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Integrating wind power into the German electricity grid: a comparison of attributional and consequential LCA.

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Univ.Prof Dipl.-Ing Dr.techn. H. Rechberger

Raphael Stermann

0928223

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2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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LIST OF ABBREVIATIONS

ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
CH	Switzerland
CC	Climate Change
CO_2	Carbon dioxide
DE	Germany
EIFER	European Institute for Energy Research
Eq	Equivalent
FD	Fossil fuel Depletion
Fe	Iron
H	Hierarchist
ISO	International Organization for Standardization
kg	Kilogram
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^2	Square meter
MFA	Material Flow Analysis
MRD	Mineral Resource Depletion
NLT	Natural Land Transformation
NMVOC	Non-methane volatile organic compounds
NOx	Nitrogen oxides
PM	Particulate Matter
PMF	Particulate Matter Formation
POF	Photochemical Ozone Formation
SO_2	Sulfur dioxide
st	Single technique
t	Tonne
TA	Terrestrial acidification
TWh	Terawatt hour
µm	Micrometer
wpi	Wind power integration

0. ABSTRACT

Renewable energies are high on the political agenda for resource depletion, security of supply and climate change concerns. In Germany, wind power is continuously gaining shares in the power plant park. The question arises to what extent its integration into the electricity mix is environmentally beneficial. Life Cycle Assessment (LCA), one of the most prominent ecological assessment tools, can help giving answers. However, different ways exist to carry out LCAs.

An attributional LCA, the traditional and most widely used LCA approach, investigates the environmentally relevant flows over a life cycle. A consequential LCA, promoted as a new alternative, explicitly investigates the changes resulting from a specific decision.

Both attributional and consequential LCA can be used to investigate the environmental benefits from the integration of wind power into a national electricity grid. For this reason, it is of interest to carry out both LCA types on this decision in Germany, looking backwards at the year 2006. The aim is to determine to what extent a consequential LCA, as opposed to an attributional LCA, leads to changes in the evaluation of the environmental performance of intermittent power generation techniques and their integration into the grid. The case of wind power is of particular interest because of its growing importance and its intermittent nature.

The modeling showed that the introduction of wind power leads to environmental benefits in various areas, notably caused by the replacement of fossil fired power generation through wind. However, attributional and consequential LCA show different results. In particular, this difference comes from the inclusion of two effects in the consequential LCA, ignored in the attributional LCA: 1) the substitutive effects from the integration of wind power into the grid and 2) the altered operation of the conventional power plant mix balancing the system to compensate for the fluctuating wind power generation.

In this study, it was demonstrated that only a consequential LCA is able to take into account multiple and interdependent consequences of a given decision, like the decision to integrate wind power into a national electricity grid. It is therefore proposed to guide future large-scale decision-making on the basis of consequential LCA results, as opposed to attributional LCA results, whenever possible.

1. INTRODUCTION

1.1. Background

Renewable energies are high on the political agenda for resource depletion, security of supply and climate change concerns. Particularly in Germany, renewable energies have rapidly gained importance and satisfied 16.1% of the gross electricity consumption in 2009 (BMU, 2010). This share shall at least attain 30% by 2020 according to the Renewable Energy Sources Act (BMU, 2009).

This Act has also consolidated the rule that “grid system operators shall immediately and as a priority purchase, transmit and distribute the entire available quantity of electricity from renewable energy sources” (BMU, 2009, Section 8 §1). The electricity produced by renewables will therefore continue to substitute electricity produced by conventional power plants, such as fossil fired power plants.

The question arises to what extent the integration of renewable energies into the electricity mix is environmentally beneficial.

The case of wind power is of particular interest for two reasons. Firstly, it is the largest renewable electricity supplier in Germany with a share of the total renewables of 40.4% in 2009 (BMU, 2010); its share in the total mix is expected to further increase in the years to come. Secondly, wind is an intermittent electric energy source. It depends on fluctuating meteorological and atmospheric conditions, and the electricity production is therefore inconstant. Wind power is not available in times of low wind speed when wind turbines are not sufficiently supplied with wind, and in times of too high wind speed when wind turbines are shut down to avoid damage to the turbines (International Energy Agency, 2005). As storage capacities are currently lacking, the fluctuating integration of wind power is compensated by the conventional power plant park that balances the system. The operation of the concerned power plants is thereby affected, which alters their efficiency i.e. their environmental performance (e.g. Wolf et al., 2007).

Life Cycle Assessment (LCA), one of the most prominent ecological assessment tools, can help determine the environmental benefits from the integration of wind power into the grid.

Two main types of methods for LCA exist: attributional and consequential LCA.

An attributional LCA, which is the traditional and most widely used LCA approach, is described in the ISO standards 14040 and 14044 (2006a, 2006b). It mainly aims at determining the flows and processes, the resources used, and the environmental impacts of an investigated life cycle.

A consequential LCA, promoted as a new alternative to the attributional LCA, explicitly investigates the changes triggered by a specific decision. In doing so, a consequential LCA takes into account consequential effects which, in principle, are ignored in an attributional LCA (Weidema, 2003). Yet, no internationally defined standard for consequential LCAs exists so far.

All the possible applications of a LCA[1] ultimately aim at change or improvement of an investigated system (e.g. Tillman, 2000) and LCAs therefore guide decision-making.

Both an attributional and a consequential LCA can be used to assess the environmental benefits from the integration of intermittent wind power into a grid. However, a consequential LCA seems more promising since it explicitly accounts for consequential effects of a specific decision that an attributional LCA ignores, following the general principles.

1.2. Objective and working hypothesis

Only a few scientific studies investigate the environmental benefits from the integration of wind power into an electricity grid following a consequential LCA approach. Two studies from Pehnt et al. (2008) and Klobasa et al. (2009) examine such benefits on the case of Germany[2]. However, both only look at the CO_2 emissions changes resulting from this integration and no methodological aspects dealing with the difference between attributional and consequential LCA are considered. The Klobasa et al. (2009) study nonetheless serves as a basis for some methodological aspects of the present study[3].

[1] All the possible applications of LCA are defined in the ISO standard 14040 (2006a).
[2] cf. section *2*
[3] cf. section *4.2*

The main objective of the present study is to determine to what extent a consequential LCA, as opposed to an attributional LCA, leads to changes in the evaluation of the environmental performance of intermittent power generation techniques and their integration into the grid.

Accordingly, both an attributional LCA and a consequential LCA on wind power integration are carried out.

It is the decision to integrate wind power into the German electricity grid and the resulting changes in terms of environmental impacts of the German power plant park in 2006 that are studied. To determine the changes, the known scenario with wind power generation is compared to a hypothetical scenario without wind power generation. The scenarios for the attributional and consequential LCA are modeled using the software tool Umberto (IFU and IFEU, 2006).

The results and the LCA methodology applied will highlight potential advantages and disadvantages of performing a consequential LCA as opposed to an attributional LCA on this specific case. A reflection on the adequacy of the two LCA approaches is thus performed.

The hypothesis is that a consequential LCA is more relevant than an attributional LCA to guide decision-making, on the example of the decision to integrate intermittent wind power into the German electricity grid.

In addition to the attributional and consequential LCA on wind power integration, a simple attributional LCA is performed for each individual power generation technique composing the investigated electricity mix. The aim is to increase the understanding of the attributional and consequential LCA results on wind power integration that only present a difference i.e. the change between two given scenarios.

2. STATE OF THE ART

As previously mentioned, there are only a few scientific studies investigating the environmental benefits from the integration of wind power into the electricity grid following a consequential LCA approach.

Two studies from Pehnt et al. (2008) and Klobasa et al. (2009) analyze the impacts of the integration of wind power into the German electricity mix from a consequential LCA perspective. Both focus on the total CO_2 emissions changes from the German power plant park resulting from this integration. Yet, both investigate these changes for different technology types (offshore versus onshore wind power, respectively) and for different time spans (looking forward until 2020 versus looking backwards at the years 2006 and 2007, respectively).

2.1. The Pehnt et al. (2008)[4] study on offshore wind

Entitled "Consequential environmental system analysis of expected offshore wind electricity production in Germany," the Pehnt et al. (2008) study investigates the environmental benefits from the integration of offshore wind power into the German electricity grid. It is specifically looking at the expected CO_2 emissions changes from the German power plant park resulting from this integration until 2020.

Recognizing that an attributional LCA fails to account for the indirect consequences from e.g. the integration of offshore wind power into the grid (Pehnt et al., 2008), the authors present the results following a consequential LCA[5] approach.

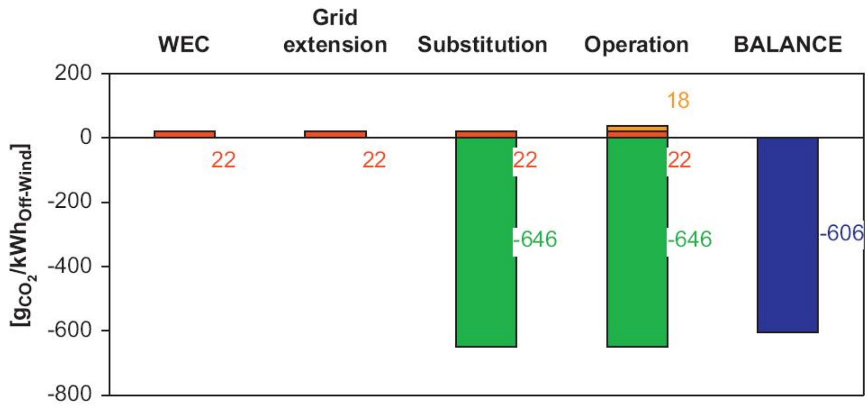
The consequential effects of the integration of offshore wind power considered in the Pehnt et al. (2008) study are: the substitutive and structural effects of offshore wind power for the supply of power; the altered operation of the conventional power plants balancing the system to compensate for the fluctuating wind power generation; the connection of the offshore wind parks to the existing electricity grid, and possible expansions or reinforcement of the grid (Pehnt et al., 2008).

[4] More specific details about the methodology and results can also be found in the Diploma thesis "Systemanalyse der Umweltwirkungen hoher Windstromanteile" (Oeser, 2006), which served as a basis for the publication of Pehnt et al. (2008).

[5] In the study from Pehnt et al. (2008), the consequential LCA approach is referred to as Consequential Environmental System Analysis (CESA).

These consequences are simulated using a stochastic model of the European electricity market called E2M2s, a linear optimization model combined with a LCA electricity system model and a LCA offshore wind model. The LCA offshore wind model determines the breakdown of the CO_2 emissions following the cradle-to-grave scope[6]. The E2M2s model determines the substitution effects and the altered efficiencies of conventional power plants. The calculated data is then transferred to the LCA electricity model which determines the results in terms of changes in CO_2 emissions per kWh. The period of observation is from 2005 to 2020.

In *Figure 1* and *2* presenting the results for the year 2020, respectively for a high and low CO_2 certificate price scenario, the consequential effects are assessed one by one before a balance with the total change in CO_2 emissions resulting from the integration of offshore wind power is shown. Note that the CO_2 emissions increase attributable to the grid extension is too low to be graphically illustrated (Oeser, 2006).



Legend: WEC: wind energy converter; Substitution: substitution of fossil fuels by offshore wind energy; Operation: altered mode of operation of conventional power plants due to additional offshore energy.

Figure 1: Specific CO_2 emissions of offshore wind power for a high CO_2 certificate price scenario in 2020 (source: Pehnt et al., 2008)

For the projected expansion of offshore wind power until 2020, the consequential LCA results for a high CO_2 certificate price scenario (cf. *Figure 1*) show CO_2 emissions savings of 606 g CO_2 per kWh of offshore wind power fed into the grid.

[6] cf. section *3.1*

Legend: WEC: wind energy converter; Substitution: substitution of fossil fuels by offshore wind energy; Operation: altered mode of operation of conventional power plants due to additional offshore energy.

Figure 2: Specific CO_2 emissions of offshore wind power for a low CO_2 certificate price scenario in 2020 (source: Pehnt et al., 2008)

For the projected expansion of offshore wind power until 2020, the consequential LCA results for a low CO_2 certificate price scenario (cf. *Figure 2*) show CO_2 emissions savings of 822 g CO_2 per kWh of offshore wind power fed into the grid.

The main methodological conclusion is that the omission of particular effects would lead to different CO_2 emissions savings results. This would lead to a biased conclusion regarding the environmental benefits from the integration of offshore wind power into the grid.

2.2. The Klobasa et al. (2009) study on onshore wind

Entitled "CO_2 abatement in the electricity sector through the use of renewable energies in 2006 and 2007 - report -"[7], the Klobasa et al. (2009) study investigates the environmental benefits from the integration of renewables-based power into the German electricity grid, including onshore wind power. It is retrospectively looking at the CO_2 emissions changes from the German power plant park that resulted from the integration of onshore wind power in 2006 and 2007.

[7] Translated from the German title "CO_2-Minderung im Stromsektor durch den Einsatz erneuerbarer Energien im Jahr 2006 und 2007 - Gutachten –"

An approach similar to a consequential LCA is pursued. Two particular consequential effects, determined via an agent-based model called PowerACE[8], are considered in the Klobasa et al. (2009) study: the substitutive effects of renewables-based power for the supply of power and the altered operation of the conventional power plants balancing the system to compensate for the fluctuating wind power generation.

The CO_2 emissions changes resulting from the integration of wind power into the German electricity grid for the years 2006 and 2007 are presented in *Table 1*. This integration enabled CO_2 emissions savings of 781 g CO_2 per kWh of wind power produced in Germany in 2006, and 762 g CO_2 per kWh of wind power produced in 2007. This respectively represents a total of 23.8 million t and 30.1 million t CO_2 emissions saved from the total electricity production in Germany in 2006 and 2007.

Table 1: CO_2 emissions savings from wind power generation in Germany (source: Klobasa et al., 2009)

	Wind electricity production [*TWh*]	**CO_2 emissions savings factor** [*g/kWh wind power produced*]	**Total CO_2 emissions savings** [*million t*]
2006	30.5	781	23.8
2007	39.5	762	30.1

While both the Pehnt et al. (2008) and Klobasa et al. (2009) studies follow a consequential LCA approach to determine the CO_2 emissions changes per kWh in Germany, the determined results differ. This is because, as previously outlined, the two studies present results for the year 2020 versus 2006, they focus on offshore wind power versus onshore wind power, and they determined the extent of the consequential effects on the basis of a stochastic model versus an agent-based model, respectively.

The Klobasa et al. (2009) study serves as a reference for some methodological aspects of the present study. The consequential effects of the integration of wind power in 2006 determined by Klobasa et al. (2009) are used to determine the consequential LCA results in the present study. More specific details are given in section *4*.

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[8] cf. section *4.2.3* for more details on the PowerACE model

3. TERMS AND DEFINITIONS

In this section, an overview of the Life Cycle Assessment method is given before defining the concepts of attributional and consequential LCA.

3.1. Life Cycle Assessment

A Life Cycle Assessment (LCA) is defined by the International Organization for Standardization (ISO) in the 14040 and 14044 standards (2006a, 2006b). It aims at identifying the environmentally relevant material, water and energy flows of a good or service[9] throughout its life cycle, thereby determining the Life Cycle Inventory (LCI) based on which the environmental impacts can be assessed.

As LCA is by default a 'cradle-to-grave' approach, a life cycle typically starts from the raw material acquisition, via the production and use phases, and ends with the waste management. Yet, the boundaries of an investigated system may be adapted according to the defined goal and scope of the study.

As illustrated in *Figure 3*, a life cycle assessment study consists of 4 main steps:

- Goal and scope definition, step in which the aim of the LCA study is determined, the life cycle and its boundaries are identified, and the environmental effects to be assessed are selected;
- Inventory analysis, step in which the energy, water, and materials usage, and the environmental releases are identified and quantified;
- Impact assessment, step in which the potential human and ecological effects from the energy, water, and materials usage, and the environmental releases are determined;
- Interpretation, step in which the results of the inventory analysis and the impact assessment are evaluated and eventually compared.

[9] A 'good' or 'service' is also named 'product.'

