS	2060		21.4			
	H2 storage	NOx	H2	2010		76.1		Spath et al 2004	
		NOx	H2	2020		76.1		Table 4	
		NOx	H2	2030		76.1		p. 3	
		NOx	H2	2040		76.1			
		NOx	H2	2050		76.1			
		NOx	H2	2060		76.1			
grid	national power supply system	NOx	NTC	2010		0.1		May-05	
		NOx	NTC	2020		0.1		Table 60	
		NOx	NTC	2030		0.1		(p. 172)	
		NOx	NTC	2040		0.1		mg Ethylene_eq	
		NOx	NTC	2050		0.1			
		NOx	NTC	2060		0.1		Own Estimate	
	high voltage, direct current (underground)	NOx	HVDC	2010					
		NOx	HVDC	2020					
		NOx	HVDC	2030					
		NOx	HVDC	2040					
		NOx	HVDC	2050					
		NOx	HVDC	2060					
	high voltage, direct current (overhead)	NOx	HVDC_O	2010		0.1		May-05	
		NOx	HVDC_O	2020		0.1		Table 60	
		NOx	HVDC_O	2030		0.1		(p. 172)	
		NOx	HVDC_O	2040		0.1		mg Ethylene_eq	
		NOx	HVDC_O	2050		0.1			
		NOx	HVDC_O	2060		0.1			

PM10 EMISSIONS in [kg/GWh]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	PM10	PV	2010		33.5		GEMIS	
			PM10	PV	2020		33.5		solar-PV-multi-framed-with-rack-DE-2010	
			PM10	PV	2030		33.5			
			PM10	PV	2040		33.5			
			PM10	PV	2050		33.5			
			PM10	PV	2060		33.5			
		photovoltaic utility	PM10	PV_U	2010		65.0		GEMIS	
			PM10	PV_U	2020		65.0			
			PM10	PV_U	2030		65.0		Solar-PV-mono-Rahmen-mit-Rack-DE-2010	
			PM10	PV_U	2040		65.0			
			PM10	PV_U	2050		65.0			
			PM10	PV_U	2060		65.0			
	wind	wind onshore	PM10	W_On	2010		8.2		GEMIS	
			PM10	W_On	2020		8.2			
			PM10	W_On	2030		8.2		wind-turbine-DE-2010-inland	
			PM10	W_On	2040		8.2			
			PM10	W_On	2050		8.2			
			PM10	W_On	2060		8.2			
		wind offshore	PM10	W_Off	2010		6.2		GEMIS	
			PM10	W_Off	2020		6.2			
			PM10	W_Off	2030		6.2		wind-turbine-DE-2010-offshore	
			PM10	W_Off	2040		6.2			
			PM10	W_Off	2050		6.2			
			PM10	W_Off	2060		6.2			
	hydro	small hydro (<1MW)	PM10	H_S	2010		3.7		GEMIS	
			PM10	H_S	2020		3.7		hydro-ROR-small-DE-2010-standalone	
			PM10	H_S	2030		3.7			
			PM10	H_S	2040		3.7			
			PM10	H_S	2050		3.7			
			PM10	H_S	2060		3.7			
		large hydro (>1MW)	PM10	H_L	2010		1.6		GEMIS	
			PM10	H_L	2020		1.6			
			PM10	H_L	2030		1.6		hydro-ROR-big-DE-2010 (update)	
			PM10	H_L	2040		1.6			
			PM10	H_L	2050		1.6			
			PM10	H_L	2060		1.6			
		organic waste	PM10	OW	2010		5.4		GEMIS	
			PM10	OW	2020		5.4			
			PM10	OW	2030		5.4		bio-waste-cogen-ST-DE-2010	
			PM10	OW	2040		5.4			
			PM10	OW	2050		5.4			
			PM10	OW	2060		5.4			
	biomass	biogas	PM10	BG	2010		16.0		GEMIS	
			PM10	BG	2020		16.0		biogas-manure-ICE-500-DE-2010/en	
			PM10	BG	2030		16.0			
			PM10	BG	2040		16.0			
			PM10	BG	2050		16.0			
			PM10	BG	2060		16.0			
		solid biomass	PM10	SB	2010		76.4		GEMIS	
			PM10	SB	2020		76.4			
			PM10	SB	2030		76.4		wood-wastes-A1-4-cogen-ST-DE_2010	
			PM10	SB	2040		76.4			
			PM10	SB	2050		76.4			
			PM10	SB	2060		76.4			
		geothermal	PM10	GEO	2010		10.1		GEMIS	
			PM10	GEO	2020		10.1			
			PM10	GEO	2030		10.1		geothermal-ST-ORC-DE-2010	
			PM10	GEO	2040		10.1			
			PM10	GEO	2050		10.1			
			PM10	GEO	2060		10.1			
	coal	hard coal	PM10	HC	2010		18.2		GEMIS	
			PM10	HC	2020		18.2			
			PM10	HC	2030		18.2		coal-ST-DE-2010	
			PM10	HC	2040		18.2			
			PM10	HC	2050		18.2			
			PM10	HC	2060		18.2			
		lignite	PM10	LG	2010		39.7		GEMIS	
			PM10	LG	2020		39.7			
			PM10	LG	2030		39.7		lignite-ST-DE-2010-Lausitz	
			PM10	LG	2040		39.7			
			PM10	LG	2050		39.7			

PM10 EMISSIONS in [kg/GWh]

Group	Subgroup	Technology	FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil			PM10	LG	2060		39.7			
		nuclear	PM10	NC	2010		7.5		GEMIS	
			PM10	NC	2020		7.5		nuclear-powerplant-PWR-DE-2010	
			PM10	NC	2030		7.5			
			PM10	NC	2040		7.5			
			PM10	NC	2050		7.5			
			PM10	NC	2060		7.5			
		gas turbine	PM10	GT	2010		10.5		GEMIS	
			PM10	GT	2020		10.5		gas-GT-DE-2010	
			PM10	GT	2030		10.5			
			PM10	GT	2040		10.5			
			PM10	GT	2050		10.5			
			PM10	GT	2060		10.5			
		gas combined cycle	PM10	GCC	2010		10.5		GEMIS	
			PM10	GCC	2020		10.5		gas-CC-DE-2010	
			PM10	GCC	2030		10.5			
			PM10	GCC	2040		10.5			
			PM10	GCC	2050		10.5			
			PM10	GCC	2060		10.5			
import		hydro power	PM10	HP	2010		16.1		GEMIS	
			PM10	HP	2020		16.1		hydro-dam-big-NO-2000	
			PM10	HP	2030		16.1			
			PM10	HP	2040		16.1			
			PM10	HP	2050		16.1			
			PM10	HP	2060		16.1			
		solar power (CSP)	PM10	CSP	2010		10.4		GEMIS	
			PM10	CSP	2020		10.4		solar-CSP-ES-2020;	
			PM10	CSP	2030		10.4			
			PM10	CSP	2040		10.4			
			PM10	CSP	2050		10.4			
			PM10	CSP	2060		10.4			
storage and grid	storage	pump storage	PM10	PS	2010		3.9		GEMIS	
			PM10	PS	2020		3.9		hydro-dam-big-generic-2000	
			PM10	PS	2030		3.9			
			PM10	PS	2040		3.9			
			PM10	PS	2050		3.9			
			PM10	PS	2060		3.9			
		H2 storage	PM10	H2	2010		51.7		Spath et al 2004 Table 4 p. 3	
			PM10	H2	2020		51.7			
			PM10	H2	2030		51.7			
			PM10	H2	2040		51.7			
			PM10	H2	2050		51.7			
			PM10	H2	2060		51.7			
	grid	national power supply system	PM10	NTC	2010		3.6		Jorge & Hertwich 2014 Table10 Own Calculation	
			PM10	NTC	2020		3.6			
			PM10	NTC	2030		3.6			
			PM10	NTC	2040		3.6			
			PM10	NTC	2050		3.6			
			PM10	NTC	2060		3.6			
		high voltage, direct current (underground)	PM10	HVDC	2010					
			PM10	HVDC	2020					
			PM10	HVDC	2030					
			PM10	HVDC	2040					
			PM10	HVDC	2050					
			PM10	HVDC	2060					
		high voltage, direct current (overhead)	PM10	HVDC_O	2010		1		May-05 Table 60 (p. 172)	
			PM10	HVDC_O	2020		1			
			PM10	HVDC_O	2030		1			
			PM10	HVDC_O	2040		1			
			PM10	HVDC_O	2050		1			
			PM10	HVDC_O	2060		1			

CUMULATED MATERIAL REQUIREMENT (non-renewable) in [t/GWh]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	CMR	PV	2010		10.9		GEMIS	
			CMR	PV	2020		10.9		solar-PV-multi-framed-with-rack-DE-2010	
			CMR	PV	2030		10.9			
			CMR	PV	2040		10.9			
			CMR	PV	2050		10.9			
			CMR	PV	2060		10.9			
		photovoltaic utility	CMR	PV_U	2010		27.0		GEMIS	
			CMR	PV_U	2020		27.0		Solar-PV-mono-Rahmen-mit-Rack-DE-2010	
			CMR	PV_U	2030		27.0			
			CMR	PV_U	2040		27.0			
			CMR	PV_U	2050		27.0			
			CMR	PV_U	2060		27.0			
	wind	wind onshore	CMR	W_On	2010		18.8		GEMIS	
			CMR	W_On	2020		18.8		wind-turbine-DE-2010-inland	
			CMR	W_On	2030		18.8			
			CMR	W_On	2040		18.8			
			CMR	W_On	2050		18.8			
			CMR	W_On	2060		18.8			
		wind offshore	CMR	W_Off	2010		6.6		GEMIS	
			CMR	W_Off	2020		6.6		wind-turbine-DE-2010-offshore	
			CMR	W_Off	2030		6.6			
			CMR	W_Off	2040		6.6			
			CMR	W_Off	2050		6.6			
			CMR	W_Off	2060		6.6			
	hydro	small hydro (<1MW)	CMR	H_S	2010		35.3		GEMIS	
			CMR	H_S	2020		35.3		hydro-ROR-small-DE-2010-standalone	
			CMR	H_S	2030		35.3			
			CMR	H_S	2040		35.3			
			CMR	H_S	2050		35.3			
			CMR	H_S	2060		35.3			
		large hydro (>1MW)	CMR	H_L	2010		18.0		GEMIS	
			CMR	H_L	2020		18.0		hydro-ROR-big-DE-2010 (update)	
			CMR	H_L	2030		18.0			
			CMR	H_L	2040		18.0			
			CMR	H_L	2050		18.0			
			CMR	H_L	2060		18.0			
		organic waste	CMR	OW	2010		0.5		GEMIS	
			CMR	OW	2020		0.5		bio-waste-cogen-ST-DE-2010	
			CMR	OW	2030		0.5			
			CMR	OW	2040		0.5			
			CMR	OW	2050		0.5			
			CMR	OW	2060		0.5			
	biomass	biogas	CMR	BG	2010		23.5		GEMIS	
			CMR	BG	2020		23.5		biogas-manure-ICE-500-DE-2010/en	
			CMR	BG	2030		23.5			
			CMR	BG	2040		23.5			
			CMR	BG	2050		23.5			
			CMR	BG	2060		23.5			
		solid biomass	CMR	SB	2010		2.8		GEMIS	
			CMR	SB	2020		2.8		wood-wastes-A1-4-cogen-ST-DE_2010	
			CMR	SB	2030		2.8			
			CMR	SB	2040		2.8			
			CMR	SB	2050		2.8			
			CMR	SB	2060		2.8			
		geothermal	CMR	GEO	2010		12.4		GEMIS	
			CMR	GEO	2020		12.4		geothermal-ST-ORC-DE-2010	
			CMR	GEO	2030		12.4			
			CMR	GEO	2040		12.4			
			CMR	GEO	2050		12.4			
			CMR	GEO	2060		12.4			
	coal	hard coal	CMR	HC	2010		14.8		GEMIS	
			CMR	HC	2020		14.8		coal-ST-DE-2010	
			CMR	HC	2030		14.8			
			CMR	HC	2040		14.8			
			CMR	HC	2050		14.8			
			CMR	HC	2060		14.8			
		lignite	CMR	LG	2010		22.8		GEMIS	
			CMR	LG	2020		22.8		lignite-ST-DE-2010-Lausitz	
			CMR	LG	2030		22.8			
			CMR	LG	2040		22.8			
			CMR	LG	2050		22.8			

CUMULATED MATERIAL REQUIREMENT (non-renewable) in [t/GWh]

		FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		CMR	LG	2060		22.8			
	nuclear	CMR	NC	2010		7.8		GEMIS	
		CMR	NC	2020		7.8		nuclear-powerplant-PWR-DE-2010	
		CMR	NC	2030		7.8			
		CMR	NC	2040		7.8			
		CMR	NC	2050		7.8			
		CMR	NC	2060		7.8			
	gas turbine	CMR	GT	2010		16.8		GEMIS	
		CMR	GT	2020		16.8		gas-GT-DE-2010	
		CMR	GT	2030		16.8			
		CMR	GT	2040		16.8			
		CMR	GT	2050		16.8			
		CMR	GT	2060		16.8			
	gas combined cycle	CMR	GCC	2010		6.2		GEMIS	
		CMR	GCC	2020		6.2		gas-CC-DE-2010	
		CMR	GCC	2030		6.2			
		CMR	GCC	2040		6.2			
		CMR	GCC	2050		6.2			
		CMR	GCC	2060		6.2			
import	hydro power	CMR	HP	2010		14.2		GEMIS	
		CMR	HP	2020		14.2		hydro-dam-big-NO-2000	
		CMR	HP	2030		14.2			
		CMR	HP	2040		14.2			
		CMR	HP	2050		14.2			
		CMR	HP	2060		14.2			
	solar power (CSP)	CMR	CSP	2010		25.9		GEMIS	
		CMR	CSP	2020		25.9		solar-CSP-ES-2020;	
		CMR	CSP	2030		25.9			
		CMR	CSP	2040		25.9			
		CMR	CSP	2050		25.9			
		CMR	CSP	2060		25.9			
storage and grid – storage	pump storage	CMR	PS	2010		16.3		GEMIS	
		CMR	PS	2020		16.3		hydro-dam-big-generic-2000	
		CMR	PS	2030		16.3			
		CMR	PS	2040		16.3			
		CMR	PS	2050		16.3			
		CMR	PS	2060		16.3			
	H2 storage	CMR	H2	2010		8.7		Spath et al 2004 Table 1 p. 2	
		CMR	H2	2020		8.7			
		CMR	H2	2030		8.7			
		CMR	H2	2040		8.7			
		CMR	H2	2050		8.7			
		CMR	H2	2060		8.7			
storage and grid – grid	national power supply system	CMR	NTC	2010		1		Jorge & Hertwich 2014 Table10 Own Calculation	
		CMR	NTC	2020		1			
		CMR	NTC	2030		1			
		CMR	NTC	2040		1			
		CMR	NTC	2050		1			
		CMR	NTC	2060		1			
	high voltage, direct current (underground)	CMR	HVDC	2010					
		CMR	HVDC	2020					
		CMR	HVDC	2030					
		CMR	HVDC	2040					
		CMR	HVDC	2050					
		CMR	HVDC	2060					
	high voltage, direct current (overhead)	CMR	HVDC_O	2010		0.1		May-05 Table 60 (p. 172)	
		CMR	HVDC_O	2020		0.1			
		CMR	HVDC_O	2030		0.1			
		CMR	HVDC_O	2040		0.1			
		CMR	HVDC_O	2050		0.1			
		CMR	HVDC_O	2060		0.1			

CAPACITY LAND USE (modified area) in [ha/MW]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	LU_C	PV	2010		0.00		Arent (2014)	
			LU_C	PV	2020		0.00		no land use accounted for	
			LU_C	PV	2030		0.00			
			LU_C	PV	2040		0.00			
			LU_C	PV	2050		0.00			
			LU_C	PV	2060		0.00			
		photovoltaic utility	LU_C	PV_U	2010		2.00		Own Estimate	
			LU_C	PV_U	2020		2.00			
			LU_C	PV_U	2030		2.00			
			[illegible]	[illegible]	2040		[illegible]			
			LU_C	PV_U	2050		2.00			
			LU_C	PV_U	2060		2.00			
	wind	wind onshore	LU_C	W_On	2010		11.00		Fthenakis & Kim(2009)	
			LU_C	W_On	2020		11.00			
			LU_C	W_On	2030		11.00			
			LU_C	W_On	2040		11.00			
			LU_C	W_On	2050		11.00			
			LU_C	W_On	2060		11.00			
		wind offshore	LU_C	W_Off	2010		0.00			
			LU_C	W_Off	2020		0.00			
			LU_C	W_Off	2030		0.00			
			LU_C	W_Off	2040		0.00			
			LU_C	W_Off	2050		0.00			
			LU_C	W_Off	2060		0.00			
	hydro	small hydro (<1MW)	LU_C	H_S	2010		0.00			
			LU_C	H_S	2020		0.00			
			LU_C	H_S	2030		0.00			
			LU_C	H_S	2040		0.00			
			LU_C	H_S	2050		0.00			
			LU_C	H_S	2060		0.00			
		large hydro (>1MW)	LU_C	H_L	2010		0.10		Arent (2014)	
			LU_C	H_L	2020		0.10			
			LU_C	H_L	2030		0.10			
			LU_C	H_L	2040		0.10			
			LU_C	H_L	2050		0.10			
			LU_C	H_L	2060		0.10			
		organic waste	LU_C	OW	2010		0.40		EPRI	
			LU_C	OW	2020		0.40			
			LU_C	OW	2030		0.40			
			LU_C	OW	2040		0.40			
			LU_C	OW	2050		0.40			
			LU_C	OW	2060		0.40			
	biomass	biogas	LU_C	BG	2010		0.40		EPRI	
			LU_C	BG	2020		0.40			
			LU_C	BG	2030		0.40			
			LU_C	BG	2040		0.40			
			LU_C	BG	2050		0.40			
			LU_C	BG	2060		0.40			
		solid biomass	LU_C	SB	2010		0.40		EPRI	
			LU_C	SB	2020		0.40			
			LU_C	SB	2030		0.40			
			LU_C	SB	2040		0.40			
			LU_C	SB	2050		0.40			
			LU_C	SB	2060		0.40			
		geothermal	LU_C	GEO	2010		0.20		Arent (2014)	
			LU_C	GEO	2020		0.20		plants, wells and pipelines over ground	
			LU_C	GEO	2030		0.20			
			LU_C	GEO	2040		0.20			
			LU_C	GEO	2050		0.20			
			LU_C	GEO	2060		0.20			
	coal	hard coal	LU_C	HC	2010		0.06		Own Estimate	
			LU_C	HC	2020		0.06		Average area of power plants: Jänschwalöde, Niederaußem, Neurath	
			LU_C	HC	2030		0.06			
			LU_C	HC	2040		0.06			
			LU_C	HC	2050		0.06			
			LU_C	HC	2060		0.06			
		lignite	LU_C	LG	2010		0.06		Own Estimate	
			LU_C	LG	2020		0.06		Average area of power plants: Jänschwalöde, Niederaußem, Neurath	
			LU_C	LG	2030		0.06			
			LU_C	LG	2040		0.06			
			LU_C	LG	2050		0.06			
			LU_C	LG	2060		0.06			