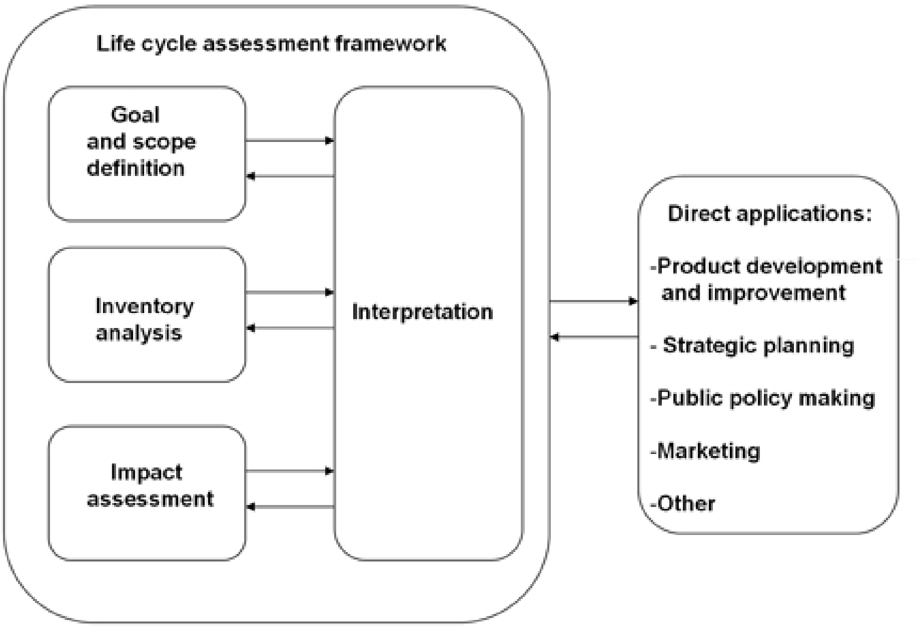


Figure 3: Stages of an LCA (source: ISO, 2006a)

In the *Goal and scope definition* phase, the purpose of the study is defined. At this stage, the appropriate LCA methodology to be applied is determined. The literature basically distinguishes between two types of LCA[10]: attributional LCA and consequential LCA.

3.2. Attributional and consequential LCA definitions

The concepts of attributional LCA and consequential LCA are respectively described in section *3.2.1* and *3.2.2*, followed by an overview of the ongoing debate on the two LCA concepts in section *3.2.3* and a summary in section *3.2.4*.

3.2.1. Attributional LCA

Other names: descriptive LCA, accounting LCA, status quo LCA, retrospective[11] LCA.

[10] A third LCA type, called decisional LCA, is also proposed but is less popular as of today. Further information can be found in section *3.2.3.*

[11] Some authors like Tillman (2000) use the term ‘retrospective LCA’ instead of ‘attributional LCA.’ In principle, however, there is no relation to time; only to the fact that it looks at a static situation.

Attributional Life Cycle Assessment (ALCA) is the traditional and most widely used LCA approach.

An attributional LCA aims at describing “the environmentally relevant physical flows to and from a life cycle and its subsystems” (Ekvall et al., 2005, p. 1). It is an exploration of a product’s life cycle, thus investigating a static situation.

An attributional LCA provides information about the inputs and outputs at each step of a defined process chain, normalized to a chosen functional unit of the investigated product output. The gathered LCI data helps assessing the environmental burdens of an investigated product using Life Cycle Impact Assessment (LCIA) methods.

The boundaries of the investigated system are by default from cradle-to-grave. These can be adapted according to the defined goal and scope of the study. However, according to the general principles for an attributional LCA, the system boundaries cannot be beyond the process chain of the investigated system (Weidema, 2003). Only the processes providing the materials, water and energy inputs needed for the product output are considered, at a defined point in time and within the defined system boundaries. Other market relations beyond the process chain are ignored.

Performing an attributional LCA involves the use of average data that reflects the actual physical flows per unit of the product output (Finnveden et al., 2009).

An attributional LCA is mainly useful for:

- defining a process chain;
- identifying the strengths and weaknesses (i.e. the hot-spots) of a process chain (e.g. in terms of environmental burdens);
- comparing (e.g. the environmental burdens of) different process chains that generate substitutable outputs; and
- comparing (e.g. the environmental burdens of) a same process chain for different scenarios.

3.2.2. Consequential LCA

Other names: change-oriented LCA, effect-oriented LCA, prospective[12] LCA.

Consequential Life Cycle Assessment (CLCA) is a more recent approach than the attributional LCA. No international standard exists at present for the consequential LCA method. Yet, research studies such as Weidema (2003) and guidelines such as the ILCD Handbook from the European Commission's Institute for Environment and Sustainability (2010) have lately been published about this alternative LCA method and its difference to the traditional i.e. attributional LCA method.

A consequential LCA aims at describing "how environmentally relevant flows will change in response to possible decisions" (Ekvall et al., 2005, p. 1). It is an exploration of the changes in a system, triggered by a specific decision. It is thus investigating a dynamic situation by assessing the changes from a given decision.

As opposed to an attributional LCA, the system boundaries in a consequential LCA can go beyond the cradle-to-grave scope, thereby considering other market relations of an investigated system. More specifically, the flows and processes that are affected by a given decision through a cause-effect relationship are considered (Curran et al., 2005) to encompass all the direct and indirect effects of the decision, whenever possible. Guidelines on consequential LCA modeling generally distinguish between the foreground system and background system. The foreground system is the system where the specific decision is realized i.e. where "direct control or decisive influence" over the processes can be exercised (EC-JRC-IES, 2010, p. 96). The background system, which is beyond the cradle-to-grave scope of the foreground system, includes the processes impacted by a given decision which are part of an overall system but on which "direct control or decisive influence" cannot be exercised (EC-JRC-IES, 2010, p. 98).

As opposed to an attributional LCA which involves the use of average data, performing a consequential LCA involves the use of marginal data. Marginal data reflects the effects of a change from a decision on the environmental burden of a system (Ekvall et al., 2005). It is used to assess the consequences of a decision. The consequences are dependent on the scale of the functional unit i.e. are

[12] Some authors like Tillman (2000) use the term 'prospective LCA' instead of 'consequential LCA.' In principle, however, there is no direct relation to time; only to the fact that it looks at the consequences of a decision.

dependent on the extent of the decision. Yet, a consequential LCA does not exclude the use of average data (Ekvall et al., 2005) while an attributional LCA excludes the use of marginal data (Finnveden et al., 2009).

A consequential LCA is useful for:

- identifying the changes (e.g. in terms of environmental burdens) resulting from specific decisions by comparing different scenarios.

3.2.3. Ongoing debate

Despite a general consensus on the conceptual differences between attributional and consequential LCA, many aspects remain debated.

While the results of both attributional and consequential LCAs are easy to communicate and understand (Frischknecht, 2006), it is often argued that consequential LCAs are more relevant for decision-making (e.g. Weidema, 2003). The reason is that consequential LCAs account for far-reaching effects of a given decision that, in principle, an attributional LCA fails to take into account.

In an attempt to set a recommended application scheme[13] to decide between performing an attributional or a consequential LCA (cf. *Figure 4*), Lundie et al. (2007) support the argument that consequential LCAs are more relevant for decision-making than attributional LCAs. However, the authors argue that the purpose to guide decision-making should not be the only criteria to decide on carrying out a consequential LCA instead of an attributional LCA. Following their recommended application scheme, two more criteria to decide on carrying out a consequential LCA are: that the change induced by the given decision impacts i.e. changes the overall status quo, and that this change can be modeled with net benefit i.e. in a “correct manner” (Lundie et al., 2007, p. 12). With this recommendation scheme, the attributional LCA is presented as the default LCA approach. However, Weidema (2003) refutes this idea of the attributional LCA being the default LCA approach. For example, as an attributional LCA has primarily a descriptive function (e.g. Tillman, 2000), it is useful to increase the understanding of a process chain. But Weidema (2003) argues that a consequential LCA is also more

[13] Under the framework of the UNEP-SETAC Life Cycle Initiative

pertinent for this kind of assessment because it encompasses the relations of a system beyond its own life cycle i.e. cradle-to-grave boundaries.

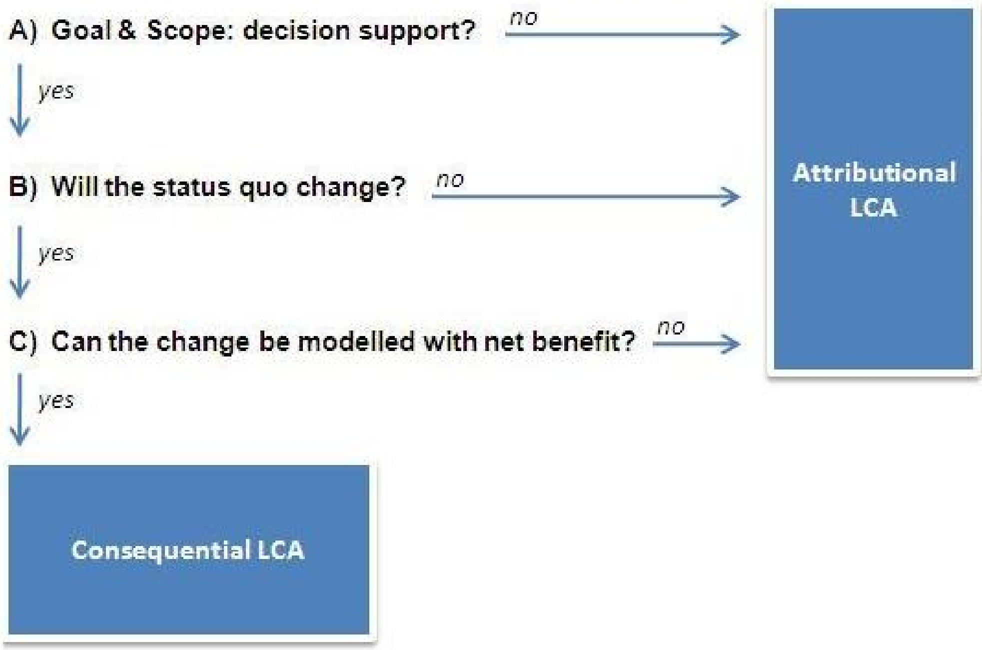


Figure 4: Application scheme as a guidance towards attributional and consequential LCA modeling (source: adapted from Lundie et al., 2007)

Some consequential LCA promoters call for a complete shift from attributional to consequential LCA for specific life cycle assessments. For instance, Norris (2003) suggests the exclusive use of consequential LCAs to address sustainable consumption analyses. Researchers like Weidema (2003) even call for a generalized shift from attributional to consequential LCA. A key argument of the promoters of such a shift is that consequential allows for system expansion.

As a matter of fact, a problem occurs when investigating multiple output processes i.e. processes in which more than one product output is generated. This is particularly critical when comparing different systems involving such processes. The ISO standard 14044 (2006b) recommends to avoid allocation whenever possible. Allocation means avoiding the partitioning of inputs and outputs flows (of materials, water and energy) to the product output under investigation. As a matter of fact, allocation problems might arise. As a recommended solution, system expansion is suggested. System expansion means including “the additional functions related to the co-products” to the process or processes without co-production (ISO, 2006b, section 4.3.4.2). It can be described as follows: System 1 has one product output A (the one under investigation), and System 2 has two product outputs A and B (cf.

Figure 5 – left hand side). The product output B i.e. the process chain necessary for its generation, present in System 2 but missing in System 1, is added to System 1 (cf. *Figure 5* – right hand side). The aim is to enable a more reliable comparison of product systems providing a same function.

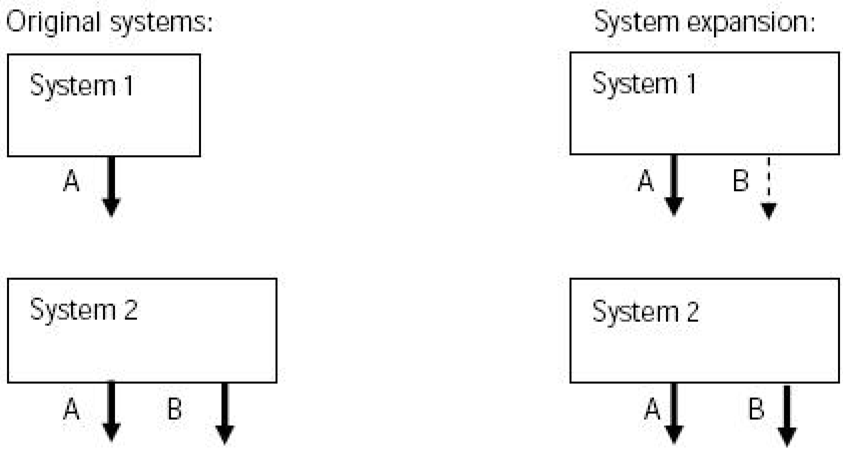


Figure 5: Accounting for co-products through system expansion (source: Weidema, 2003)

The promoters of consequential LCA like Weidema thus argue that an advantage of a consequential LCA, as opposed to an attributional LCA, is the ability to apply system expansion in order to avoid allocation and the related problems. Yet, beyond the question if system expansion is really able to eliminate the problems arising with allocation methods, the question of the applicability remains unsolved. On the one hand, Weidema (2003), similarly to e.g. Lundie et al. (2007), argues that system expansion is "always possible" for consequential LCAs and "never [possible]" for attributional LCAs. On the other hand, Ekvall and Finnveden (2001) show that system expansion is in practice also applied in attributional LCAs. Moreover, on investigations of the consequences of a decision, Ekvall and Finnveden (2001, p. 206) recommend the use of system expansion only when indirect effects are "important" for a decision, unlike Weidema (2003) arguing for a generalized use of system expansion for consequential LCAs.

On the idea of a generalized shift from attributional to consequential LCA, a major obstacle is that consequential LCI databases are presently not available (Frischknecht, 2006). Such databases are currently under development. For example, the renowned LCI data provider ecoinvent intends to include data and models for consequential LCA modeling in its 3rd database version (Weidema et al., 2011). However, the current situation does not allow for a generalized shift from attributional to consequential LCA.

Moreover, the results of an attributional LCA are generally said to be more transparent since a consequential LCA is conceptually more complex (Finnveden et al., 2009).

In particular, the identification of marginal technology i.e. the processes impacted by a defined decision in the background system is related to uncertainty. Especially in prospective studies, the further in the future the expected effects are assessed, the greater the uncertainty is (Mathiesen et al., 2009).

Uncertainty in consequential LCA is also related to the effects considered. While an attributional LCA as a matter of principle ignores consequential effects, it is unlikely that a consequential LCA will comprehensively cover all the possible effects from a specific decision (Lundie et al., 2007). Nevertheless, Lundie et al. (2007) also argue that simply leaving all the consequential effects out is not pertinent and therefore give a few recommendations on how to incorporate main potential effects, such as price effects and technology dynamics.

This subsequently raises the issue of the system boundaries in consequential LCAs. So far, no approved international standard or general practice on the consequences to integrate or to ignore in a consequential LCA exists. For e.g. Ekvall and Weidema (2004), the system boundaries of a consequential LCA should stop where the consequences are too small or the uncertainties too large, which is in line with the idea of Lundie et al. (2007) to model only changes with net benefits (cf. *Figure 4*). On the contrary, Sandén and Karlström (2007) have demonstrated that the most important effects of a decision, though difficult to assess and presenting sensitive results, should not be left out of a consequential LCA.

Additionally, there are even different schools on consequential LCA. An alternative definition to the consequential LCA exists, referred to as the decisional approach. It is however only proposed by Frischknecht and co-workers[14]. In a nutshell, a decisional LCA exclusively considers business-to-business relations i.e. “the financial and contractual relations between economic actors” (Frischknecht, 2006), and thus differs from the consequential approach which considers the impacted

[14] The distinction between attributional, consequential and decisional LCA shall therefore not further be explored in this study

economic activity as a whole. Accordingly, Frischknecht and Stucki (2010) propose a criterion to decide on the most appropriate LCA approach[15] to use: the relative economic size of the object under investigation. For a small relative economic size, an attributional approach shall be applied; for a medium relative economic size, a decisional approach shall be applied; and for a large relative economic size, a consequential approach shall be applied. However, only tentative delimitations have been suggested for this quantitative criterion.

All in all, the potential advantages and disadvantages of a consequential LCA as opposed to an attributional LCA are still debated in the scientific community. The concept of consequential LCA is still under development and not yet standardized, as opposed to the attributional LCA. The main interest in standardizing the consequential LCA approach is that many researchers disapprove the usefulness and appropriateness of the traditional LCA approach (Frischknecht, 2006), especially regarding its relevance for decision support. Some may however also argue that any consequential approach shall not be called LCA but rather an “environmental systems analysis using LCA methodology,” especially when system expansion is applied (Finnveden et al., 2009, p. 6).

3.2.4. Summary

A consequential LCA cannot be regarded as a mere alternative to the traditional i.e. attributional LCA: it is a distinctive concept. Both approaches answer different questions, use partly different methodologies, and therefore present different results. Both have application areas of their own.

While an attributional LCA investigates the environmentally relevant flows over a life cycle, a consequential LCA investigates in a much broader approach how environmentally relevant flows change in response to possible decisions.

The key differences between the two concepts as generally agreed upon in the scientific community are presented in *Table 2*.