CAPACITY LAND USE (modified area) in [ha/MW]

Group	Technology	FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil	nuclear	LU_C	NC	2010		0.04		Own Estimate	
		LU_C	NC	2020		0.04		Average area of power plants: Phillipsburg, Grundremmingen, Brunsbüttel	
		LU_C	NC	2030		0.04			
		LU_C	NC	2040		0.04			
		LU_C	NC	2050		0.04			
		LU_C	NC	2060		0.04			
	gas turbine	LU_C	GT	2010		0.02		Own Estimate	
		LU_C	GT	2020		0.02		Average area of power plants: Ahrenfelde, Linden, Kirchlenger	
		LU_C	GT	2030		0.02			
		LU_C	GT	2040		0.02			
		LU_C	GT	2050		0.02			
		LU_C	GT	2060		0.02			
	gas combined cycle	LU_C	GCC	2010		0.02		Own Estimate	
		LU_C	GCC	2020		0.02		average area from gas turbine	
		LU_C	GCC	2030		0.02			
		LU_C	GCC	2040		0.02			
		LU_C	GCC	2050		0.02			
		LU_C	GCC	2060		0.02			
import	hydro power	LU_C	HP	2010		658		GEMIS hydro-dam-big-NO-2000	
		LU_C	HP	2020		658			
		LU_C	HP	2030		658			
		LU_C	HP	2040		658			
		LU_C	HP	2050		658			
		LU_C	HP	2060		658			
	solar power (CSP)	LU_C	CSP	2010		10.00		Hess 2013 Table 34 (p. 101)	
		LU_C	CSP	2020		10.00			
		LU_C	CSP	2030		10.00			
		LU_C	CSP	2040		10.00			
		LU_C	CSP	2050		10.00			
		LU_C	CSP	2060		10.00			
storage and grid / storage	pump storage	LU_C	PS	2010		0.07		Own Estimate	
		LU_C	PS	2020		0.07		Average area of power plants: Goldisthal, Koepchenwerk, Langenprozelten	
		LU_C	PS	2030		0.07			
		LU_C	PS	2040		0.07			
		LU_C	PS	2050		0.07			
		LU_C	PS	2060		0.07			
	H2 storage	LU_C	H2	2010		1.6		Own Estimate	
		LU_C	H2	2020		1.6		Average area of power plants: P2G Thüga, P2G	
		LU_C	H2	2030		1.6			
		LU_C	H2	2040		1.6			
		LU_C	H2	2050		1.6			
		LU_C	H2	2060		1.6			
storage and grid / grid	national power supply system	LU_C	NTC	2010		1.7		DUH 2012 (p. 3)	
		LU_C	NTC	2020		1.7			
		LU_C	NTC	2030		1.7			
		LU_C	NTC	2040		1.7			
		LU_C	NTC	2050		1.7			
		LU_C	NTC	2060		1.7			
	high voltage, direct current (underground)	LU_C	HVDC	2010		0.8		Hess 2013 Table 48 (p. 152)	
		LU_C	HVDC	2020		0.8			
		LU_C	HVDC	2030		0.8			
		LU_C	HVDC	2040		0.8			
		LU_C	HVDC	2050		0.8			
		LU_C	HVDC	2060		0.8			
	high voltage, direct current (overhead)	LU_C	HVDC_O	2010		3.6		Hess 2013 Table 48 (p. 152)	
		LU_C	HVDC_O	2020		3.6			
		LU_C	HVDC_O	2030		3.6			
		LU_C	HVDC_O	2040		3.6			
		LU_C	HVDC_O	2050		3.6			
		LU_C	HVDC_O	2060		3.6			

GENERATION LAND USE (modified area) in [ha/GWh]

			FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
renewables		photovoltaic (building integrated)	LU_G	PV	2010		0.00			
			LU_G	PV	2020		0.00			
			LU_G	PV	2030		0.00			
			LU_G	PV	2040		0.00			
			LU_G	PV	2050		0.00			
			LU_G	PV	2060		0.00			
		photovoltaic utility	LU_G	PV_U	2010		0.00			
			LU_G	PV_U	2020		0.00			
			LU_G	PV_U	2030		0.00			
			LU_G	PV_U	2040		0.00			
			LU_G	PV_U	2050		0.00			
			LU_G	PV_U	2060		0.00			
	wind	wind onshore	LU_G	W_On	2010		0.00			
			LU_G	W_On	2020		0.00			
			LU_G	W_On	2030		0.00			
			LU_G	W_On	2040		0.00			
			LU_G	W_On	2050		0.00			
			LU_G	W_On	2060		0.00			
		wind offshore	LU_G	W_Off	2010		0.00			
			LU_G	W_Off	2020		0.00			
			LU_G	W_Off	2030		0.00			
			LU_G	W_Off	2040		0.00			
			LU_G	W_Off	2050		0.00			
			LU_G	W_Off	2060		0.00			
	hydro	small hydro (<1MW)	LU_G	H_S	2010		0.00			
			LU_G	H_S	2020		0.00			
			LU_G	H_S	2030		0.00			
			LU_G	H_S	2040		0.00			
			LU_G	H_S	2050		0.00			
			LU_G	H_S	2060		0.00			
		large hydro (>1MW)	LU_G	H_L	2010		0.00			
			LU_G	H_L	2020		0.00			
			LU_G	H_L	2030		0.00			
			LU_G	H_L	2040		0.00			
			LU_G	H_L	2050		0.00			
			LU_G	H_L	2060		0.00			
		organic waste	LU_G	OW	2010		0.00			
			LU_G	OW	2020		0.00			
			LU_G	OW	2030		0.00			
			LU_G	OW	2040		0.00			
			LU_G	OW	2050		0.00			
			LU_G	OW	2060		0.00			
	biomass	biogas	LU_G	BG	2010		59.00		Agentur für EE	
			LU_G	BG	2020		59.00			
			LU_G	BG	2030		59.00			
			LU_G	BG	2040		59.00			
			LU_G	BG	2050		59.00			
			LU_G	BG	2060		59.00			
		solid biomass	LU_G	SB	2010		59.00		Agentur für EE	
			LU_G	SB	2020		59.00			
			LU_G	SB	2030		59.00			
			LU_G	SB	2040		59.00			
			LU_G	SB	2050		59.00			
			LU_G	SB	2060		59.00			
		geothermal	LU_G	GEO	2010		0.00			
			LU_G	GEO	2020		0.00		above ground	
			LU_G	GEO	2030		0.00			
			LU_G	GEO	2040		0.00			
			LU_G	GEO	2050		0.00			
			LU_G	GEO	2060		0.00			
	coal	hard coal	LU_G	HC	2010		0.00			
			LU_G	HC	2020		0.00		above ground	
			LU_G	HC	2030		0.00			
			LU_G	HC	2040		0.00			
			LU_G	HC	2050		0.00			
			LU_G	HC	2060		0.00			
		lignite	LU_G	LG	2010		0.13		Agentur für EE	
			LU_G	LG	2020		0.13			
			LU_G	LG	2030		0.13			
			LU_G	LG	2040		0.13			
			LU_G	LG	2050		0.13			
			LU_G	LG	2060		0.13			

GENERATION LAND USE (modified area) in [ha/GWh]

Group	Subgroup	Technology	FactorID	TechID	Year	Min	Mid	Max	SOURCE	Learning curve
fossil		nuclear	LU_G	NC	2010		0.24		McDonald (2009)	
			LU_G	NC	2020		0.24			
			LU_G	NC	2030		0.24			
			LU_G	NC	2040		0.24			
			LU_G	NC	2050		0.24			
			LU_G	NC	2060		0.24			
		gas turbine	LU_G	GT	2010		0.03		Fthenakis&Kim(2009)	
			LU_G	GT	2020		0.03			
			LU_G	GT	2030		0.03			
			LU_G	GT	2040		0.03			
			LU_G	GT	2050		0.03			
			LU_G	GT	2060		0.03			
		gas combined cycle	LU_G	GCC	2010		0.03		Fthenakis&Kim(2009)	
			LU_G	GCC	2020		0.03			
			LU_G	GCC	2030		0.03			
			LU_G	GCC	2040		0.03			
			LU_G	GCC	2050		0.03			
			LU_G	GCC	2060		0.03			
import		hydro power	LU_G	HP	2010		0.00			
			LU_G	HP	2020		0.00			
			LU_G	HP	2030		0.00			
			LU_G	HP	2040		0.00			
			LU_G	HP	2050		0.00			
			LU_G	HP	2060		0.00			
		solar power (CSP)	LU_G	CSP	2010		0.00			
			LU_G	CSP	2020		0.00			
			LU_G	CSP	2030		0.00			
			LU_G	CSP	2040		0.00			
			LU_G	CSP	2050		0.00			
			LU_G	CSP	2060		0.00			
storage and grid	storage	pump storage	LU_G	PS	2010		0			
			LU_G	PS	2020		0			
			LU_G	PS	2030		0			
			LU_G	PS	2040		0			
			LU_G	PS	2050		0			
			LU_G	PS	2060		0			
		H2 storage	LU_G	H2	2010		0			
			LU_G	H2	2020		0			
			LU_G	H2	2030		0			
			LU_G	H2	2040		0			
			LU_G	H2	2050		0			
			LU_G	H2	2060		0			
	grid	national power supply system	LU_G	NTC	2010		0.00			
			LU_G	NTC	2020		0.00			
			LU_G	NTC	2030		0.00			
			LU_G	NTC	2040		0.00			
			LU_G	NTC	2050		0.00			
			LU_G	NTC	2060		0.00			
		high voltage, direct current (underground)	LU_G	HVDC	2010		0			
			LU_G	HVDC	2020		0			
			LU_G	HVDC	2030		0			
			LU_G	HVDC	2040		0			
			LU_G	HVDC	2050		0			
			LU_G	HVDC	2060		0			
		high voltage, direct current (overhead)	LU_G	HVDC_O	2010		0			
			LU_G	HVDC_O	2020		0			
			LU_G	HVDC_O	2030		0			
			LU_G	HVDC_O	2040		0			
			LU_G	HVDC_O	2050		0			
			LU_G	HVDC_O	2060		0			