[15] cf. *Figure 4* for an alternative method to decide on the most appropriate LCA method, as proposed by Lundie et al. (2007)

Table 2: Key conceptual differences between attributional LCA and consequential LCA (source: own creation)

	ALCA	CLCA
Context	Static	Dynamic
Purpose	Describes (e.g. the environmental burdens or impacts of) a process chain	Describes the changes (e.g. in environmental burdens or impacts) resulting from a specific decision
Market relations beyond the cradle-to-grave scope	Excluded	Included
System boundaries	Foreground system, as defined in the scope definition	Foreground and background system, i.e. the impacted processes through a cause-effect relationship
LCI data	Average data (independent on the scale of the functional unit); use of marginal data excluded	Marginal data (dependent on the scale of the functional unit); use of average data not excluded
Handling multiple output processes	Allocation*	System expansion

Legend: *: The ISO standard 14044 (2006b, section 4.3.4.2) recommends the use of system expansion wherever possible but the literature generally seems to agree that system expansion is rarely applicable in attributional LCAs.

Though methodologically different, both attributional and consequential LCA can help assess the environmental benefits from the integration of wind power into a national grid.

It is therefore of interest to carry out both LCA types on this specific decision in Germany, looking backwards at the year 2006. The aim is to determine to what extent a consequential LCA, as opposed to an attributional LCA, leads to changes in the evaluation of the environmental performance of intermittent power generation techniques and their integration into the grid.

Section *4* of this study presents the LCA methodologies applied; section *5* presents the respective models and results; and section *6* presents a discussion on the findings of this study.

4. METHODOLOGY

As presented in section *3* (cf. *Figure 3*), the first step of an LCA study is the definition of its goal and scope. Hence, the goal and scope of the LCAs carried out in this study are defined in section *4.1*. As well, the data and tools used for the purpose of this study are described in section *4.2*.

An attributional and a consequential LCA on the integration of wind power into the German electricity grid in 2006 are carried out. Additionally, a simple attributional LCA is performed on each individual power generation technique composing the investigated electricity mix to increase the understanding of the LCA results on wind power integration.

To differentiate between the three LCA types carried out in this study, the following naming is respectively proposed:

- attributional LCA on wind power integration (ALCA-wpi)
- consequential LCA on wind power integration (CLCA-wpi)
- attributional LCA on the single power generation techniques composing the investigated electricity mix (ALCA-st)

4.1. Goal and scope definition

The goal and scope of three LCA types are defined in this section. A summarizing overview of the goal and scope definitions is presented in *Table 3*.

Table 3: Goal and scope definition for the purpose of this study (source: own creation)

	ALCA	ALCA	CLCA
	Single technique	Wind power integration	
GOAL DEFINITION			
Goal	To increase the understanding of the LCA results on wind power integration	To determine to what extent a consequential LCA, as opposed to an attributional LCA, leads to changes in the evaluation of the environmental performance of intermittent power generation techniques and their integration into the grid	
Application and audience	To help LCA practitioners identify the potential advantages and disadvantages of performing a consequential LCA, as opposed to an attributional LCA, with regard to large-scale decision-making, like the decision to integrate intermittent wind power into a national electricity grid		
SCOPE DEFINITION			
System analyzed	The individual power generation techniques composing the German power plant mix in 2006	The German power plant mix in 2006	The part of the German power plant mix impacted by the decision to integrate wind power in 2006
Functional unit	kWh of electricity produced at the power plant	kWh of electricity produced by the German power plant portfolio	kWh of electricity produced by the impacted part of the German power plant portfolio
Reference flow	1 kWh		

	ALCA	ALCA	CLCA
	Single technique	**Wind power integration**	
System boundaries	Cradle-to-grave scope for each power plant type separately	Electricity mix, with cradle-to-grave scope for each power plant type separately	Impacted electricity mix, with cradle-to-grave scope for each power plant type separately
LCIA	ReCiPe Midpoint (H), looking at: - climate change - fossil fuel depletion - mineral resource depletion - natural land transformation - particulate matter formation - photochemical ozone formation - terrestrial acidification		
Additional information	No sensitivity analysis envisaged at present		

4.1.1. Goal definition

The goal of performing the different LCAs in this study is first defined. Then, the intended application and audience of this study are identified.

- **Goal**

As outlined in the *Introduction* section, the main objective of the present study is to determine to what extent a consequential LCA, as opposed to an attributional LCA, leads to changes in the evaluation of the environmental performance of intermittent power generation techniques and their integration into the grid.

Accordingly, both an attributional LCA and a consequential LCA on wind power integration are carried out.

It is the decision to integrate wind power into the German electricity grid and the resulting changes in terms of environmental impacts of the German power plant park in 2006 that are studied. To determine the changes, the known scenario with wind power generation is compared to a hypothetical scenario without wind power generation.

The results and the LCA methodology applied shall highlight potential advantages and disadvantages of performing a consequential LCA as opposed to an attributional LCA on this specific case. A reflection on the adequacy of the two LCA approaches is thus performed.

In addition to the attributional and consequential LCA on wind power integration, a simple attributional LCA is performed for each individual power generation technique composing the investigated electricity mix. The aim is to increase the understanding of the attributional and consequential LCA results on wind power integration that only present a difference i.e. the change between two given scenarios.

- **Intended application and audience**

This study is written in the frame of work carried out at the European Institute for Energy Research (EIFER) that looks at the potential weaknesses of the traditional i.e. attributional LCA, particularly regarding the ecological assessment of intermittent power generation techniques.

The intended application of this study is to help LCA practitioners identify the potential advantages and disadvantages of performing a consequential LCA, as opposed to an attributional LCA, with regard to large-scale decision-making, like the decision to integrate intermittent wind power into a national electricity grid.

4.1.2. Scope definition

The scope specific to each LCA type carried out in this study is distinctively defined in this section. Only the information specific to the LCIA and some additional information are jointly detailed for the three LCA types at the end of this section.

Note that detailed information about the LCA modeling and the data used in this study is detailed in section *4.2*.

- **Attributional LCA on the single power generation techniques**

The systems under investigation are the individual power generation techniques that compose the German power plant park in 2006. Separate LCAs are carried out for the lignite, hard coal, natural gas, oil, nuclear, hydropower, photovoltaics, and wind power generation techniques (cf. section *4.2.1*). The functional unit for each power generation technique is the “kWh of electricity produced at the power plant” and the reference flow is “1 kWh.” Each LCA follows the cradle-to-grave scope (cf. section *3.1*) and thus includes LCI data aggregated to the production of 1 kWh of electricity.

- **Attributional LCA on wind power integration**

The system analyzed is Germany’s power plant park in 2006. The known scenario with wind power is compared to a hypothetical scenario without wind power, following the attributional LCA principles. The German power plant park is represented by the average mix, which includes the lignite, hard coal, natural gas, oil, nuclear, hydropower, photovoltaics, and wind power generation techniques. The functional unit for both scenarios is the “kWh of electricity produced by the German power plant portfolio” and the reference flow is “1 kWh.” The system boundaries are thus delimited to the average German power plant park, once with and once without wind power generation. The cradle-to-grave scope is respected for the LCI data of each power generation technique in this mix.

- **Consequential LCA on wind power integration**

The system analyzed is the part of Germany’s power plant park i.e. the marginal technologies impacted by the decision to integrate wind power into the electricity grid in 2006. Similarly to the attributional LCA on wind power integration, the known scenario with wind power is compared to a hypothetical scenario without wind power, yet following the consequential LCA principles. The impacted power plant park is thus represented by the marginal mix, which includes the lignite, hard coal, natural gas, oil, and wind power generation techniques. The functional unit for both scenarios is the “kWh of electricity produced by the impacted part of the German power plant portfolio” and the reference flow is “1 kWh.” The system boundaries are thus delimited to the part of German power plant mix impacted by the decision to integrate wind power into the German electricity grid in 2006, once with wind and once without power generation. The cradle-to-grave scope is respected for the LCI data of each power generation technique in this mix.

- **Life Cycle Impact Assessment**[16]

A Life Cycle Impact Assessment (LCIA) aims at determining the environmental impacts on the basis of the LCI results.

The ReCiPe 2008 method can provide results at both midpoint and endpoint results, for impact categories that reflect issues of direct environmental relevance (Goedkoop et al., 2009). Endpoint indicators are the “physical elements which society determines as worthy of protection” such as human health, while midpoint indicators are “some point on the cause-effect between the stressors and the endpoints” such as smog formation (Bare and Gloria, 2008, p. 1029). The relations

[16] Applies to the attributional and the consequential LCA on wind power integration as well as to the attributional LCA on the single power generation techniques.

between the LCI data, the midpoint indicators and the endpoint indicators of the ReCiPe 2008 method are illustrated in *Figure 6*.

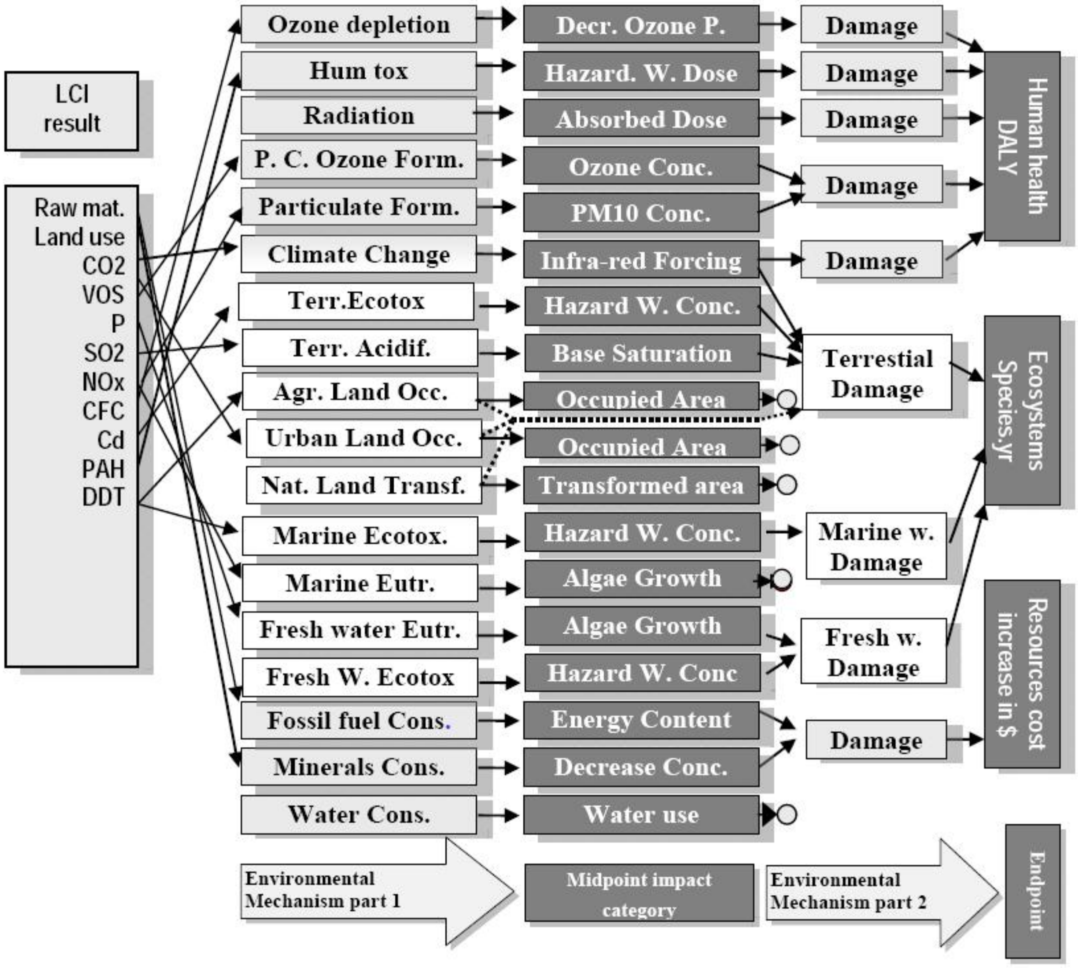


Figure 6: Overall structure of the LCIA method ReCiPe (source: Goedkoop et al., 2009)

The analysis in this study focuses on the midpoint level. It is assumed that assessments at midpoint level involve less uncertainty than assessments at endpoint level (Goedkoop et al., 2009).

ReCiPe also distinguishes between three cultural perspectives: Individualist, Hierarchist, and Egalitarian. The three cultural perspectives involve distinctive methodological choices. The Hierarchist perspective is based on the “most common policy principles” regarding time frames and other issues; the Individualist perspective is the most short-term oriented approach and focuses on short-term impacts; and the Egalitarian perspective follows the most precautionary approach and is therefore long-term oriented (Goedkoop et al., 2009).

The midpoint level assessment carried out in this study is taken from a hierarchist (H) perspective. More specifically, the following impact categories are examined:

- Climate Change (CC), which determines the greenhouse gas emissions over 100 years (in kg CO_2-Eq);
- Fossil fuel Depletion (FD), which determines the amount of resources containing hydrocarbons consumed (in kg oil-Eq);
- Mineral Resource Depletion (MRD), which determines the amount of minerals consumed (in kg Fe-Eq);
- Natural Land Transformation (NLT), which determines the occupation and transformation of an area (in m^2);
- Particulate Matter Formation (PMF), which determines the amount of Particulate Matter of 10 µm and less equivalent diameter emitted (in kg PM10-Eq);
- Photochemical Ozone Formation (POF), which determines the amount of photochemical oxidants emitted (in kg NMVOC-Eq);
- Terrestrial Acidification (TA), which determines the acidification of the soil over 100 years resulting from the atmospheric deposition of inorganic substances (in kg SO_2-Eq).

These impact categories are selected for the specific purpose of this study. The integration of wind power into the grid is expected to have an impact on the air pollution potential of the power plant park as well as the subsequent direct and indirect effects of this air pollution, in addition to having an impact on resource consumption. The selected impact categories are considered to be the most relevant to highlight these impacts.

Detailed methodological information about the impact categories can be found in the Goedkoop et al. (2009) report that describes the LCIA method ReCiPe 2008.

- **Additional information**[17]

No sensitivity analyses are envisaged at present. The dataset used for the LCAs is strictly the same for the German electricity production shares in 2006 as well as for the LCI data of the investigated power generation techniques (cf. section *4.2.1*).

[17] Applies to the attributional and the consequential LCA on wind power integration as well as to the attributional LCA on the single power generation techniques.

Moreover, the LCI data from the ecoinvent database provides data specific to the electricity production from the investigated power generation techniques. There are therefore no multiple out processes involved. Hence, no sensitivity analyses on possible allocation or system expansion methods are needed.

Sensitivity analyses should however be envisaged at a later stage. This is discussed in section *6.3.2*.

4.2. Data and tools

The data and tools used for the purpose of this study are presented in this section.

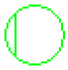
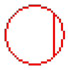
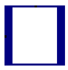
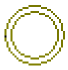
4.2.1. The tool Umberto

For the LCA modeling, the software tool Umberto version 5 (IFU and IFEU, 2006) is used. Umberto is a software intended for Material Flow Analysis (MFA) but also for LCA. It allows for the integration of LCI data from the ecoinvent database version 2.2 (ecoinvent Centre, 2007), a renowned and widely used LCI data provider.

This software and database combination is used to model the LCAs needed for the purpose of this study, to collect the LCI data of the investigated power generation techniques, and to perform the selected LCIAs.

The elements to model LCAs in Umberto are described in *Table 4*.

Table 4: Elements to model LCAs in Umberto (source: own creation)

Symbol	Name	Function
	Input place	Gathers all the inputs needed for the production output throughout a defined process chain, including e.g. the raw materials and the energy input needed for the output production
	Output place	Gathers all the outputs from a defined process chain, including e.g. the emissions outputs and the waste management throughout the life cycle. Note that generally, releases and wastes are modeled with a different output place than the intended outputs (such as electricity production)
	Transition	Represents the conversion processes throughout the life cycle, including transports
	Connection	Connecting two transitions

As the goal of this study is neither to describe the process chain nor to identify the hot-spots of the investigated power generation techniques, their life cycles are modeled in a simplified way illustrated in *Figure 7*. Though simplified, this modeling integrates the complete LCI data for each defined power generation technique as provided by ecoinvent, including the infrastructure of each process chain.

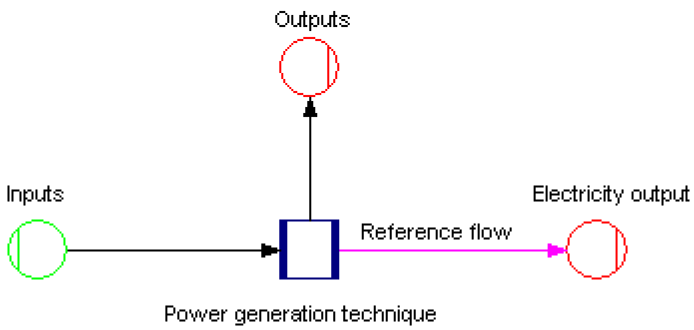


Figure 7: Illustration of the simplified modeling (source: own creation)

Note that connections (cf. *Table 4*) are only used in the attributional and consequential LCA scenarios on wind power integration. These LCAs look at the German electricity mix as a whole and connections are used to gather the electricity output of the different power generation techniques into a total production output[18].