A.3 Factor Calculation

Table A.2
Conversion of factors with GWh as functional unit to MW

	Load	Lifetime	Power	Energy	CMR [t/...]		CO2 [t/...]		SO2 [kg/...]		Nox [kg/...]		PM10 [kg/...]	
TechID	**[h/a]**	**[a]**	**[MW]**	**[GWh]**	**GWh**	**MW**	**GWh**	**MW**	**GWh**	**MW**	**GWh**	**MW**	**GWh**	**MW**
BG	8,000	15	0.50	60	23.5	2,820	188.1		851.1		509.1		16	
CSP	3,000	25	50	3,750	25.9	1,943	11.8	885	34.4	2,580	28.7	2,153	10.4	780
GCC	6,000	15	450	40,500	6.2	558	405.2		399.5		555.1		10.5	
GEO	7,500	30	1.00	225	12.4	2,790	91.8		131.5		98.2		10.1	
GT	1,000	15	150	2,250	16.8	252	701.3		788.4		1090.7		10.5	
H_L	5,000	80	10	4,000	18	7,200	2.8	1,120	6.9	2,760	7.5	3,000	1.6	640
H_S	6,100	70	0.18	77	35.3	15,073	6.4	2,733	20.1	8,583	18.2	7,771	3.7	1,580
H2	1,507	15	0.12	2.6	8.7	197	6.5	147	69.5	1,571	76.1	1,721	51.7	1,169
HC	6,000	30	700	126,000	14.8	2,664	867		600.5		429.7		18.2	
HP	5,000	50	1,000	250,000	16.3	4,075	10.3	2,575	18.2	4,550	21.4	5,350	3.9	975
HVDC_O	6,710	30	10,000	2,013,000	0.1	20	0.1	20	3.3	664	0.1	20	1	201
LG	6,000	30	800	144,000	22.8	4,104	982		942		364.4		39.7	
NC	6,500	30	1,250	243,750	7.8	1,521	21.9		59.7		57.7		7.5	
NTC	995	40	216,000	8,600,000	1	40	1	40	5	199	0.1	4	3.6	143
OW	7,000	15	10	1,050	0.5	53	11.5		595.6		854.6		5.4	
PS	5,000	50	200	50,000	14.2	3,550	14.1	3,525	38.5	9,625	28.6	7,150	16.1	4,025
PV	900	30	0.15	4.1	10.9	294	68.3	1,844	140.1	3,783	88.5	2,390	33.5	905
PV_U	1,000	30	0.34	10	27	810	134.3	4,029	258.5	7,755	173.3	5,199	65	1,950
SB	6,000	15	20	1,800	2.8	252	13.6		1028.5		1423.1		76.4	
W_Off	3,000	20	4	216	6.6	396	5.9	354	17.4	1,044	12	720	6.2	372
W_On	2,200	20	2	97	18.8	827	9.2	405	25.7	1,131	19.3	849	8.2	361

Table A.3
Land use estimates with plant data from Bundesnetzagentur (2014) and area measurement with Poskanzer (2014)

Technology	Plant	Capacity [MW]	Area [ha]	Land use [ha/MW]
coal	Jänschwalde	3,000	264.4	0.088
	Niederaußem	3,627	121.8	0.034
	Neurath	4,000	153.0	0.038
			compromise:	**0.06**
nuclear	Phillipsburg	2,394	58.5	0.024
	Grundremmingen	2,688	30.9	0.011
	Brunsbüttel	806	67.9	0.084
			compromise:	**0.04**
gas turbine	Ahrenfelde	152	4.0	0.026
	Linden (Hannover)	225	3.7	0.016
	Kirchlengern	185	3.4	0.018
			compromise:	**0.02**

Technology	Plant	Capacity [MW]	Area [ha]	Land use [ha/MW]
pump storage	Goldisthal	1,060	55.0	0.052
	Koepchenwerk	153	15.0	0.098
	Langenprozelten	160	11.6	0.073
			compromise:	**0.07**
H2 storage	P2G Thüga	0.32	0.46	1.438
	P2G	0.50	0.86	1.720
			compromise:	**1.60**

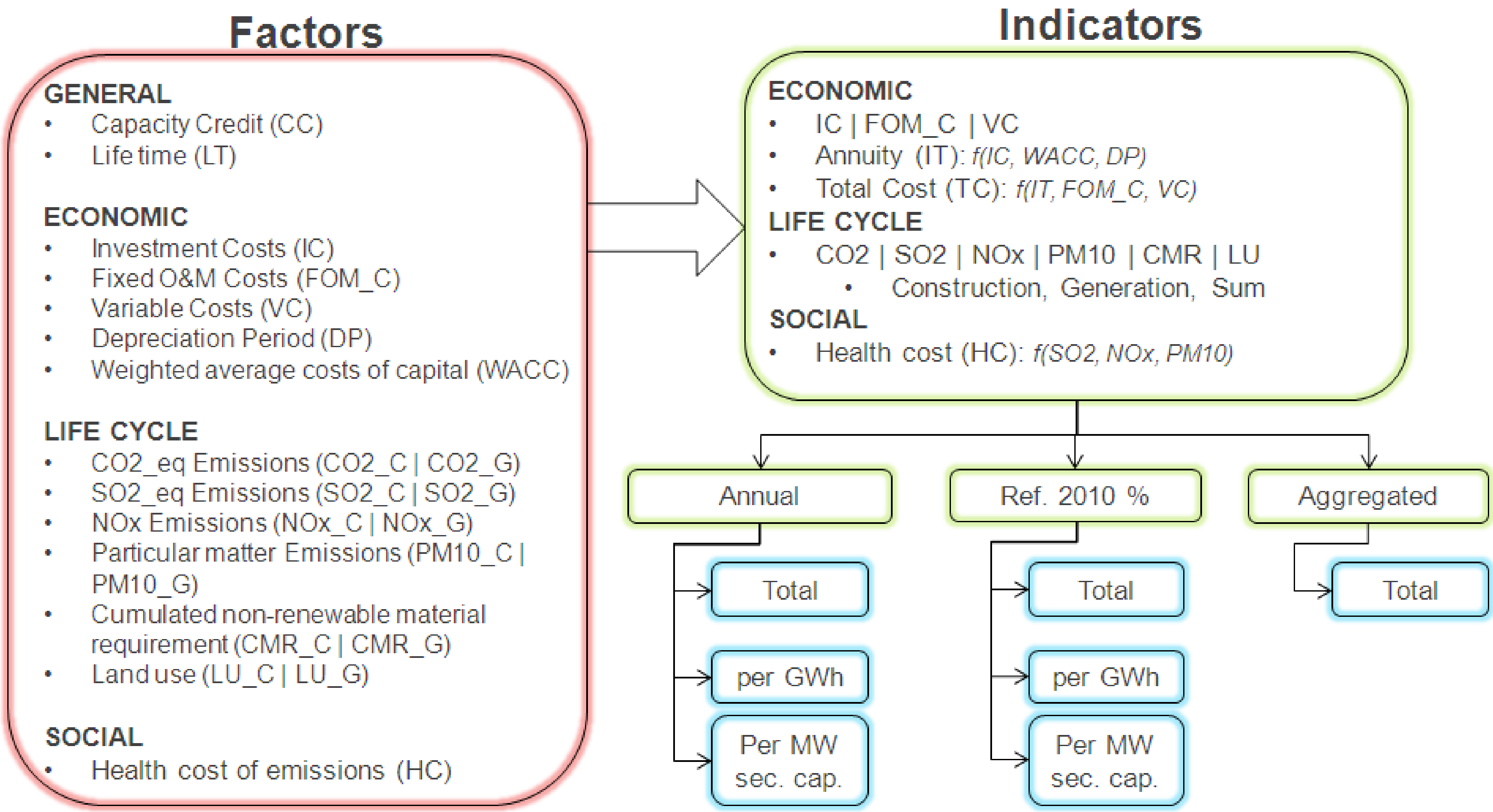


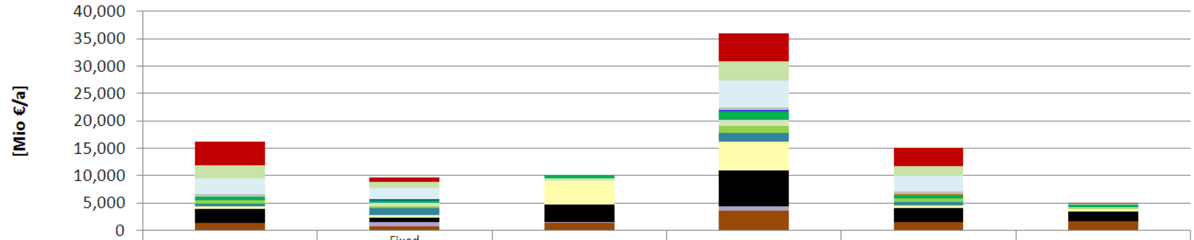
Fig. A.4. Structure of the SEnSys model with input factors (red), calculated indicators (green) and possible outputs (blue)

B. Results

B.1 Reference year 2020

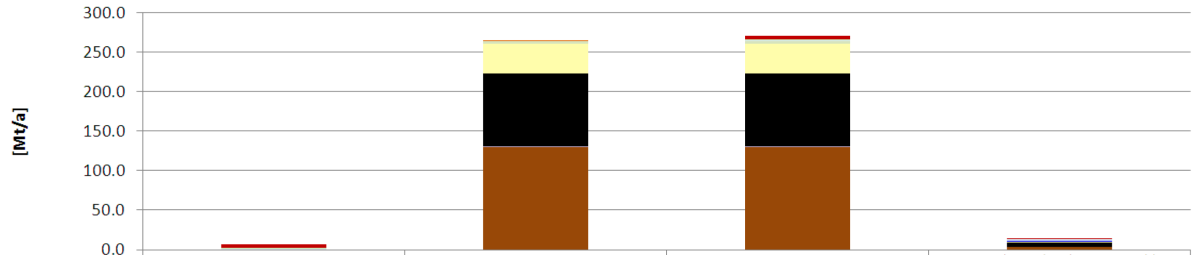
Table B.1
Full list of indicators for 2020. Given as annual numbers and normalized to GWh and MW secured capacity

Indicator	Annual	per GWh	per MW sec. capacity
Annuity capital costs	16,201	27.2	163.4
Fixed operation&maintenance cost	9,631	16.2	97.1
Variable Cost	10,098	17.0	101.9
Total Costs	35,931	60.4	362.4
Investment Costs	15,021	25.2	151.5
CO2_eq Emissions - Construction	7	12.0	72.1
CO2_eq Emissions - Generation	264	443.7	2,663.9
Summed CO2_eq Emissions	271	455.7	2,736.0
SO2_eq Emissions - Generation	339,572	570.5	3,425.0
SO2_eq Emissions	355,607	597.5	3,586.8
Summed SO2_eq Emissions - Construction	16,036	26.9	161.7
Nox Emissions - Construction	10,810	18.2	109.0
Nox Emissions - Generation	202,379	340.0	2,041.3
Summed Nox Emissions	213,188	358.2	2,150.3
CMR - Construction	15	24.6	147.7
CMR - Generation	0	0.0	0.0
Summed CMR	15	24.6	147.7
Particular matter Emissions (PM10) - Construction	4,351	7.3	43.9
Particular matter Emissions (PM10) - Generation	10,733	18.0	108.3
Summed Particular matter Emissions (PM10)	15,084	25.3	152.1
Land use for Capacity	5,179	0.9	5.2
Land use for Generation	26,049	4.4	26.3
Summed Land use	31,229	5.2	31.5
Health cost from air pollution - Construction	239	0.4	2.4
Health cost from air pollution - Generation	4,728	7.9	47.7
Summed Health cost from air pollution	4,967	8.3	50.1



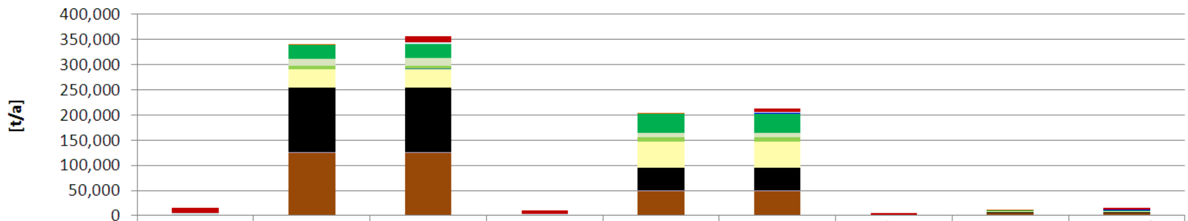
	Annuity capital costs [Mio €/a]	Fixed operation&maintenance cost [Mio €/a]	Variable Cost [Mio €/a]	Total Costs [Mio €/a]	Investment Costs [Mio €/a]	Summed Health cost from air pollution [Mio €/a]
photovoltaic	4,293	793	0	5,086	3,342	158
wind offshore	2,477	1,031	0	3,508	1,663	12
wind onshore	2,856	2,076	0	4,932	2,895	48
gas turbine	367	101	0	468	506	0
hydrogen storage	0	0	0	0	0	0
pumped storage	40	73	0	113	65	15
solar power (CSP)	0	0	0	0	0	0
import hydro	0	0	0	0	0	0
geothermal	62	28	0	91	62	1
solid biomass	552	475	602	1,629	589	452
biogas	0	683	408	1,091	0	201
organic waste	696	377	81	1,155	755	106
running hydro	441	1,264	0	1,704	607	5
gas combined cycle	482	439	4,228	5,149	495	597
hard coal	2,527	789	3,339	6,654	2,596	1,683
nuclear	0	740	100	840	0	23
lignite	1,408	607	1,342	3,356	1,447	1,664
grid connection	0	155	0	155	0	0
HVDC overhead	0	0	0	0	0	0

Fig. B.1. Share of technologies in annual indicators only in reference year 2020 in [Mio. €/a]



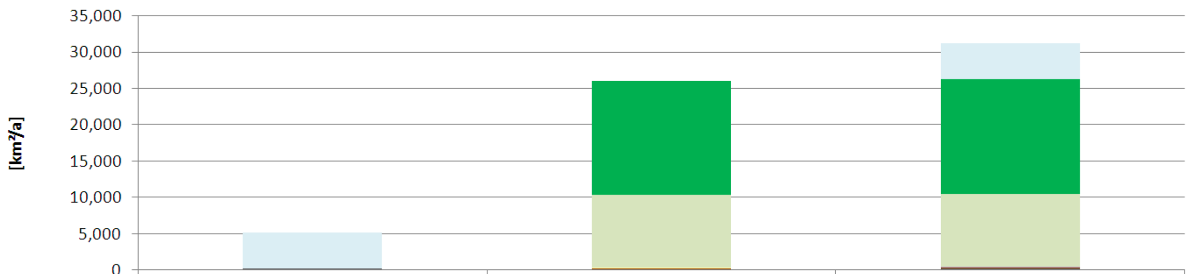
	CO2_eq Emissions - Construction [Mt/a]	CO2_eq Emissions - Generation [Mt/a]	Summed CO2_eq Emissions [Mt/a]	Summed Cumulated non-renewable material requirement [Mt/a]
photovoltaic	5.3	0.0	5.3	0.8
wind offshore	0.3	0.0	0.3	0.3
wind onshore	1.1	0.0	1.1	2.3
gas turbine	0.0	0.0	0.0	0.3
hydrogen storage	0.0	0.0	0.0	0.0
pumped storage	0.4	0.0	0.4	0.4
solar power (CSP)	0.0	0.0	0.0	0.0
import hydro	0.0	0.0	0.0	0.0
geothermal	0.0	0.1	0.1	0.0
solid biomass	0.0	0.4	0.4	0.1
biogas	0.0	3.2	3.2	0.0
organic waste	0.0	0.1	0.1	0.0
running hydro	0.1	0.0	0.1	0.9
gas combined cycle	0.0	37.1	37.1	0.4
hard coal	0.0	92.4	92.4	5.3
nuclear	0.0	0.5	0.5	0.0
lignite	0.0	130.3	130.3	3.9
grid connection	0.0	0.0	0.0	0.0
HVDC overhead	0.0	0.0	0.0	0.0

Fig. B.2. Share of technologies in annual indicators only in reference year 2020 in [Mt/a]



	SO2_eq Emissions - Construction [t/a]	SO2_eq Emissions - Generation [t/a]	Summed SO2_eq Emissions [t/a]	Nox Emissions - Construction [t/a]	Nox Emissions - Generation [t/a]	Summed Nox Emissions [t/a]	Particular matter Emissions (PM10) - Construction [t/a]	Particular matter Emissions (PM10) - Generation [t/a]	Summed Particular matter Emissions (PM10) [t/a]
photovoltaic	10,781	0	10,781	6,810	0	6,810	2,578	0	2,578
wind offshore	818	0	818	564	0	564	291	0	291
wind onshore	3,144	0	3,144	2,361	0	2,361	1,003	0	1,003
gas turbine	0	0	0	0	0	0	0	0	0
hydrogen storage	0	0	0	0	0	0	0	0	0
pumped storage	963	0	963	715	0	715	403	0	403
solar power (CSP)	0	0	0	0	0	0	0	0	0
import hydro	0	0	0	0	0	0	0	0	0
geothermal	0	95	95	0	71	71	0	7	7
solid biomass	0	27,465	27,465	0	38,002	38,002	0	2,040	2,040
biogas	0	14,475	14,475	0	8,659	8,659	0	272	272
organic waste	0	6,459	6,459	0	9,268	9,268	0	59	59
running hydro	331	0	331	360	0	360	77	0	77
gas combined cycle	0	36,547	36,547	0	50,781	50,781	0	961	961
hard coal	0	128,051	128,051	0	45,815	45,815	0	1,940	1,940
nuclear	0	1,476	1,476	0	1,427	1,427	0	185	185
lignite	0	125,003	125,003	0	48,356	48,356	0	5,268	5,268
grid connection	0	0	0	0	0	0	0	0	0
HVDC overhead	0	0	0	0	0	0	0	0	0

Fig. B.3. Share of technologies in annual indicators only in reference year 2020 in [t/a]



	Land use for Capacity [km²/a]	Land use for Generation [km²/a]	Summed Land use [km²/a]
photovoltaic	0	0	0
wind offshore	0	0	0
wind onshore	4,950	0	4,950
gas turbine	3	0	3
hydrogen storage	0	0	0
pumped storage	5	0	5
solar power (CSP)	0	0	0
import hydro	0	0	0
geothermal	0	0	0
solid biomass	16	15,755	15,771
biogas	10	10,035	10,045
organic waste	6	0	6
running hydro	5	0	5
gas combined cycle	6	27	34
hard coal	18	0	18
nuclear	3	59	63
lignite	12	173	185
grid connection	145	0	145
HVDC overhead	0	0	0