[18] Umberto does not allow for the direct linking of two transitions.

The following processes from ecoinvent are used for the purpose of this study (ecoinvent Centre, 2007):

- “electricity, hard coal, at power plant [DE]”;
- “electricity, lignite, at power plant [DE]”;
- “electricity, natural gas, at power plant [DE]”;
- “electricity, oil, at power plant [DE]”;
- “electricity, nuclear, at power plant [DE]”;
- “electricity, hydropower, at power plant [DE]”;
- “electricity, production mix photovoltaic, at plant [DE]”;
- “electricity, at wind power plant 800 kW [CH]”.

Note that no LCI data is available for the German wind power generation technique in the ecoinvent database (ecoinvent Centre, 2007). In this database, the European wind mix available is composed of 98% onshore wind power plants with 800 kW technology and 2% offshore wind power plants with 2 MW technology (Burger and Bauer, 2007). It is therefore assumed that the LCI data of the 800 kW wind power technology from Switzerland is also representative for Germany, knowing that no offshore wind power was integrated into the German electricity grid in 2006.

The reference year for the LCI data as provided by ecoinvent is 2004/2005 (Frischknecht et al., 2007).

4.2.2. Electricity production shares in Germany in 2006

Similarly to the Klobasa et al. (2009) study which serves as reference for the consequential LCA methodology applied in the current study, the German electricity production data for 2006 is taken from the German Federal Ministry of Economics and Technology’s (BMWi) dataset (cf. *Table 5*, second column).

However, in this study, the complete dataset i.e. the total electricity production in Germany in 2006 is not considered. Three electricity sources are ignored: waste, biomass, and other.

For the electricity production from waste incineration, no specific LCI data is available in the ecoinvent database. In fact, the creators of the “electricity from waste, at municipal waste incineration plant” process attribute 100% of the environmental burden to the waste disposal function and 0% to the energy production function because the purpose of waste incineration is to get rid of the waste and not primarily to produce electricity (Doka, 2003). The categories ‘Biomass’ and ‘Other’ as defined by the working group on energy balances AG Energiebilanzen (providing the electricity production dataset for the BMWi) respectively includes subcategories like ‘biodiesel and other liquid biogas’ or ‘geothermal energy’ (Arbeitsgemeinschaft Energiebilanzen, 2010). For these, neither LCI data from the ecoinvent database nor the specific production shares for the year 2006 are available.

These three electricity production sources are gathered under the electricity source ‘Other’ in *Table 5*. The German electricity production data and shares from 2006 considered in this study are presented in the last two columns of *Table 5*.

Table 5: Gross electricity production in Germany in 2006 and shares considered in this study (source: adapted from Arbeitsgemeinschaft Energiebilanzen, 2008)

Power generation techniques	Electricity production [TWh]	Considered electricity production [TWh]	Considered electricity production shares
Lignite	151	151	0.25
Hard coal	138	138	0.23
Natural gas	73	73	0.12
Oil	11	11	0.02
Nuclear	167	167	0.28
Hydropower	27	27	0.04
Photovoltaics	2	2	0.01
Wind	31	31	0.05
Other	37	-	-
TOTAL	637	600	1

Ignoring these three electricity production sources means ignoring 37 TWh from a total of 637 TWh of electricity produced from the German power plant park in 2006. This represents 5.8% of the total electricity production and is not assumed to be a significant burden to the purpose of this study that is primarily methodological. The

German power plant mix investigated is thus composed of the lignite, hard coal, natural gas, oil, nuclear, hydropower, photovoltaics and wind power generation techniques. Altogether, they produced 600 TWh of electricity in 2006 (cf. *Table 5*, third column).

4.2.3. Marginal data quantifying changes

Two types of consequences from the integration of wind power into the German electricity grid in 2006 are taken into account in the consequential LCA. These consequential effects are based on marginal data used or identified by Klobasa et al. (2009). The two effects are:

- the substitutive effects from the integration of wind power into the German electricity grid in 2006; and
- the altered operation the conventional power plants mix balancing the system to compensate for the fluctuating wind power generation.

- **The substitutive effects**

One of the two consequential effects from the integration of wind power into the grid considered in this study is the substitutive effects. These effects concern the electricity production from the conventional power plant mix that is substituted by the integration of electricity produced by wind.

In Germany in 2006, the electricity production from hard coal, lignite, natural gas and oil were substituted through the integration of wind power (Klobasa et al., 2009).

The related substitution factors are presented in *Table 6*.

Table 6: Substitution factors from the integration of wind power in Germany in 2006 (source: Klobasa et al., 2009)

Power generation techniques	Substitution factors (kWh conventional per kWh wind) [%]
Hard coal	63
Natural gas	24
Lignite	11
Oil	2
TOTAL	100

This table reads as follows: for e.g. 1 kWh of wind power fed into the grid, 0.63 kWh electricity that would have otherwise been produced by the hard coal power plants were substituted, 0.24 kWh from the natural gas power plants, 0.11 kWh from the lignite power plants, and 0.02 kWh from oil power plants.

The substitutive effects from the integration of wind power into the German electricity grid in 2006 were determined via the PowerACE model illustrated in *Figure 8*. PowerACE is a comprehensive agent-based model of the German electricity sector, relying on real data from multiple databases (Klobasa et al., 2009). It simulates the behavior of the main actors and comprises an electricity market, several regulating-energy-markets as well as a carbon trading market. This model integrates and combines multiple models. Key is the analysis of the effects of renewable energy on the prices on the German electricity market. Specific to wind power, the ISI-Wind-Model is connected to the overall model. It provides supply curves of the wind power generation based on meteorological data and assumptions about the regional distribution of the plants.

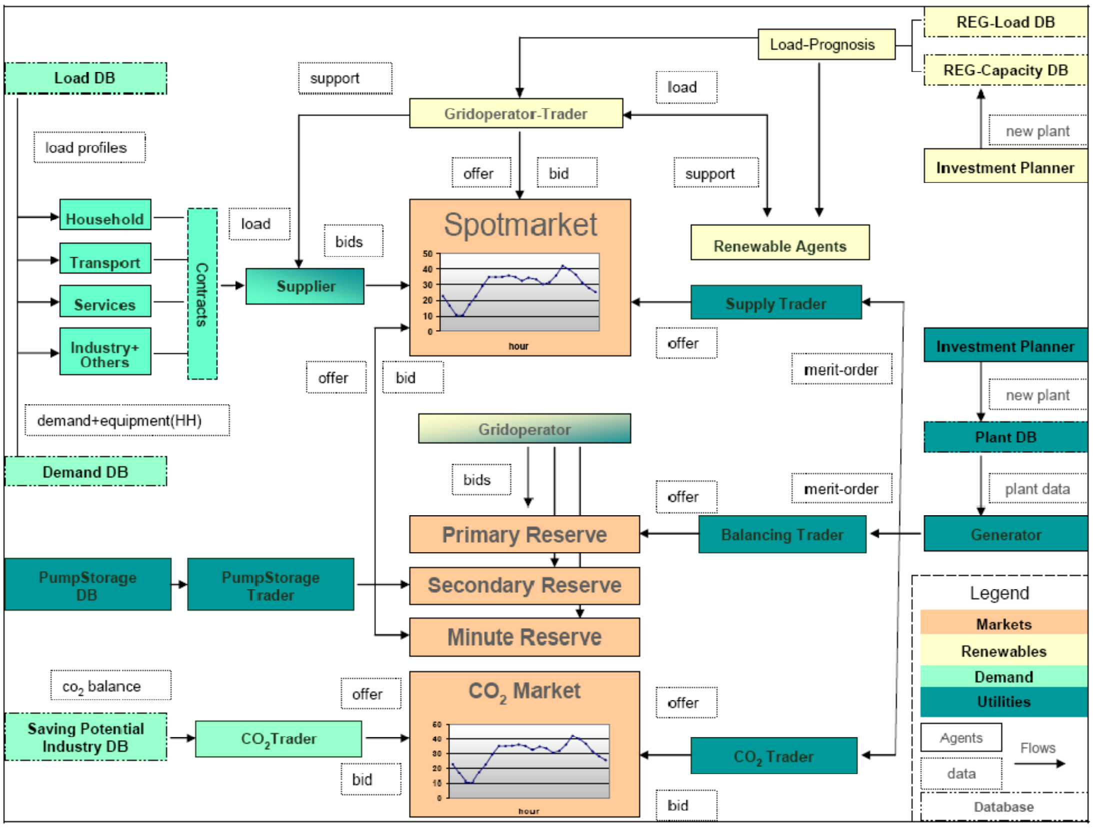


Figure 8: PowerACE platform (source: Klobasa et al., 2009)

- **The altered operation of the conventional power plant mix**

Another consequential effect considered in the present study is in fact a combination of impacts from the integration of wind power into the German electricity grid, as applied in the Klobasa et al. (2009) study.

Wind being an intermittent electricity source, reserve capacities are needed to balance the system in the case of too little or too much wind. As such, the conventional power plants balancing the system have more frequent start-up procedures, partial operation load and increased provision of instantly available power (Klobasa et al., 2009). This altered operation of the impacted power plants affects their efficiency and thus their environmental performance (Wolf et al., 2007).

In order to reflect this combination of impacts, a 7% cutback of the changes in terms of environmental impacts determined is applied in the Klobasa et al. (2009) study. This 7% cutback has been validated in other studies cited in the Klobasa et al. (2009) study and is therefore also applied in this study’s consequential LCA.

5. MODELS AND RESULTS

The LCAs modeled for the purpose of this study and the respective LCIA results are presented:

- for the attributional LCAs on the single power generation techniques in section *5.1*;
- for the attributional LCA on wind power integration in section *5.2*; and
- for the consequential LCA on wind power integration in section *5.3*.

Additionally (for information purposes), the changes in terms of environmental impacts determined by the attributional and consequential LCA on wind power integration are presented for selected LCI results (CO_2, NOx, SO_2 and PM) in *Annex A*, *Figure 19*.

5.1. Attributional LCA on the single power generation techniques

The models and the LCIA results of the attributional LCAs on the single power generation techniques are presented in this section.

5.1.1. Models

As outlined in section *4.2.1*, the individual LCAs on the power generation techniques composing the German power plant park in 2006 have been modeled in a simplified manner. For example, *Figure 9* represents the LCA of the wind power generation technique. The lignite, hard coal, natural gas, oil, nuclear, hydropower, photovoltaics, and wind power generation techniques are modeled analogously.

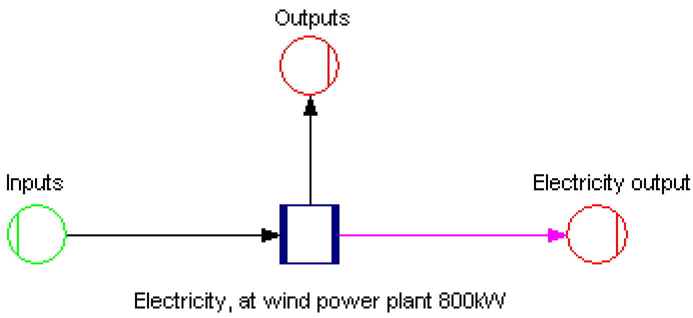
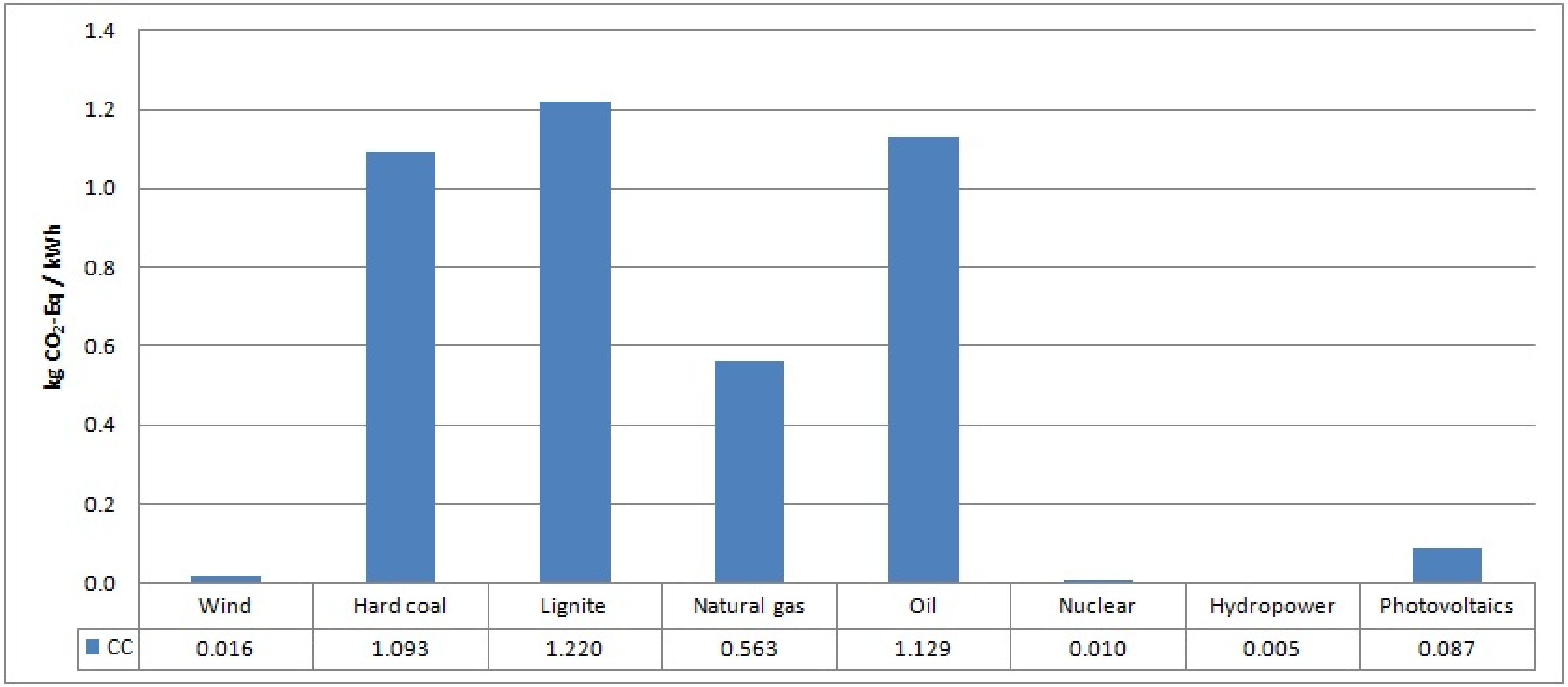


Figure 9: Wind LCA model (source: own creation)

5.1.2. Results

As outlined in section *4.1*, the reference flow for each individual power generation techniques is 1 kWh of electricity produced at the power plant; the LCIA results are accordingly aggregated.

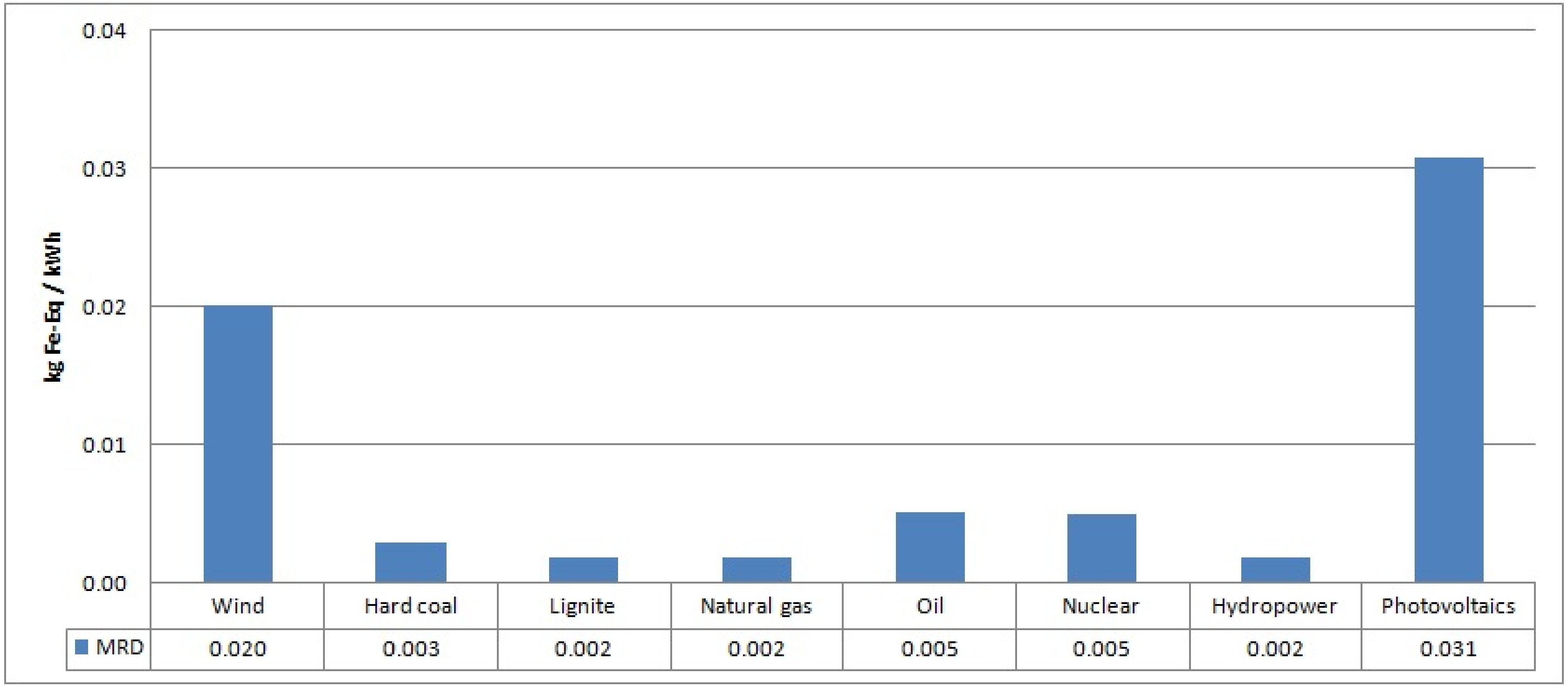
For the three LCA types (ALCA-st, ALCA-wpi, and CLCA-wpi), the same selected environmental impact categories are investigated. Yet, the goal of the attributional LCAs on the single power generation techniques is primarily informative i.e. to increase the understanding of the attributional and consequential LCA results on wind power integration. Hence, only the results for climate change and mineral resource depletion of the power generation techniques under investigation are presented in this section, respectively in *Figure 11* and *12*. The results for fossil fuel depletion, natural land transformation, Particulate Matter formation, photochemical oxidant formation, and terrestrial acidification are presented in *Annex B* (in *Figure 20 to 24*, respectively).



Legend: CC: Climate Change.

Figure 10: Climate change potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H) (source: own creation, based on data from the ecoinvent Centre, 2007)

As illustrated in *Figure 10*, the hydropower, nuclear, wind, and photovoltaics power generation techniques emit less CO_2-Eq per kWh electricity produced at the power plant than the other power generation techniques under investigation (i.e. the fossil fired techniques).



Legend: MRD: Mineral Resource Depletion.

Figure 11: Mineral resource depletion potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H)
(source: own creation, based on data from the ecoinvent Centre, 2007)

As illustrated by *Figure 11*, the photovoltaics and the wind power generation techniques consume more Fe-Eq per kWh electricity produced at the power plant than the other power generation techniques under investigation.

5.2. Attributional LCA on wind power integration

The dataset for the attributional LCA scenarios with and without wind power as well as the respective models and LCIA results are presented in this section.

5.2.1. Dataset for the scenarios

For the attributional LCA scenario with wind power, the production shares of the German power plant park in 2006 are used (cf. *Table 5*).

The dataset of the scenario with wind power is the basis to determine the dataset of the hypothetical scenario without wind power. To study the changes in terms of environmental impacts from the integration of wind power into the grid, the known scenario with wind power is compared to a hypothetical scenario without wind power.

To determine the hypothetical scenario without wind power, the average technologies are considered according to the attributional LCA principles. For this reason, the real substitutive effects (cf. *Table 6*) are not taken into account because these are considered to be marginal effects i.e. a consequence from the integration of wind power into the grid (cf. section *3.2* on the conceptual definitions of attributional LCA and consequential LCA).

For the hypothetical scenario without wind power, this means that the production output of each power generation technique (besides wind) is proportionally increased by $1/7^{th}$ of the total production output of the wind power technique from the known scenario with wind power (since there are 7 different power generation techniques excluding wind composing the power plant mix under investigation). The determined values for the scenario with wind power and without wind power are presented in *Table 7*.

Table 7: Electricity production shares in Germany in 2006 for the attributional LCA scenarios with and without wind power generation (source: own compilation)

Power generation techniques	**Electricity production shares, with wind power** (cf. *Table 5*)	**Electricity production shares, without wind power**
Lignite	0.25	0.26
Hard coal	0.23	0.24
Natural gas	0.12	0.13
Oil	0.02	0.02
Nuclear	0.28	0.29
Hydropower	0.04	0.05
Photovoltaics	0.01	0.01
Wind	0.05	-
TOTAL	1	1

5.2.2. Models

Figure 12 and *Figure 13* respectively represent the German power plant mix as investigated for an attributional LCA scenario with wind power and without wind power.

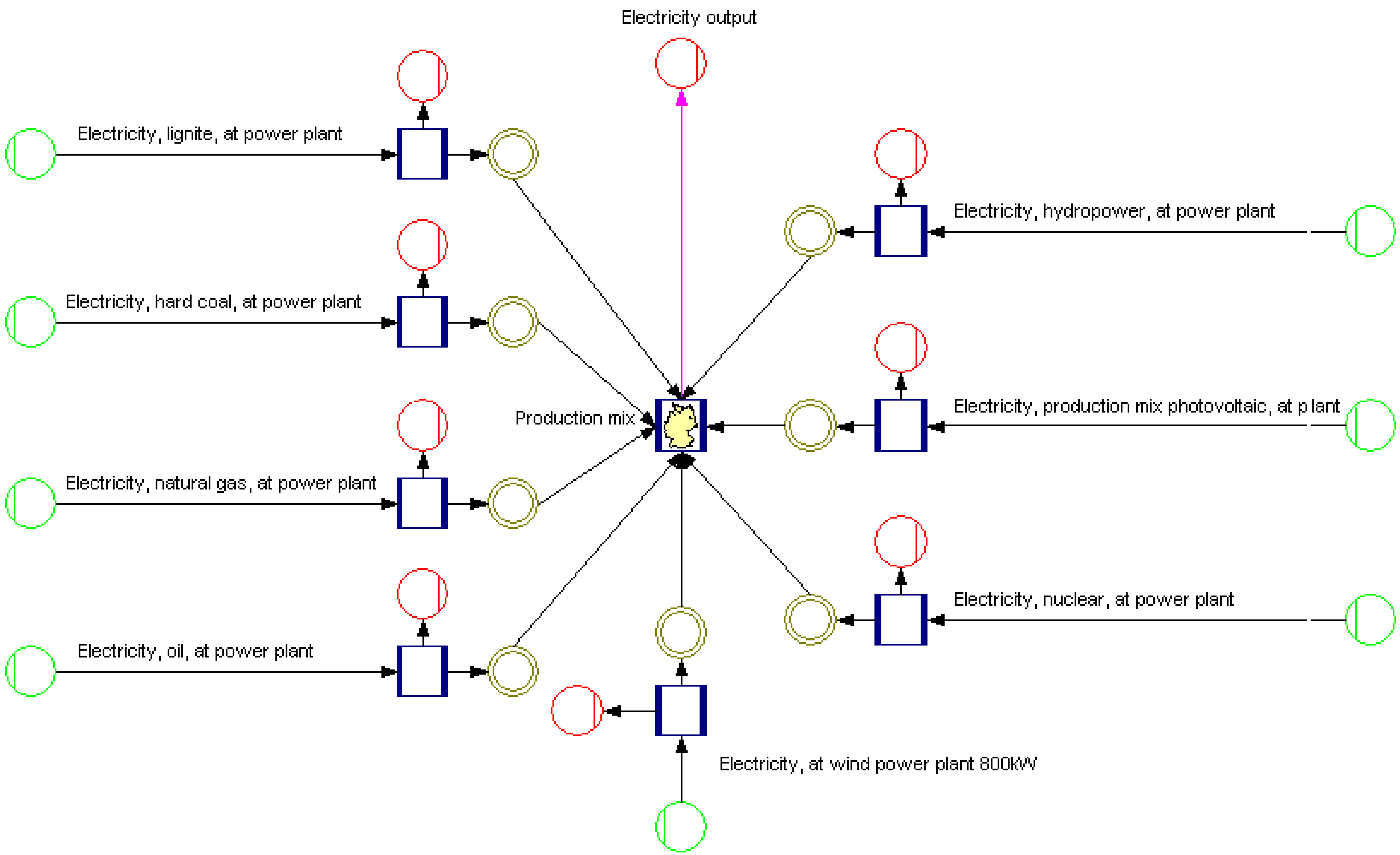


Figure 12: Average German power plant mix, 2006 - attributional LCA scenario including wind power (source: own creation)

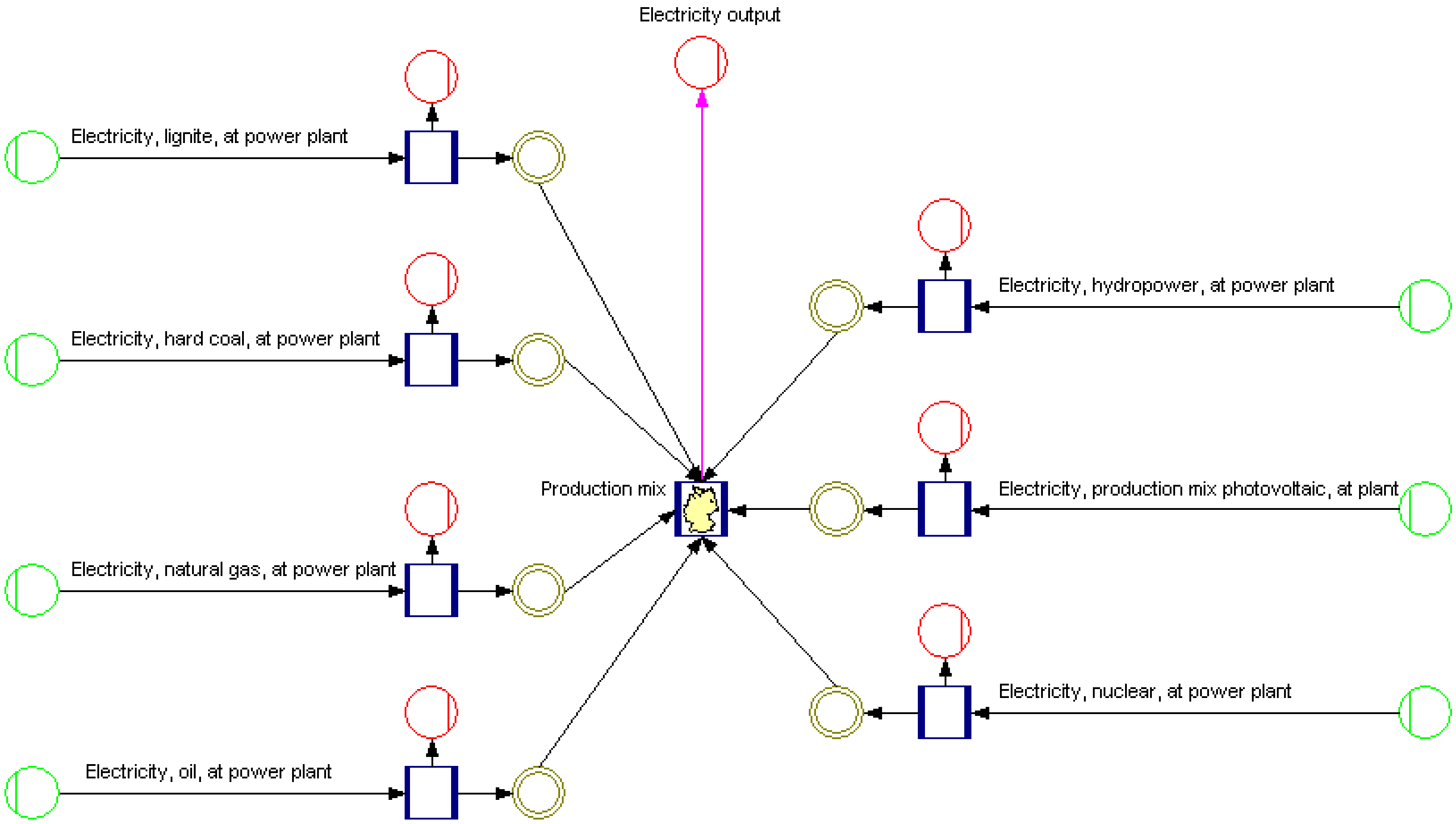
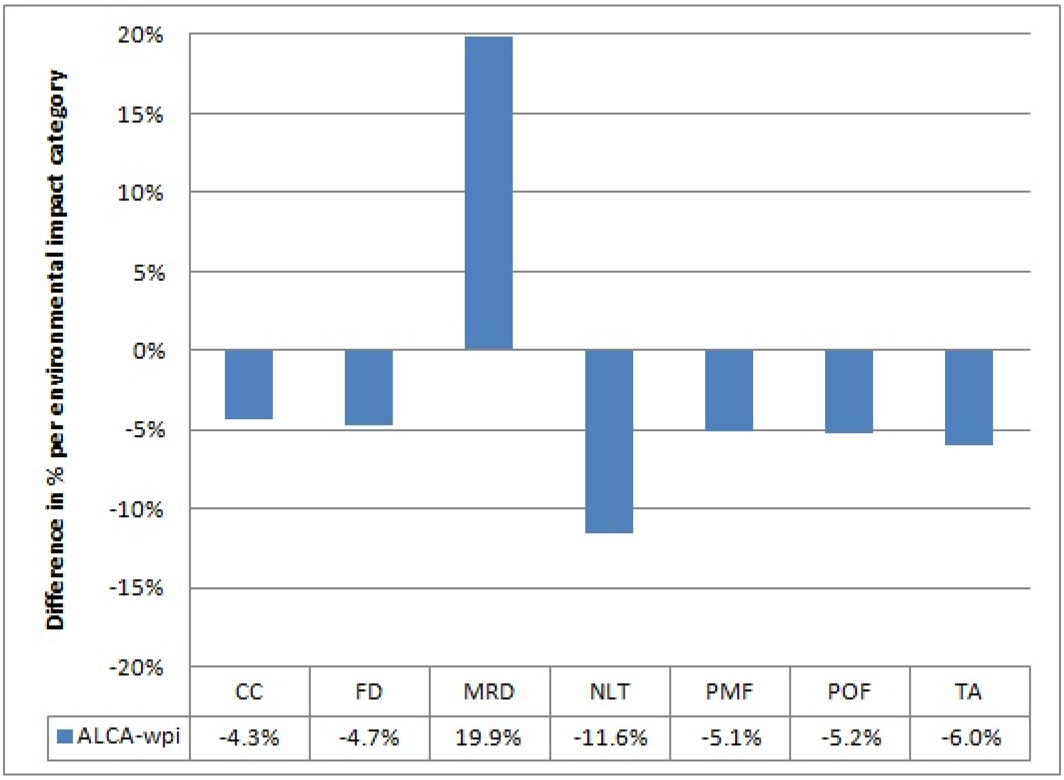


Figure 13: Average German power plant mix, 2006 - attributional LCA scenario excluding wind power (source: own creation)

5.2.3. Results

Figure 14 presents the changes in terms of environmental impacts (in %) resulting from the integration of wind power into the German electricity grid in 2006, following an attributional LCA approach. The known scenario with wind power is compared to a hypothetical scenario without wind power to obtain these results.



Legend: CC: Climate change; FD: Fossil fuel depletion; MRD: Mineral resource depletion; NLT: Natural land transformation; PMF: Particulate Matter formation; POF: Photochemical ozone formation; TA: Terrestrial acidification.

Figure 14: Changes resulting from the integration of wind power into the German electricity grid in 2006 for selected ReCiPe 2008 (H) impact categories, following an attributional LCA approach (source: own creation)

A 19.9% increase of the mineral resource consumption from the German power plant park resulted from the integration of wind power into the grid in 2006. For all the other analyzed impact categories, a decrease resulted from this integration in the range of approximately -4.3 to -11.6%.

5.3. Consequential LCA on wind power integration

The dataset for the consequential LCA scenarios with and without wind power as well as the respective models and LCIA results are presented in this section.

5.3.1. Dataset for the scenarios

For the consequential LCA on wind power integration, only the marginal technologies i.e. the processes impacted by the integration of wind power into the grid are considered. In Germany in 2006, these are the lignite, hard coal, natural gas, and oil power generation techniques (cf. section *4.2.3*), in addition to wind.

The data basis for the scenario with wind power is again the electricity production shares in Germany in 2006 presented in *Table 5*, except that only the 5 relevant power generation techniques are taken into account. Their share of the total electricity production from the German power plant mix in 2006 is then scaled up to obtain a total of 1 kWh, as illustrated in *Table 8*.

As for the attributional LCA on wind power integration, the dataset for the hypothetical scenario without wind power is determined from the dataset of the scenario with wind power. As the marginal technologies are considered, use is made of the information on the substitutive effects. The substitution factors presented in *Table 6* are therefore used to determine the dataset for the scenario without wind power (presented in the last column of *Table 8*). This for example means that the production output from the hard coal power plants in the scenario without wind power is increased by 63% of the total production output of the wind power plants (i.e. 63% of 31 TWh).