Fig. B.4. Share of technologies in land use only in reference year 2020 in [km^2/a]

B.2 Comparision Trieb1 and Trieb2

Table B.2
Full list of installed, shut down, connected, secured and additional capacity in both scenarios for all technologies

	Installed	Shut Down	Connected	Secured	Additional
Trieb1 - 2020	**220,800**	**4,600**	**216,200**	**99,144**	**119,312**
biogas	2,568	0	2,568	2,054	0
gas combined cycle	31,000	0	31,000	27,900	7,000
gas turbine	12,500	0	12,500	11,250	12,500
geothermal	100	0	100	90	90
hard coal	30,000	0	30,000	27,000	19,750
hydrogen storage	0	0	0	0	0
import hydro	0	0	0	0	0
lignite	20,000	0	20,000	18,000	9,540
nuclear	8,600	4,600	4,000	3,600	0
organic waste	1,500	0	1,500	1,200	1,500
photovoltaic	45,000	0	45,000	0	28,500
pumped storage	7,500	0	7,500	0	1,000
running hydro	5,000	0	5,000	2,350	1,200
solar power (CSP)	0	0	0	0	0
solid biomass	4,032	0	4,032	3,226	2,600
wind offshore	8,000	0	8,000	584	7,832
wind onshore	45,000	0	45,000	1,890	27,800
Trieb2 - 2020	**220,800**	**4,600**	**216,200**	**99,144**	**119,312**
biogas	2,568	0	2,568	2,054	0
gas combined cycle	31,000	0	31,000	27,900	7,000
gas turbine	12,500	0	12,500	11,250	12,500
geothermal	100	0	100	90	90
hard coal	30,000	0	30,000	27,000	19,750
hydrogen storage	0	0	0	0	0
import hydro	0	0	0	0	0
lignite	20,000	0	20,000	18,000	9,540
nuclear	8,600	4,600	4,000	3,600	0
organic waste	1,500	0	1,500	1,200	1,500
photovoltaic	45,000	0	45,000	0	28,500
pumped storage	7,500	0	7,500	0	1,000
running hydro	5,000	0	5,000	2,350	1,200
solar power (CSP)	0	0	0	0	0
solid biomass	4,032	0	4,032	3,226	2,600
wind offshore	8,000	0	8,000	584	7,832
wind onshore	45,000	0	45,000	1,890	27,800
Trieb1 - 2030	**272,530**	**7,530**	**265,000**	**98,080**	**113,560**

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Table B.2 – *...Continued from previous page*

	Installed	Shut Down	Connected	Secured	Additional
biogas	413	0	413	330	0
gas combined cycle	25,000	0	25,000	22,500	3,250
gas turbine	36,000	0	36,000	32,400	23,500
geothermal	500	0	500	450	410
hard coal	24,420	4,420	20,000	18,000	0
hydrogen storage	2,000	0	2,000	0	2,000
import hydro	0	0	0	0	0
lignite	13,110	3,110	10,000	9,000	0
nuclear	0	0	0	0	0
organic waste	2,000	0	2,000	1,600	500
photovoltaic	60,000	0	60,000	0	26,500
pumped storage	10,000	0	10,000	0	2,500
running hydro	5,500	0	5,500	2,585	1,100
solar power (CSP)	0	0	0	0	0
solid biomass	8,587	0	8,587	6,870	4,600
wind offshore	25,000	0	25,000	1,825	17,000
wind onshore	60,000	0	60,000	2,520	32,200
Trieb2 - 2030	**237,030**	**17,530**	**219,500**	**98,180**	**78,060**
biogas	413	0	413	330	0
gas combined cycle	38,000	0	38,000	34,200	16,250
gas turbine	26,000	0	26,000	23,400	13,500
geothermal	1,000	0	1,000	900	910
hard coal	24,420	9,420	15,000	13,500	0
hydrogen storage	0	0	0	0	0
import hydro	2,000	0	2,000	1,600	2,000
lignite	13,110	8,110	5,000	4,500	0
nuclear	0	0	0	0	0
organic waste	2,000	0	2,000	1,600	500
photovoltaic	45,000	0	45,000	0	11,500
pumped storage	7,500	0	7,500	0	0
running hydro	5,000	0	5,000	2,350	600
solar power (CSP)	8,500	0	8,500	7,650	8,500
solid biomass	6,587	0	6,587	5,270	2,600
wind offshore	15,000	0	15,000	1,095	7,000
wind onshore	42,500	0	42,500	1,785	14,700
Trieb1 - 2040	**358,970**	**47,470**	**311,500**	**97,028**	**147,900**
biogas	0	0	0	0	0
gas combined cycle	15,450	15,450	0	0	0
gas turbine	89,000	0	89,000	80,100	53,000
geothermal	500	0	500	450	0

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Table B.2 – *...Continued from previous page*

	Installed	**Shut Down**	**Connected**	**Secured**	**Additional**
hard coal	20,950	20,950	0	0	0
hydrogen storage	5,000	0	5,000	0	3,000
import hydro	0	0	0	0	0
lignite	11,070	11,070	0	0	0
nuclear	0	0	0	0	0
organic waste	2,000	0	2,000	1,600	1,500
photovoltaic	84,000	0	84,000	0	29,000
pumped storage	15,000	0	15,000	0	5,000
running hydro	5,500	0	5,500	2,585	300
solar power (CSP)	0	0	0	0	0
solid biomass	8,500	0	8,500	6,800	3,300
wind offshore	39,000	0	39,000	2,847	22,000
wind onshore	63,000	0	63,000	2,646	30,800
Trieb2 - 2040	**263,470**	**38,970**	**224,500**	**96,040**	**87,900**
biogas	0	0	0	0	0
gas combined cycle	28,450	13,450	15,000	13,500	0
gas turbine	50,000	0	50,000	45,000	24,000
geothermal	3,500	0	3,500	3,150	2,500
hard coal	20,950	14,450	6,500	5,850	0
hydrogen storage	0	0	0	0	0
import hydro	3,500	0	3,500	2,800	1,500
lignite	11,070	11,070	0	0	0
nuclear	0	0	0	0	0
organic waste	3,500	0	3,500	2,800	3,000
photovoltaic	45,000	0	45,000	0	5,000
pumped storage	7,500	0	7,500	0	0
running hydro	5,500	0	5,500	2,585	800
solar power (CSP)	12,500	0	12,500	11,250	4,000
solid biomass	7,000	0	7,000	5,600	3,800
wind offshore	25,000	0	25,000	1,825	18,000
wind onshore	40,000	0	40,000	1,680	25,300
Trieb1 - 2050	**387,540**	**32,540**	**355,000**	**95,530**	**140,090**
biogas	0	0	0	0	0
gas combined cycle	3,250	3,250	0	0	0
gas turbine	84,000	0	84,000	75,600	7,500
geothermal	500	0	500	450	90
hard coal	19,750	19,750	0	0	0
hydrogen storage	20,000	0	20,000	0	15,000
import hydro	0	0	0	0	0
lignite	9,540	9,540	0	0	0
nuclear	0	0	0	0	0

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Table B.2 – ...*Continued from previous page*

	Installed	**Shut Down**	**Connected**	**Secured**	**Additional**
organic waste	2,000	0	2,000	1,600	500
photovoltaic	95,000	0	95,000	0	39,500
pumped storage	20,000	0	20,000	0	5,000
running hydro	5,500	0	5,500	2,585	600
solar power (CSP)	0	0	0	0	0
solid biomass	11,000	0	11,000	8,800	7,700
wind offshore	51,000	0	51,000	3,723	29,000
wind onshore	66,000	0	66,000	2,772	35,200
Trieb2 - 2050	**270,540**	**45,540**	**225,000**	**94,736**	**89,090**
biogas	0	0	0	0	0
gas combined cycle	16,250	16,250	0	0	0
gas turbine	65,000	0	65,000	58,500	27,500
geothermal	4,000	0	4,000	3,600	590
hard coal	19,750	19,750	0	0	0
hydrogen storage	0	0	0	0	0
import hydro	4,000	0	4,000	3,200	500
lignite	9,540	9,540	0	0	0
nuclear	0	0	0	0	0
organic waste	4,000	0	4,000	3,200	1,000
photovoltaic	45,000	0	45,000	0	28,500
pumped storage	7,500	0	7,500	0	0
running hydro	5,500	0	5,500	2,585	600
solar power (CSP)	16,000	0	16,000	14,400	3,500
solid biomass	7,000	0	7,000	5,600	3,200
wind offshore	27,000	0	27,000	1,971	9,000
wind onshore	40,000	0	40,000	1,680	14,700

Table B.3
Full list of all aggregated indicators for both scenarios from 2011 to 2050