Table 8: Electricity production shares in Germany in 2006 for the consequential LCA scenarios with and without wind power generation (source: own compilation)

Power generation techniques	**Electricity production shares, with wind power** (cf. *Table 5*)	**Electricity production shares, with wind power, scaled up to 1**	**Electricity production shares, without wind power**
Lignite	0.25	0.37	0.38
Hard coal	0.23	0.34	0.39
Natural gas	0.12	0.18	0.20
Oil	0.02	0.03	0.03
Wind	0.05	0.08	-
TOTAL	0.67	1	1

5.3.2. Models

Figure 15 and 16 respectively represent the German power plant mix as investigated for a consequential LCA scenario with wind power and without wind power.

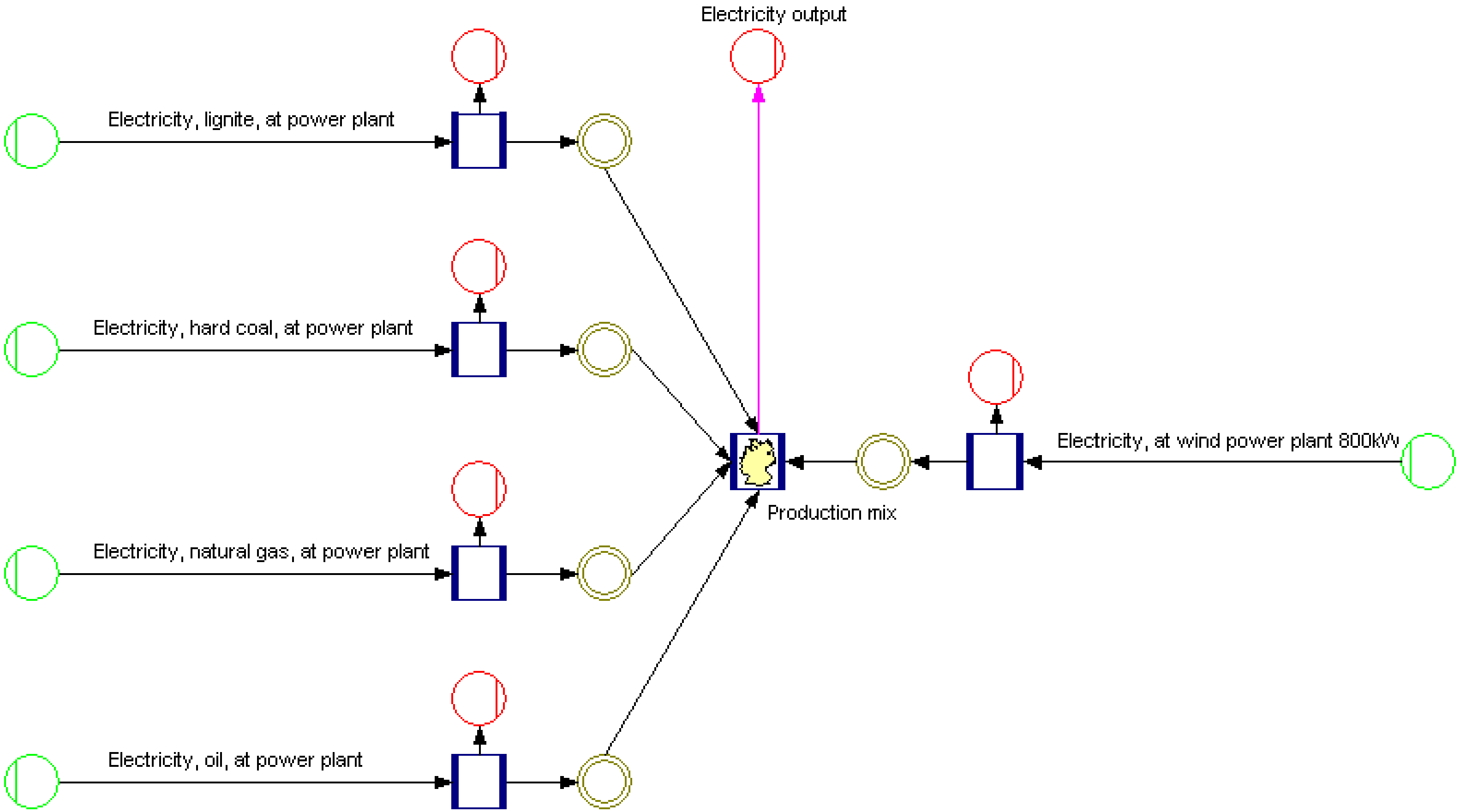


Figure 15: Marginal German power plant mix in 2006 - consequential LCA scenario including wind power (source: own creation)

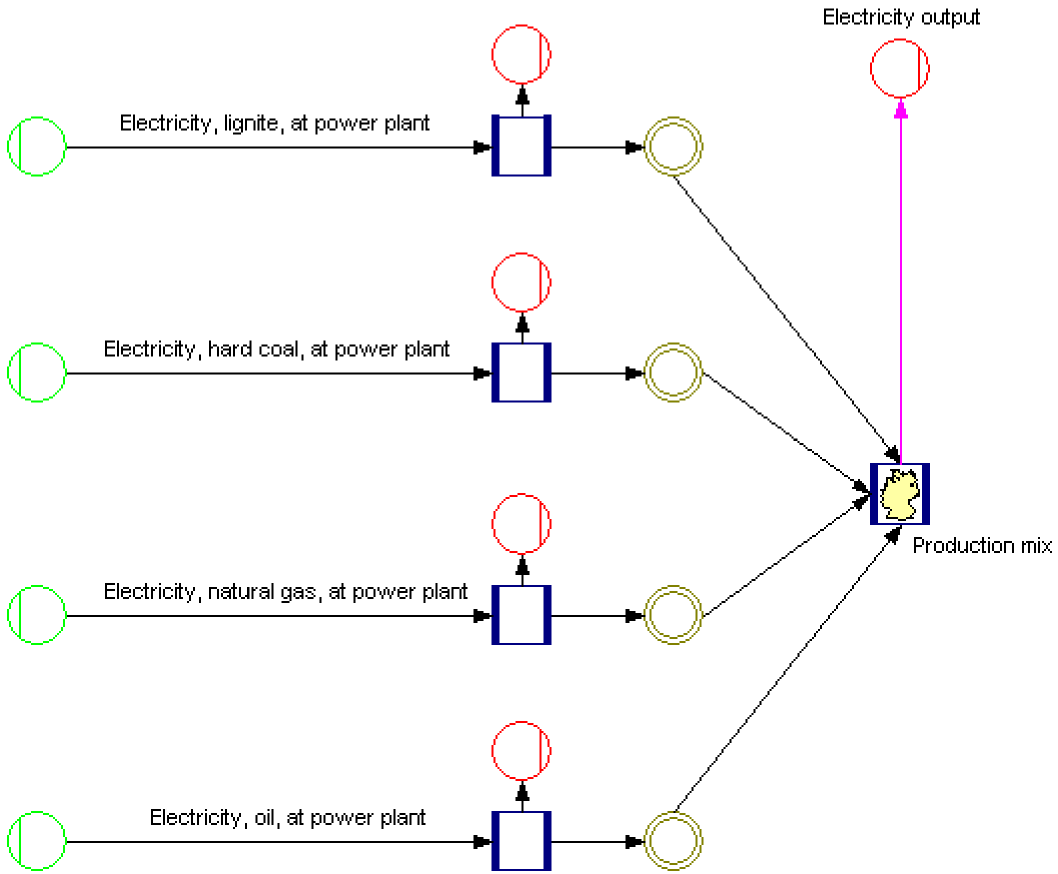
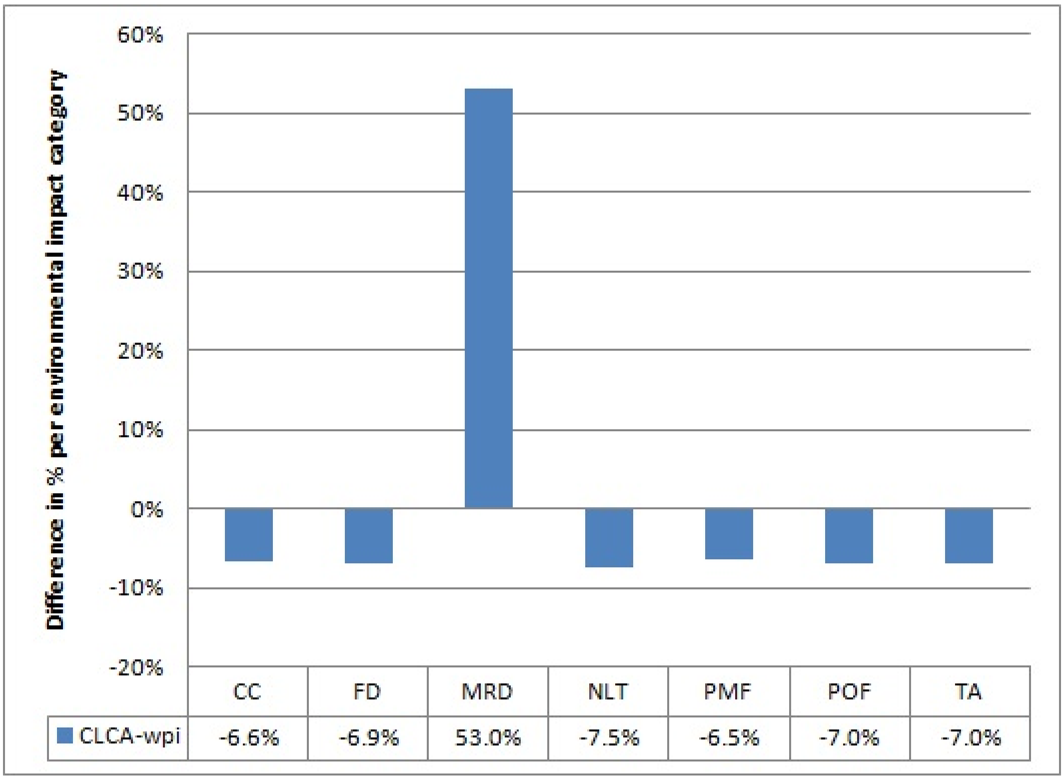


Figure 16: Marginal German power plant mix in 2006 - consequential LCA scenario excluding wind power (source: own creation)

5.3.3. Results

Figure 17 presents the changes in terms of environmental impacts (in %) resulting from the integration of wind power into the German electricity grid in 2006, following a consequential LCA approach. The known scenario with wind power is compared to the hypothetical scenario without wind power to obtain these results.



Legend: CC: Climate change; FD: Fossil fuel depletion; MRD: Mineral resource depletion; NLT: Natural land transformation; PMF: Particulate Matter formation; POF: Photochemical ozone formation; TA: Terrestrial acidification.

Figure 17: Changes resulting from the integration of wind power into the German electricity grid in 2006 for selected ReCiPe 2008 (H) impact categories, following a consequential LCA approach (source: own creation)

A 53% increase of the metal consumption from the German power plant park resulted from the integration of wind power into the grid in 2006. For all the other analyzed impact categories, a decrease resulted from this integration in the range of -6.6 to -7.5%.

6. DISCUSSION

At first, the attributional and consequential LCA results on the integration of wind power into the German electricity grid in 2006 and the respective LCA methodologies are discussed, respectively in section *6.1* and *6.2*. In section *6.3*, a summary of the findings and the related limitations are highlighted. Finally, in section *6.4*, recommendations are proposed.

Note that in section *6.1.1*, the plausibility of the attributional and consequential LCA results on wind power integration is discussed.

6.1. Quantitative comparison of the LCA results on wind power integration

The plausibility of the attributional and consequential LCA results on wind power integration is discussed before performing a quantitative comparison of the results.

6.1.1. Plausibility of the LCA results on wind power integration

For the attributional LCA on wind power generation carried out in this study, no comparison of the results with external references can be performed as no study, specifically following an attributional LCA approach, investigates the changes in terms of environmental impacts resulting from the integration of wind power into the German electricity in 2006. Yet, the LCI data for the power generation techniques composing the investigated electricity mix can be validated. As outlined in section *4.2.1*, the LCI data is taken from the ecoinvent database which is a renowned LCI data provider. As well, ReCiPe 2008 is a renowned LCIA method. Hence, the LCIA results of the attributional LCA on wind power integration which are based on the ecoinvent LCI data (without any modifications) are assumed to be valid.

For the consequential LCA results on wind power integration, the Klobasa et al. (2009) study can be used to validate the results determined in this study. The soundness of this study's consequential LCA results can be verified by comparing the CO_2 emissions changes determined in this study and the CO_2 emissions changes determined by Klobasa et al. (2009); both studies investigated changes resulting from the integration of wind power into the Germany electricity grid in 2006.

To determine the CO_2 emissions changes resulting from the integration of wind power into the grid, the LCI result "CO_2, fossil" for the German power plant park is compared between the consequential LCA scenario with wind power and without wind power. A factor in g per kWh as well as a total value can thereby be determined for Germany in 2006.

The consequential LCA results in this study reflect an abatement factor of 815 g CO_2 per kWh electricity produced by wind, which represents 25 million t CO_2 emissions saved in Germany in 2006 from the integration of wind power into the grid. In the Klobasa et al. (2009) study, they found that the integration of wind power into the German electricity grid saved 23.8 million t CO_2 emissions in 2006, which represents an abatement factor of 781 g CO_2 per kWh electricity produced by wind (Klobasa et al., 2009). These results are outlined in *Table 9*.

Table 9: Comparison of the CO_2 emissions changes determined following a consequential LCA approach by Klobasa et al. (2009) and in the present study (source: own creation)

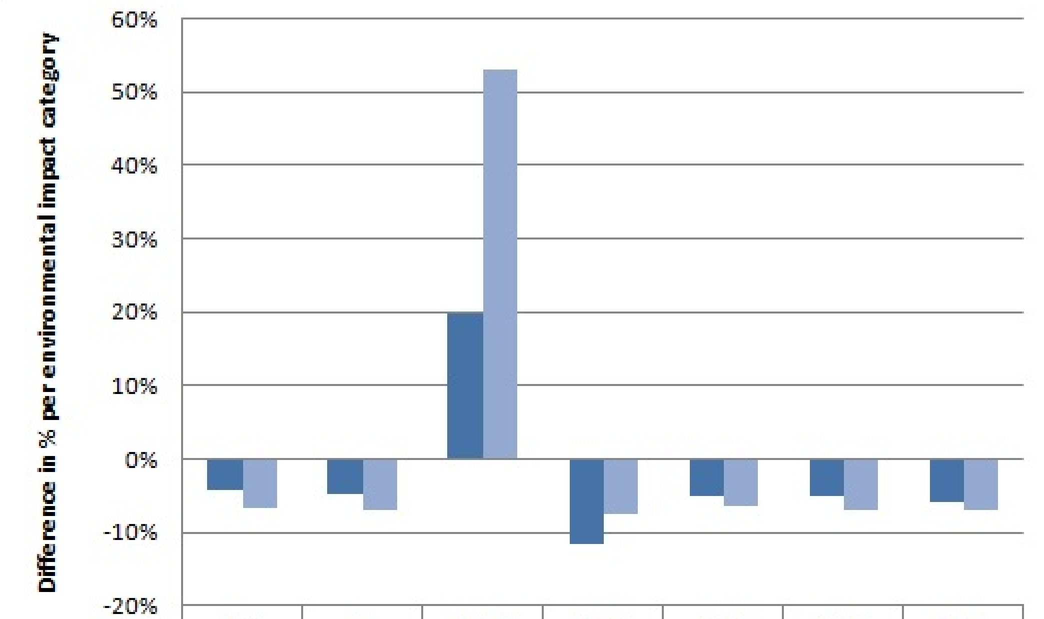
	Klobasa et al. (2009)	Current study
CO_2 abatement factor [*g/kWh wind power produced*]	781	815
CO_2 emissions [*million t CO_2*]	23.8	25

The results of the current study are close to the results from Klobasa et al. (2009). The slight difference may come from the LCI data used for the investigated power generation techniques or from a different rounding of the electricity production data since the methodology applied for the consequential LCA approach is in both studies strictly the same.

6.1.2. Quantitative comparison

As presented in *Figure 10, 11*, and *20* to *24*, the results of the attributional LCAs on the single power generation techniques show the environmental impacts per selected impact category for each technique under investigation. This is the classical way of carrying out LCAs of power generation techniques (e.g. Weisser, 2007). Yet, the results determined in this study are mainly intended to increase the understanding of the results of the attributional and consequential LCA on wind power integration. These LCAs look at the same selected impact categories as the attributional LCA on the single power generation techniques, but they present results in percentual difference.