Indicators	Trieb1	Trieb2	**Δ Trieb1 to Trieb2**
Annuity capital costs in [Mio €]	1,062,606	941,637	11.4%
Fixed operation&maintenance cost in [Mio €]	467,925	453,775	3.0%
Variable Cost in [Mio €]	383,883	367,028	4.4%
Total Costs in [Mio €]	1,914,413	1,762,439	7.9%
Investment Costs in [Mio €]	658,257	518,634	21.2%
CO2_eq Emissions - Construction in [Mt]	361	216	40.3%
CO2_eq Emissions - Generation in [Mt]	6,766	6,497	4.0%
Summed CO2_eq Emissions in [Mt]	7,127	6,713	5.8%
Summed CMR in [Mt]	375	320	14.7%
SO2_eq Emissions - Construction in [t]	865,273	503,558	41.8%
SO2_eq Emissions - Generation in [t]	11,442,219	11,613,416	-1.5%
Summed SO2_eq Emissions in [t]	12,307,492	12,116,974	1.5%
Nox Emissions - Construction in [t]	597,372	348,718	41.6%
Nox Emissions - Generation in [t]	7,546,733	7,387,326	2.1%
Summed Nox Emissions in [t]	8,144,105	7,736,045	5.0%
PM10 - Construction in [t]	269,657	137,482	49.0%
PM10 - Generation in [t]	324,186	325,293	-0.3%
Summed PM10 in [t]	593,843	462,775	22.1%
Health cost - Construction in [Mio €]	13,053	7,539	42.2%
Health cost - Generation in [Mio €]	139,727	138,054	1.2%
Summed Health cost in [Mio €]	152,780	145,593	4.7%

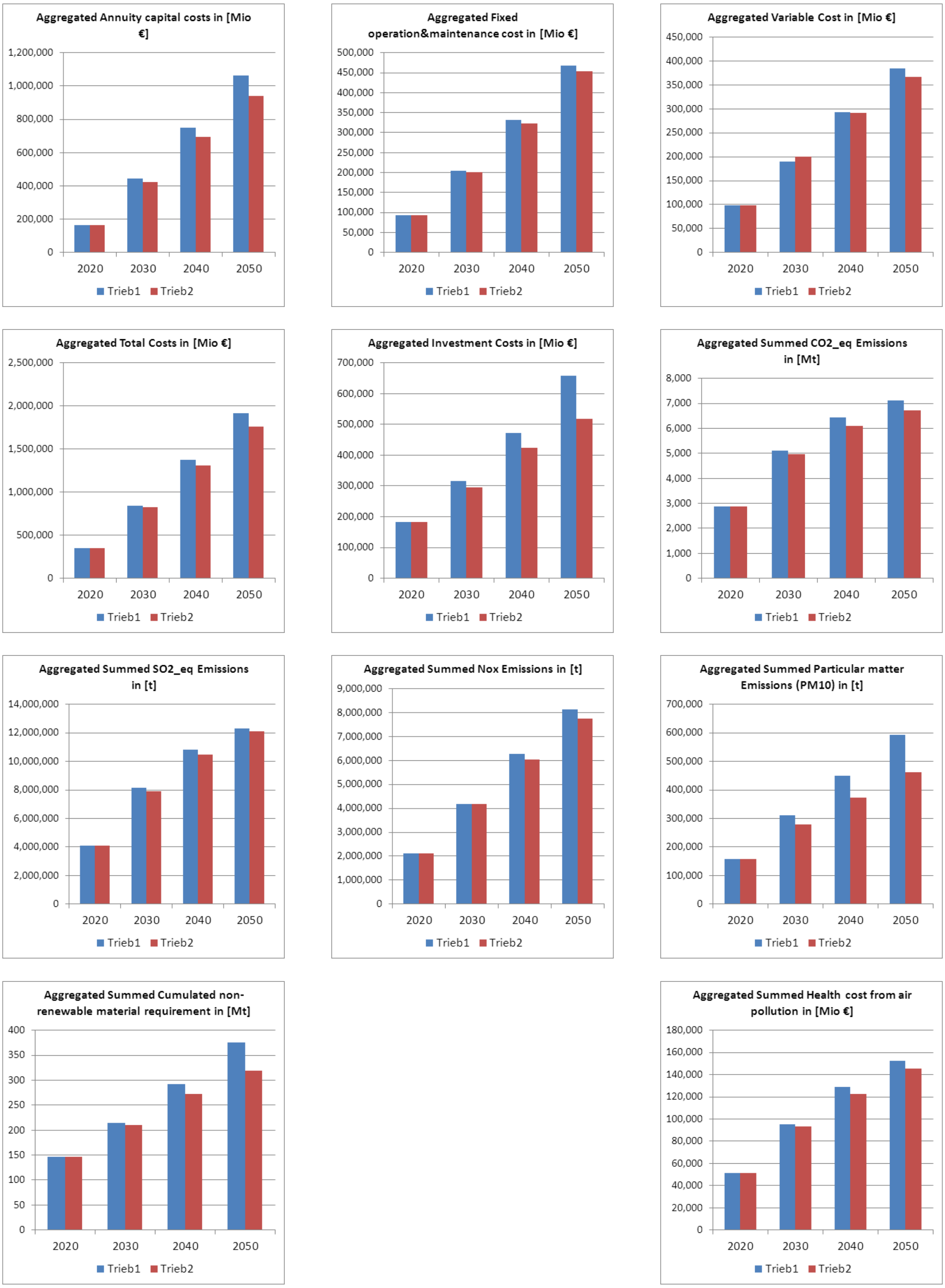

Fig. B.5. Comparison between Trieb1 and Trieb2 in aggregated indicators from 2011 to 2050

Table B.4
Relative changes in relation to reference year 2020 for all indicators in both scenarios

	2030		2040		2050	
Indicators	**Trieb1**	**Trieb2**	**Trieb1**	**Trieb2**	**Trieb1**	**Trieb2**
Annuity capital costs	74.5%	63.5%	91.7%	70.5%	92.2%	57.0%
Fixed operation&maintenance cost	15.9%	8.9%	30.8%	30.6%	40.8%	35.7%
Variable Cost	-12.9%	9.1%	26.0%	-18.3%	-37.5%	-28.7%
Total Costs	34.2%	33.6%	56.9%	34.8%	42.0%	27.2%
Investment Costs	-15.7%	-29.5%	0.2%	-17.4%	21.4%	-41.2%
CO2_eq Emissions - Construction	9.7%	-41.0%	30.3%	-55.0%	65.9%	-7.0%
CO2_eq Emissions - Generation	-37.0%	-45.7%	-71.3%	-77.7%	-86.7%	-90.4%
Summed CO2_eq Emissions	-35.7%	-45.6%	-68.6%	-77.1%	-82.6%	-88.2%
Summed CMR	-53.6%	-58.9%	-48.0%	-59.8%	-43.8%	-73.1%
SO2_eq Emissions - Construction	15.4%	-35.3%	40.2%	-47.4%	84.8%	-7.5%
SO2_eq Emissions - Generation	-27.0%	-34.4%	-58.0%	-59.7%	-72.8%	-70.8%
Summed SO2_eq Emissions	-25.1%	-34.5%	-53.6%	-59.2%	-65.7%	-67.9%
NOx Emissions - Construction	18.1%	-30.8%	42.7%	-41.6%	92.7%	-8.9%
NOx Emissions - Generation	-8.6%	-3.9%	0.9%	-20.8%	-37.3%	-23.1%
Summed NOx Emissions	-7.2%	-5.2%	3.0%	-21.9%	-30.7%	-22.4%
PM10 - Construction	27.1%	-34.6%	64.3%	-41.9%	129.7%	-11.8%
PM10 - Generation	-20.5%	-29.7%	-54.8%	-50.3%	-62.0%	-59.0%
Summed PM10	-6.7%	-31.1%	-20.4%	-47.9%	-6.7%	-45.4%
Land use for Capacity	33.4%	19.6%	44.9%	27.2%	61.4%	38.1%
Land use for Generation	12.4%	11.8%	10.2%	11.8%	2.8%	13.8%
Summed Land use	15.9%	13.1%	16.0%	14.3%	12.5%	17.8%
Health cost - Construction	16.5%	-34.6%	41.9%	-46.3%	88.5%	-8.0%
Health cost - Generation	-24.5%	-30.4%	-50.3%	-54.6%	-68.1%	-64.4%
Summed Health cost	-22.5%	-30.6%	-45.8%	-54.2%	-60.6%	-61.7%