Investigating the power plant park by means of an attributional LCA and a consequential LCA is in fact the core of this study. Both, as carried out in this study, investigate the changes in terms of environmental impacts resulting from the integration of wind power into the German electricity grid in 2006, by comparing the known scenario with wind power to a hypothetical scenario without wind power. *Figure 18* displays the respective results (cf. *Figure 14* and *17*).



	CC	FD	MRD	NLT	PMF	POF	TA
ALCA-wpi	-4.3%	-4.7%	19.9%	-11.6%	-5.1%	-5.2%	-6.0%
CLCA-wpi	-6.6%	-6.9%	53.0%	-7.5%	-6.5%	-7.0%	-7.0%

Legend: CC: Climate change; FD: Fossil fuel depletion; MRD: Mineral resource depletion; NLT: Natural land transformation; PMF: Particulate Matter formation; POF: Photochemical ozone formation; TA: Terrestrial acidification."

Figure 18: Changes resulting from the integration of wind power into the German electricity grid in 2006 for selected ReCiPe 2008 (H) impact categories, respectively following an attributional LCA and a consequential LCA approach (source: own creation)

The main conclusion to be drawn is that the changes in terms of environmental impacts resulting from the integration of wind power into the German electricity grid in 2006 determined following an attributional and a consequential LCA approach are different for the selected impact categories.

For example, through the integration of wind power, the CO_2-Eq emissions of the German power plant portfolio decreased by 4.3% according to the attributional LCA approach, as opposed to a 6.6% decrease according to the consequential LCA approach.

On this particular example, a greater decrease in CO_2-Eq emissions is determined with the consequential LCA because this approach reflects a greater decrease of electricity production from the fossil fired techniques. In fact, while the attributional LCA considers the average technologies of the power plant mix for the determination of the hypothetical scenario without wind power, the consequential LCA considers the marginal technologies. As detailed in section *4.2.3*, the marginal technologies are the lignite, hard coal, natural gas, and oil power generation techniques. These are fossil fired techniques which have higher CO_2-Eq emissions per kWh electricity produced than the other power generation techniques of the investigated mix (e.g. Weisser, 2007). The consequential LCA thus reflects a higher decrease of the electricity production from e.g. hard coal (63% of the total wind production as opposed to $1/7^{th}$ in the attributional LCA). Therefore, taking into account the marginal technologies in the consequential LCA, as opposed to the average technologies in the attributional LCA, leads to a differentiated result such as for the changes in CO_2-Eq emissions of the power plant mix resulting from the integration of wind power into the grid.

The difference in terms of results thus comes from the difference in the methodology of the two LCA types.

6.2. Methodological comparison of the LCAs on wind power integration

As carried out in this study, following the general guidelines, no consequential effects are included in the attributional LCA on wind power integration.

As demonstrated in this study, the integration of wind power into a national electricity grid has far-reaching consequences beyond the cradle-to-grave scope of the wind power generation process. This is particularly true because of its intermittent nature. Consequential effects of the integration of wind power into the German electricity grid in 2006 are for instance the substitutive effects and the altered operation of the conventional power plant mix. A comprehensive ecological impact assessment study should consider such effects. However, following the general principles, these are effects that a traditional i.e. attributional LCA fail to account for.

On the contrary, following the general principles, consequential LCAs take into account consequential effects beyond the cradle-to-grave scope of an investigated process chain. As demonstrated in this study, the far-reaching consequences of the integration of wind power into the German electricity grid are taken into account in a consequential LCA.

One of the consequences from the integration of the fluctuating wind power into the German electricity grid in 2006 is for instance the altered operation of the conventional power plant mix. As discussed earlier, this altered operation of the power plants impacted by the fluctuating wind power fed into the grid consequently affects their efficiency and thus their environmental performance. Ignoring this consequence, that is directly attributable to wind power generation and its integration into the German electricity grid in 2006, is a failure to comprehensively assess the impacts resulting from this decision i.e. the integration of intermittent wind power into the grid.

Accordingly, it is concluded that the consequential LCA results determined in this study are more comprehensive than the attributional LCA results on wind power integration. A consequential LCA is therefore more relevant to assess the changes resulting from the integration of intermittent wind power into a national electricity grid.

As mentioned in section *3.2.3*, there is an ongoing debate whether or not consequential LCAs are more demanding than attributional LCAs in terms of modeling effort. Specific to the case investigated in this study, the modeling effort was less demanding for the consequential LCA than the attributional LCA on wind power integration. The attributional LCA considered the average technologies i.e.

the average power plant mix composed of 8 power generation techniques (including wind) in this study's investigation. All these power generation techniques were modeled in the attributional LCA scenario (with wind power – cf. *Figure 12* of section *5*) and the sum of LCI data of this mix of techniques was collected. On the contrary, only the marginal technologies i.e. the marginal power plant mix composed of 5 power generation techniques (including wind – cf. *Figure 15* of section *5*) was modeled in the consequential LCA.

Yet, consequential LCAs may generally not be less demanding in terms of modeling efforts than attributional LCAs. In fact, the marginal data used in this study was already available from other studies and did not require further investigation efforts. However, in other cases, one may first need to determine the marginal data before being able to carry out a consequential LCA. In such case, the modeling efforts would be significantly higher for a consequential LCA than for an attributional LCA which uses average data (that might be more easily available).

Moreover, as highlighted in section *3.2.3*, consequential LCA results may be bound to high uncertainties. This is particularly true when carrying out consequential LCAs on prospective scenarios. Consequential LCAs might therefore present more sensitive results than attributional LCAs.

6.3. Summary of the findings and limitations

A summary of the findings detailed in sections *6.1* and *6.2* and the limitations to these findings are specified in this section.

6.3.1. Summary of the findings

A summary of the findings in terms of results and methodology, as detailed in sections *6.1* and *6.2*, is presented in *Table 10*.

Table 10: General and case-specific outcomes from this study (source: own creation)

	ALCA		CLCA
	Single technique	Wind power integration	
RESULTS			
What they present	Show the environmental impacts per investigated power generation technique	Show the changes in terms of environmental impacts resulting from a specific decision	
- *Case-specific*	*Environmental impacts per PGT (e.g.: kg-CO_2-Eq/kWh)*	*Changes in the range from +19.9% to -11.6%*	*Changes in the range from +53% to -7.5%*
What purpose they can serve	Present and compare the environmental impacts of power generation techniques	Present and compare the changes (e.g. in terms of environmental impacts) of different possible decisions i.e. scenarios	
METHODOLOGY			
Assessing the changes resulting from a specific decision	Not completely; omission of the possible consequential effects beyond the cradle-to-grave scope	Not completely; omission of the possible consequential effects beyond the cradle-to-grave scope	More completely; to the extent that the consequential effects are known and considered with regard to the Goal and Scope definition
- *Case-specific*	*Does not directly investigate the changes in terms of environmental impacts resulting from the integration of wind power into the grid*	*Investigates the changes in terms of environmental impacts resulting from the integration of wind power into the grid, but not completely and with unspecific assumptions*	*Investigates the changes in terms of environmental impacts resulting from the integration of wind power into the grid, to the extent that the consequential effects are known and considered*

6.3.2. Limitations

This study has demonstrated that a consequential LCA is more promising than an attributional LCA to determine the changes resulting from the integration of wind power into the grid. Yet, the consequential LCA results specific to the case investigated in this study can be improved.

As a matter of fact, not all the consequences from the integration of wind power into the electricity grid are taken into account in this study. This is because the purpose of this study is primarily methodological. Hence, a more complete and precise assessment of the impacts resulting from the integration of wind power into the German electricity grid in 2006 could be achieved by including all the expected consequential effects missing in the present study, such as possible grid expansions and reinforcement.

Uncertainties about the known and eventually unknown (or not possible to model) consequences are equally to be determined for a better assessment of the reliability of the presented consequential LCA results. Relevant sources of uncertainty are for example the extent of the impact of wind power generation on the environmental performance of the conventional power plants. The 7% cutback applied both in the Klobasa et al. (2009) study and in this study for Germany in 2006 is not a precise assessment of this impact, though validated in other studies cited in Klobasa et al. (2009).

Sensitivity analyses should also be envisaged, not only for the consequences included in a consequential LCA on wind power integration, but also for other aspects. For example, different impact assessment methods like Impact 2002+ or the alternative cultural perspectives (Egalitarian and Individualist) available for the ReCiPe 2008 method should be performed. As well, LCI data specific to wind power plants in Germany, which is currently not available in the ecoinvent database, shall be used.

Furthermore, this study is not prospective but retrospective. Looking at prospective scenarios would be a way to highlight further uncertainties linked to the use of a consequential LCA method to guide decision-making. This is particularly relevant when deciding to further extend wind power's contribution to the electricity mix.

6.4. Recommendations

For the purpose of studying the changes in terms of environmental impacts resulting from the integration of intermittent wind power into the German electricity grid in 2006, a consequential LCA should be carried out.

In this study, it was demonstrated that only a consequential LCA is able to take into account the multiple and interdependent consequences of such decision.

It is therefore proposed to guide future large-scale decision-making on the basis of consequential LCA results, as opposed to attributional LCA results, whenever possible.

When presenting the results of a consequential LCA on prospective scenarios intended to guide decision-marking, as well as for retrospective investigations, it is important to highlight the possible uncertainties that might bias the results and to perform sensitivity analyses to consolidate the determined results.

However, note that the extent to which consequential effects shall be considered in consequential LCA studies was not investigated in the present study and therefore remains an unsolved issue (cf. section *3.2.3*).

7. CONCLUSION AND OUTLOOK

This study has shown that an attributional LCA is less adequate to support a decision to fundamentally change the pattern of energy supply in a country, which has broad implications on the existing power plant park.

On the specific case investigated in this study, the assumption has been confirmed that a consequential LCA is more relevant than an attributional LCA to determine the changes resulting from the integration of wind power into the German electricity grid. As demonstrated, only a consequential LCA is able to take into account multiple and interdependent consequences of a given decision, such as the decision to integrate wind power into a national grid.

Decisions supported by a consequential LCA rather than an attributional LCA thereby gain in reliability and therefore in credibility with professionals as well as with a broader non-professional public interested in the subject matter.

In line with the findings of this study, it is therefore proposed to guide future large-scale decision-making on the basis of consequential LCA results, as opposed to attributional LCA results, whenever possible.

However, it has not been possible to assess all the expected consequential effects from the integration of wind power into the German electricity grid in 2006 (such as possible grid extensions or reinforcement). The prime focus of this study was to investigate the adequacy of the consequential LCA method as opposed to the attributional LCA method. Future research should therefore aim at further improving the consequential LCA results by including more consequential effects of the integration of wind power into the German electricity mix in 2006. Sensitivity analyses should equally be envisaged to consolidate the determined results.

It would thereafter be interesting to see how the environmental burdens attributable to the production of e.g. 1 kWh of electricity from wind change when consequential effects are accounted for. In fact, commonly published figures of the environmental performance of power generation techniques are usually determined following an attributional LCA approach (e.g. Weisser, 2007). Such environmental performance results generally ignore the consequential effects of the power generation techniques and their integration into the grid, which are particularly critical when assessing the environmental performance of e.g. intermittent power generation techniques.

Yet, a key issue remains unsolved: is it even possible to compare (e.g. the environmental performance of) intermittent and non-intermittent power generation techniques? In this study, the consequential LCA results show that wind does not substitute base load capacities. This suggests that wind power and e.g. nuclear are not substitutes. Therefore, an investigation on the extent to which considering consequential effects in a LCA of the wind power generation technique enables to cope with this availability issue should also be carried out. Alternatively, if wind was to provide the same service as base load power, several options could be envisaged e.g. considering storage options or dedicated backup capacities (e.g. Bélanger and Gagnon, 2002). Accordingly, LCAs on wind power generation may be combined to LCAs of the dedicated storage options or backup capacities to enable a reliable comparison of (e.g. the environmental performance of) intermittent and non-intermittent power generation techniques.

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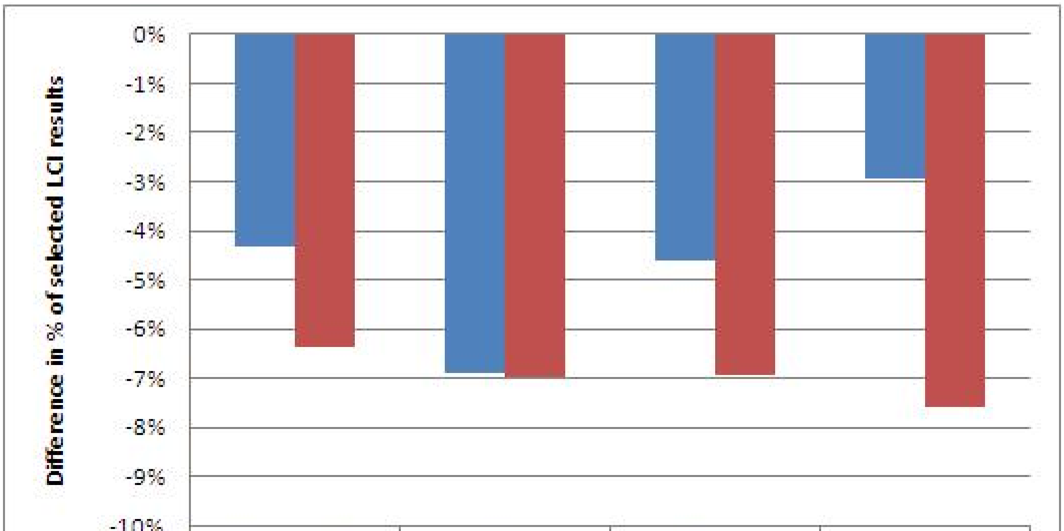
ANNEX A: Selected LCI results

For information purposes, the changes in environmental impacts for selected LCI results (CO_2, NOx, SO_2, PM) resulting from of the integration of wind power into the German electricity grid in 2006 are presented in *Figure 19*, respectively for the attributional LCA and the consequential LCA on wind power integration.

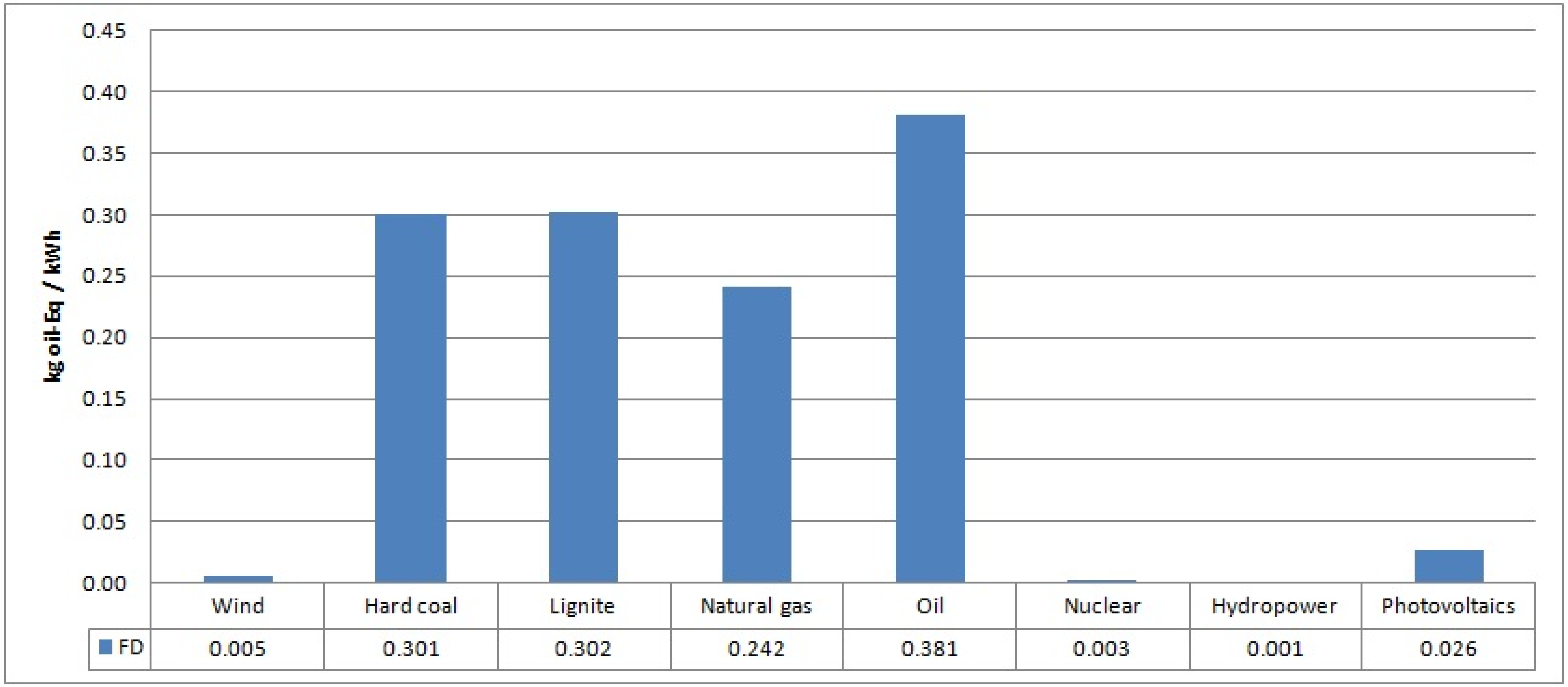


	CO2, fossil	SO2	NOx	PM
ALCA-wpi	-4.3%	-6.9%	-4.6%	-2.9%
CLCA-wpi	-6.4%	-7.0%	-6.9%	-7.6%