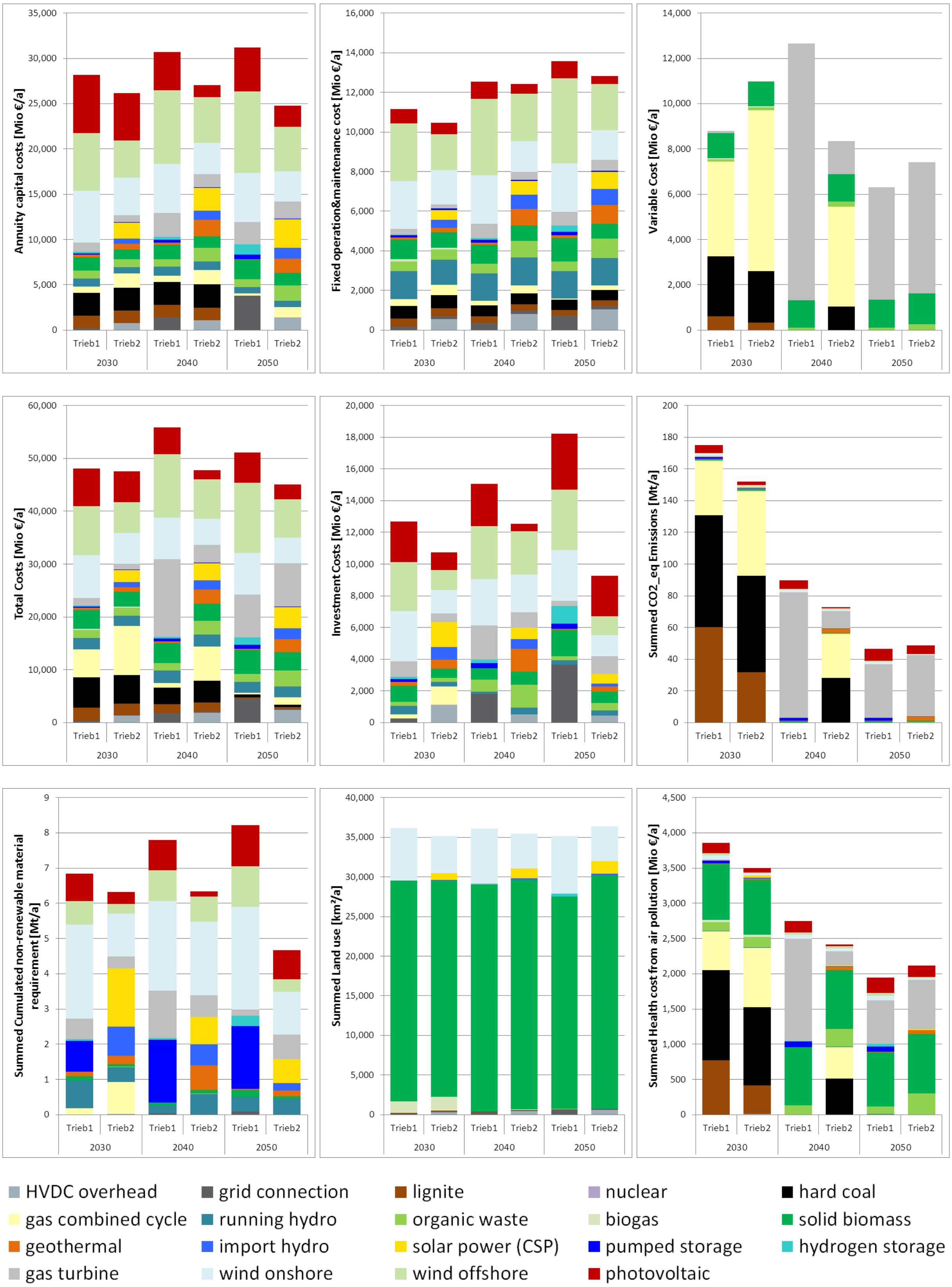

Fig. B.6. Share of technologies in main annual indicators for both scenarios

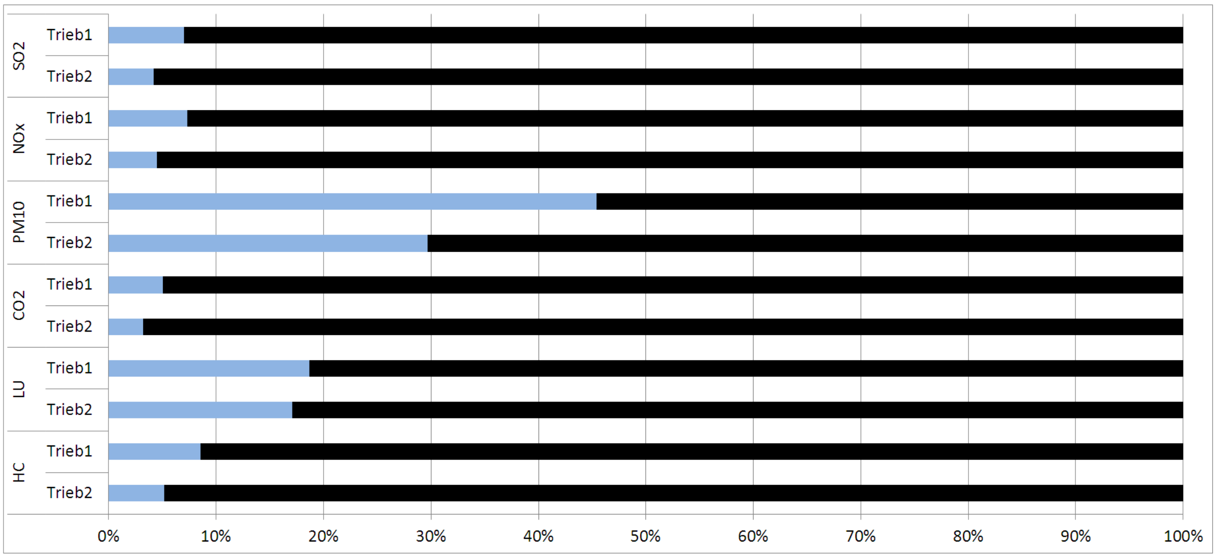

Fig. B.7. Relative share of construction (blue) and generation (black) in aggregated indicators from 2011 to 2050

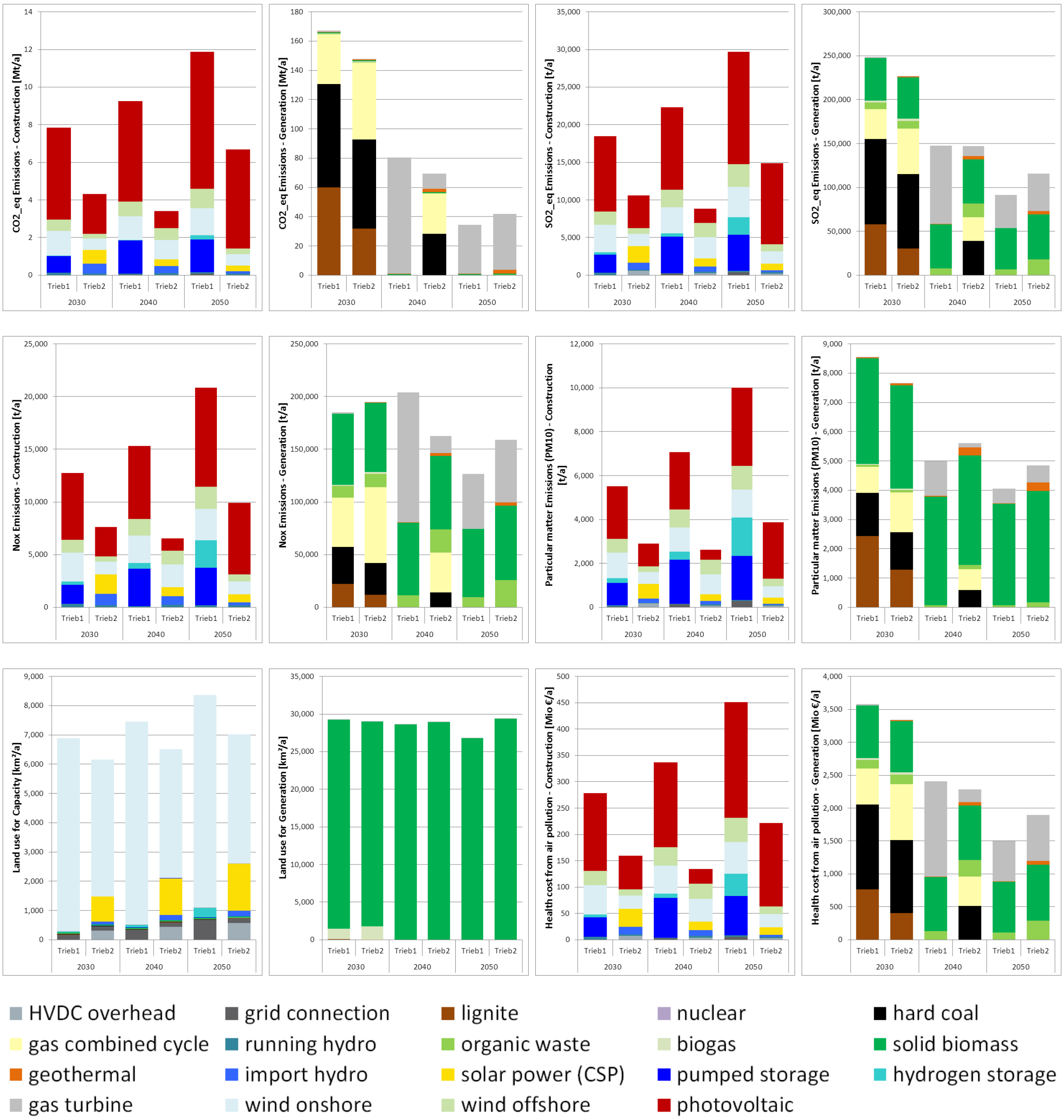

Fig. B.8. Share of technologies in life cycle indicators by construction and generation impacts for both scenarios

C. Discussion

C.1 Comparison with previous study

Table C.1
Data for comparison of Trieb (2013b) with SEnSys results

O R I G I N A L (Trieb, 2013b)				
Scenario Trieb 1	**2020**	**2030**	**2040**	**2050**
Summed CO2_eq Emissions [Mt/a]	306	198	79	46
Summed Land use [km^2]	27235	26551	28237	24146
Investment Costs [Bil. €]	360.9	365.5	352.0	436.4
LCOE [ct/kWh]	10.5	10.3	10.5	10.5
Scenario Trieb 2	**2020**	**2030**	**2040**	**2050**
Summed CO2_eq Emissions [Mt/a]	306	170	83	50
Summed Land use [km^2]	27235	29879	29727	30191
Investment Costs [Bil. €]	360.9	322.6	316.9	305.2
LCOE [ct/kWh]	10.5	10.1	9.4	9.1
S E N S Y S				
Scenario Trieb 1	**2020**	**2030**	**2040**	**2050**
Summed CO2_eq Emissions [Mt/a]	271	175	90	46
Summed Land use [km^2]	31229	36157	36094	35153
Investment Costs [Bil. €]	15.0	12.7	15.1	18.2
LCOE [ct/kWh]	6.0	8.0	9.5	8.4
Scenario Trieb 2	**2020**	**2030**	**2040**	**2050**
Summed CO2_eq Emissions [Mt/a]	271	152	73	49
Summed Land use [km^2]	31229	35163	35470	36406
Investment Costs [Bil. €]	15.0	10.7	12.5	9.3
LCOE [ct/kWh]	6.0	8.2	8.3	8.0