Figure 19: Changes in selected LCI results from the integration of wind power into the German electricity grid in 2006, following an attributional and a consequential LCA approach (source: own creation)

ANNEX B: Complementary results of the attributional LCA on the single power generation techniques

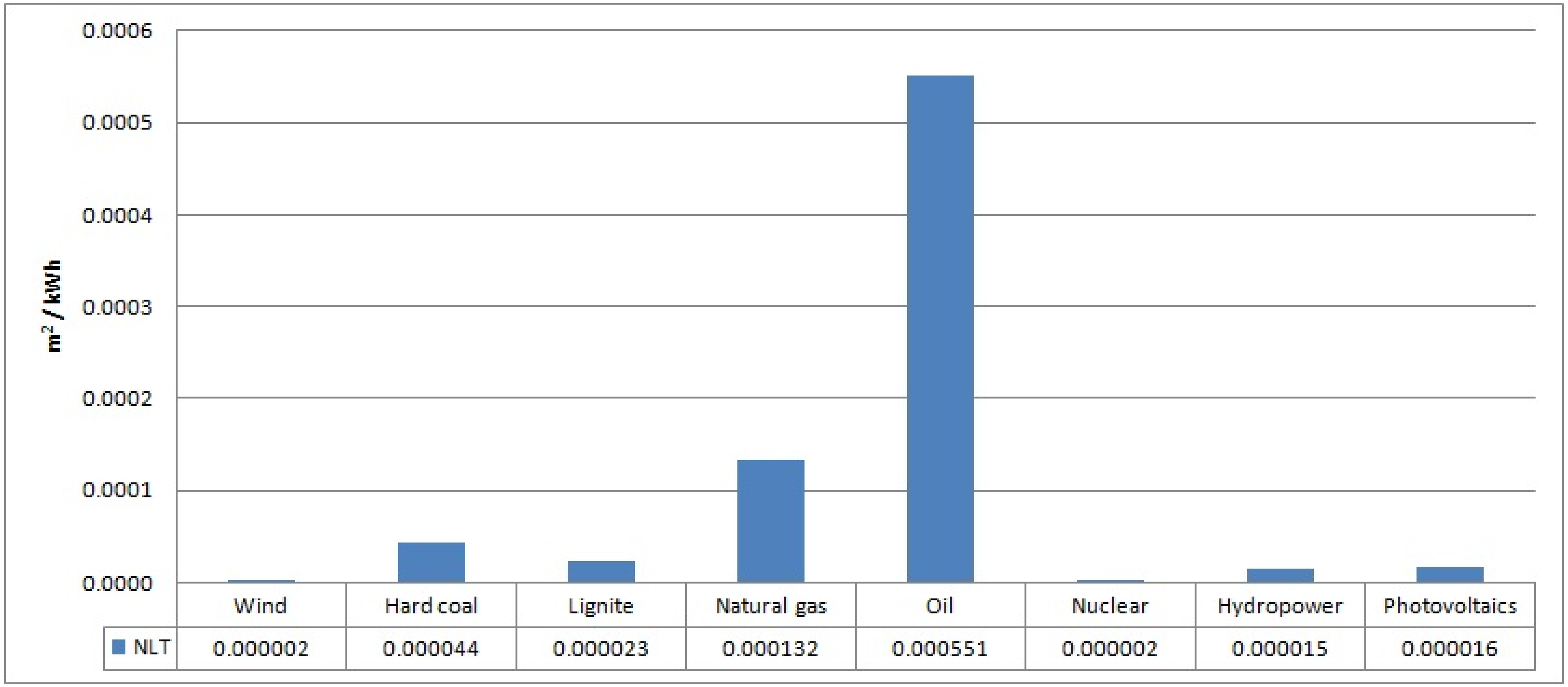
The LCIA results of the attributional LCA on the single power generation techniques that are not presented in section *5.1.2* are shown below, for the following impact indicators: fossil fuel depletion, natural land transformation, Particulate Matter formation, photochemical oxidant formation and terrestrial acidification (*Figure 20* to *24*, respectively).



Legend: FD: Fossil fuel Depletion.

Figure 20: Fossil fuel depletion potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H)
(source: own creation, based on data from the ecoinvent Centre, 2007)

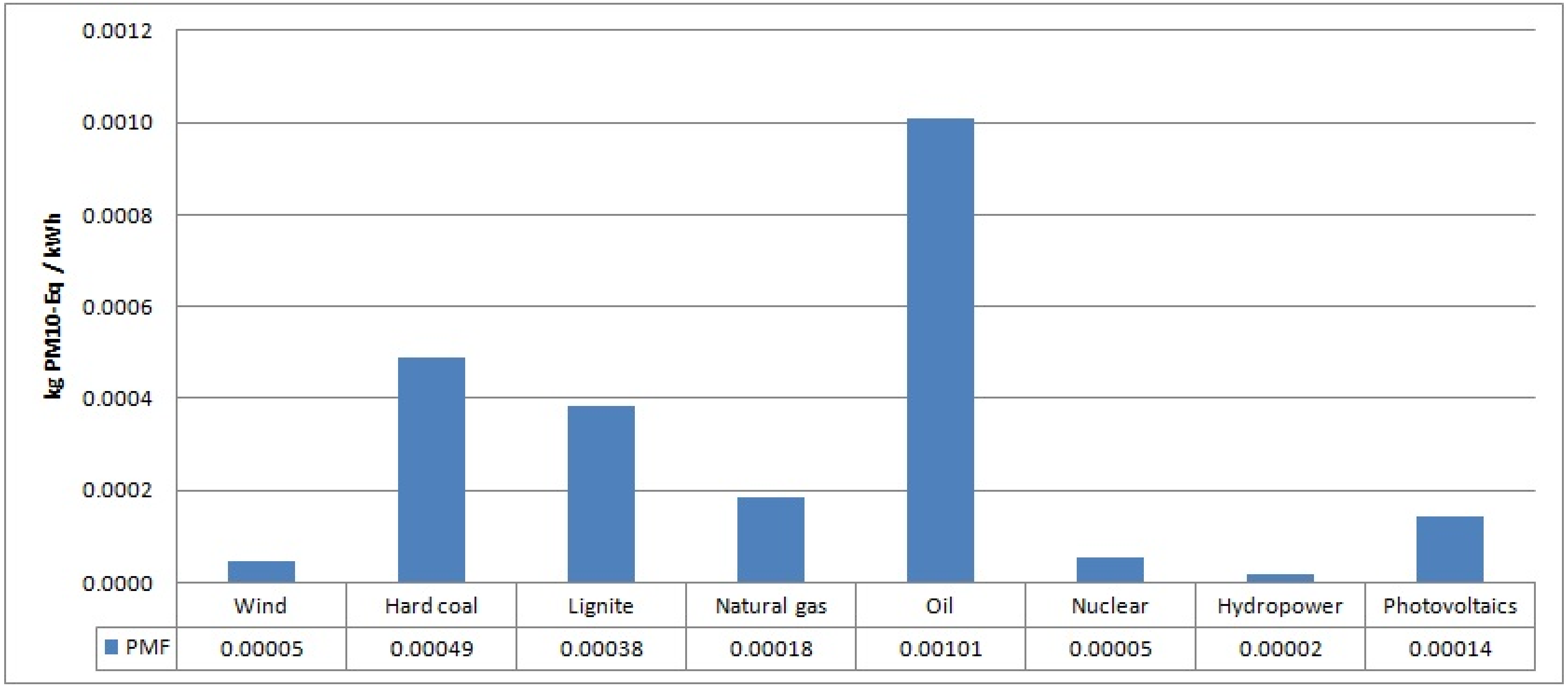
As illustrated in *Figure 20*, the hydropower, nuclear, wind, and photovoltaics power generation techniques use less oil-Eq per kWh electricity produced at the power plant than the other power generation techniques under investigation (i.e. the fossil fired techniques).



Legend: NLT: Natural Land Transformation.

Figure 21: Natural land transformation potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H)
(source: own creation, based on data from the ecoinvent Centre, 2007)

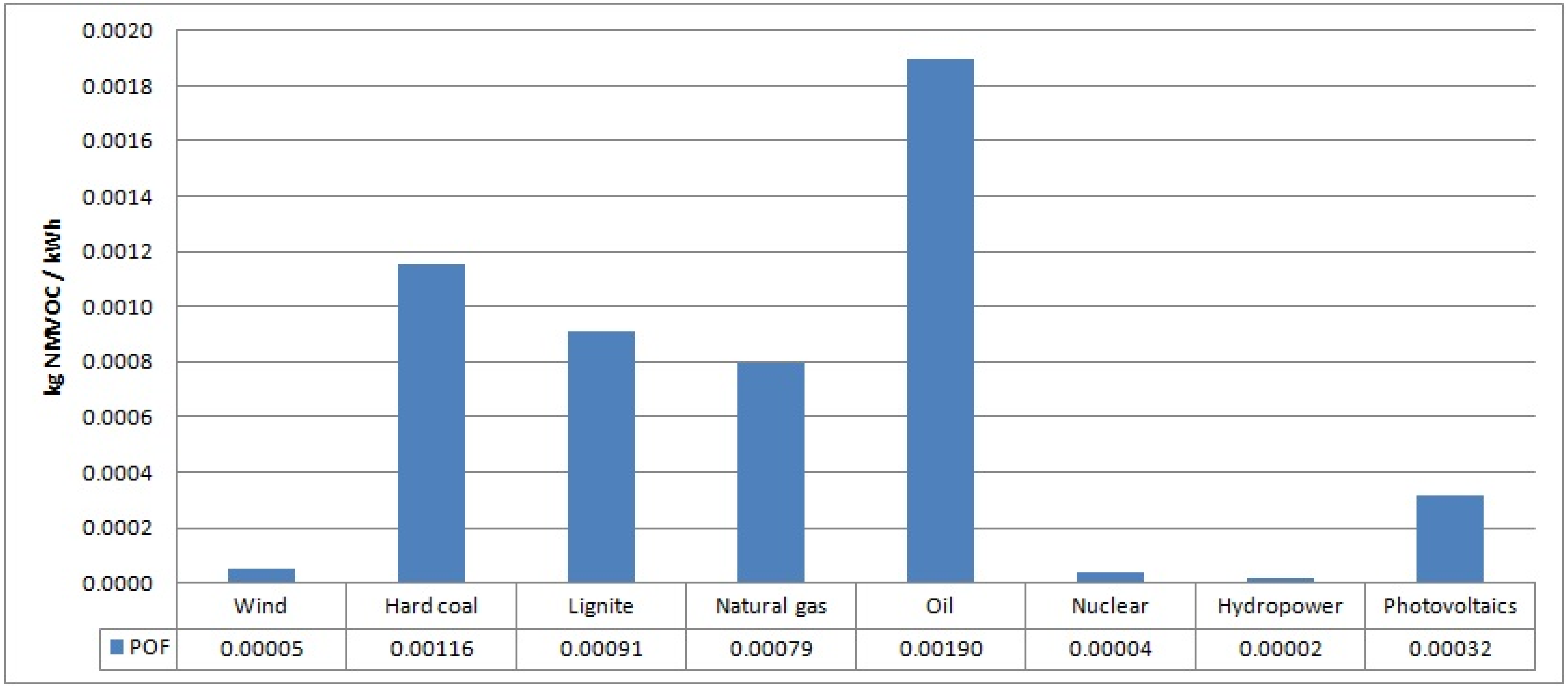
As illustrated in *Figure 21*, the wind, nuclear, hydropower, and photovoltaics power generation techniques use less m^2 land per kWh electricity produced at the power plant than the other power generation techniques under investigation (i.e. the fossil fired techniques).



Legend: PMF: Particulate Matter Formation.

Figure 22: Particulate Matter formation potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H)
(source: own creation, based on data from the ecoinvent Centre, 2007)

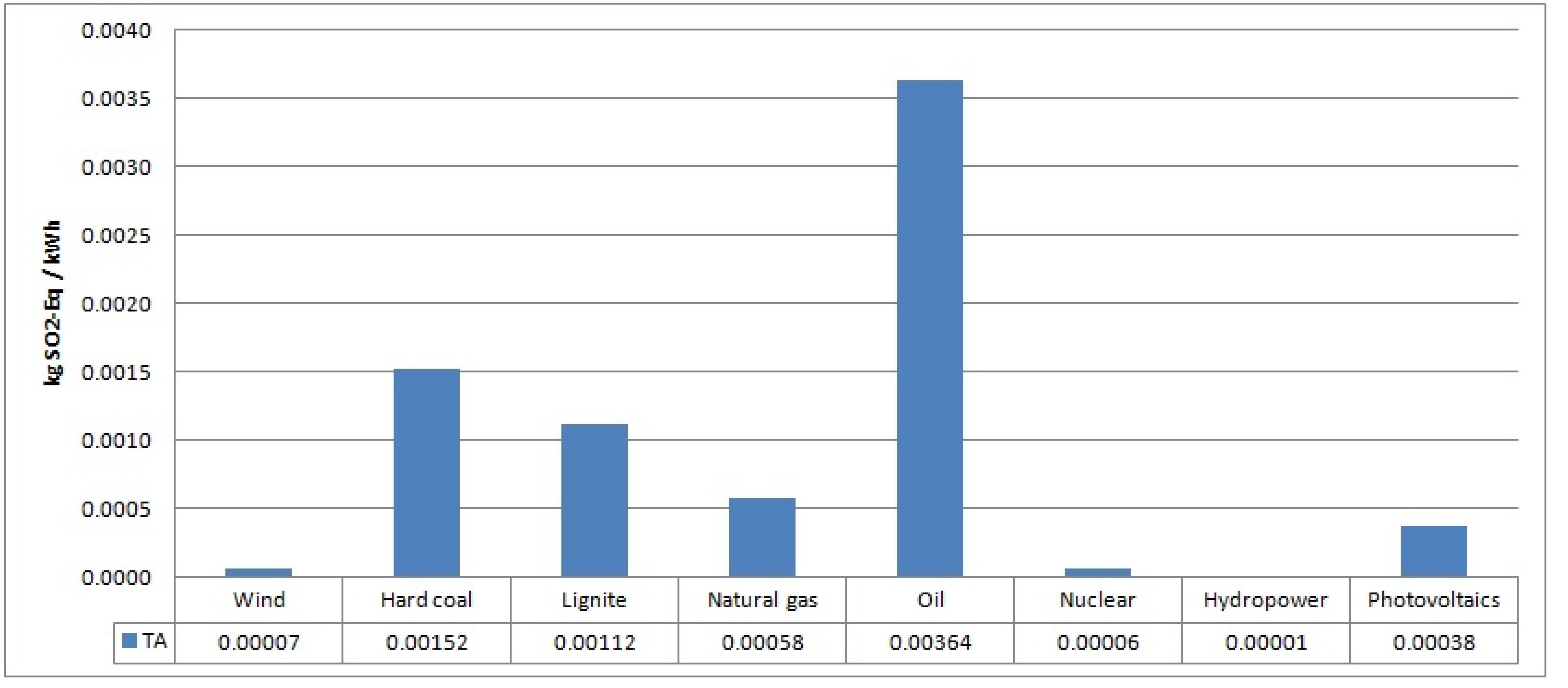
As illustrated in *Figure 22*, the hydropower, nuclear, wind, and photovoltaics power generation techniques emit less PM10-Eq per kWh electricity produced at the power plant than the other power generation techniques under investigation (i.e. the fossil fired techniques).



Legend: POF: Photochemical Ozone Formation.

Figure 23: Photochemical ozone formation potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H)
(source: own creation, based on data from the ecoinvent Centre, 2007)

As illustrated in *Figure 23*, the hydropower, nuclear, wind, and photovoltaics power generation techniques emit less NMVOC-Eq per kWh electricity produced at the power plant than the other power generation techniques under investigation (i.e. the fossil fired techniques).



Legend: TA: Terrestrial Acidification.

Figure 24: Terrestrial acidification potential for each power generation technique considered for the German power plant portfolio in 2006, determined via the LCIA method ReCiPe 2008 (H) (source: own creation, based on data from the ecoinvent Centre, 2007)

As illustrated in *Figure 24*, the hydropower, nuclear, wind, and photovoltaics power generation techniques add less SO_2-Eq to the soil per kWh electricity produced at the power plant than the other power generation techniques under investigation (i.e. the fossil fired techniques).