Comparative Life Cycle Assessment of selected renewable electricity generation technologies

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Abstract:
This master thesis aims to analyze the environmental performance of wind and solar PV technologies in Denmark and Spain on a consequential Life Cycle Assessment (LCA). The goal and scope of this study is to assess the environmental impacts of the entire life cycle stages of these technologies, compare the environmental impacts into the different geographical regions and define which parameters can improve their performance.

The LCA method, which is based on principles and guidelines of ISO standards $14040/14044$, is applied throughout the study. Furthermore, for scenarios in Denmark, the changes of electricity demand based on Danish energy mix are also included. One more alternative scenario for Denmark is also analyzed in order to define the need for regulatory system for wind and solar PV production. The regulatory system has been chosen to be either Hydro reservoir or Natural gas. The environmental impacts of these scenarios are also included in the calculations. For scenarios in Spain, there was not data available for the changes of electricity demand in energy system, consequently they are not included.

The most important findings of the thesis are that wind is performing better than solar PV and the geographical region plays a considerable role in their performance. Additionally, the manufacturing stage is responsible for the increased environmental impacts for both technologies. Finally, the extended lifetime of the power plant and ideal location are the parameters which can improve significantly its performance.

Maria Tsagkaraki

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Preface

This master thesis has been conducted for the 4^{th} semester of Master in Sustainable Energy Planning and Management, in the Department of Development and Planning at Aalborg University from February to June 2015. Jannick H. Schmidt has been supervising the project report.

The thesis report has been edited using Latex and SimaPro has been used for the analysis of the report. Abbreviations are located in the begin of the report so the reader can refer there for any understandable symbol. Moreover, the tables and figures included in the report are numbered according to the corresponding chapter. Each symbol of [] which contains a number inside associates with the reference of the bibliography, which can be found after the last chapter of the report. Finally, a CD with the results of the analysis is also provided.

The author would like to thank the supervisor Jannick H. Schmidt for his continues support, the helpful comments and the constructive discussions throughout the master thesis writing. Finally, thanks are also given to Alexandros Koutentakis and Iraklis Amoiridis for their support in this period.

Abbreviations

BAHY	Biodiversity Adjusted Hectare Year
BOS	Balance of the System
CEESA	Coherent Energy and Environmental System Analysis
CHP	Combined Heat and Power
EIA	Energy Information Administration
GHG	Greenhouse Gas Emissions
GWEC	Global Wind Energy Council
iLUC	Indirect Land Use Change
ISO	International Organization foe Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LUC	Land Use Change
mc-Si	Multi Crystalline Silicon
OECD	Organization for Economic Co-operation and Development
PDF	Potentially Disappeared Fraction of species
PP	Power Plant
QALY	Quality Adjusted Life Years
sc-Si	Single Crystalline Silicon
Solar$_{DK}$	Solar PV scenario in Denmark
Solar$_{ES}$	Solar PV scenario in Spain
UNEP	United Nations Environment Program
Wind$_{DK}$	Wind scenario in Denmark
Wind$_{ES}$	Wind scenario in Spain

Contents

Chapter 1

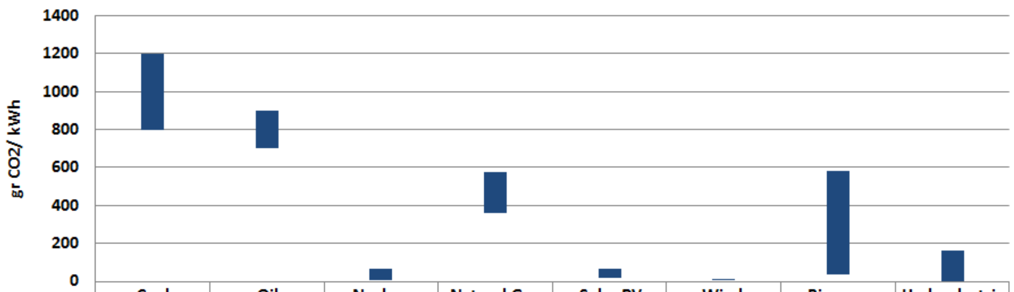
Introduction

Contents

Increased greenhouse gas (GHG) emissions has raised the global interest in recent decades. In 2014, 37 gigatonnes of CO_2 were emitted, which is 61% higher than 1990 and 2.5% higher than 2013 level of CO_2 emissions [14]. The fact of the increasing CO_2 emissions can definitely lead to severe effects on the earth, affecting the climate change.

Electricity generation accounts for 37% of the total global CO_2 emissions, which is a considerable share and it is expected to increase in the future [53]. Additionally, electricity demand is increasing twice as fast as the energy use and it is estimated to be more than two-thirds higher in 2035 [53]. This considerable increase, leads to the installation of new electricity generation technologies. Therefore, electricity generation is becoming more and more important, as it involves in the GHG emissions due to the consumption of fossil-fuel sources.

The global increase in CO_2 emissions is highly related to the increase of fossil-fuel electricity generation technologies. Figure 1.1 presents the GHG emissions intensity of fossil and non-fossil electricity generation technologies, based on numerous studies. All the studies which are included use the same functional unit and are not older than 15 years. The emission rates vary a lot from study to study, as different parameters and assumptions are taken into account in each study. For example, LCA studies for the same fossil-fuel technology analyze different types of the technology, which results in extreme range of the GHG emissions. Furthermore, in some studies for biomass the land use change (LUC) is included, while in other studies it is not, resulting in large differences in the LCA results. This concludes, that LCA literature includes a lot of uncertainties and considering the fact that different parameters can affect the results, there is always need for continuous research in LCA of electricity generation technologies.



	Coal	Oil	Nuclear	Natural Gas	Solar PV	Wind	Biomass	Hydroelectric
High	1200	900	65	575	68	10.5	579	160
Low	800	700	8.9	360	21	6.6	35	1
Average	1079	798	25	473	42	8	184	87

Figure 1.1: Life cycle GHG emissions intensity of electricity generation technologies based on: [51], [15], [45], [9], [50], [37], [6], [1], [38], [29], [27], [47], [19], [52].

It is notable that fossil-fuel technologies can emit around thirty times higher CO_2 than the non-fossil fuel technologies. The use of renewable technologies is an urgent need, since they are clean and energy efficient technologies. The available renewable electricity generation technologies are wind, solar PV, biomass and hydroelectric. On the other hand, renewable technologies are not emission-free during their life cycle stages (manufacturing, transport, installation, maintenance and dismantling). Therefore, renewable technologies are not "clean" in all life cycle stages and an assessment of the environmental impacts throughout their entire life cycle stages is crucial [2].

1.1 Problem analysis

Sustainable development requires methods and tools to measure the environmental impacts of the technologies [34]. Life cycle assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product [22]. LCA analyzes the raw materials and energy used throughout the lifetime of a product, defining the environmental impacts from "cradle to grave" and the level of GHG emissions of the energy technologies [22].

Life cycle assessment (LCA) is a method that can provide a deeper understanding of the pollutant emissions of electricity generation technologies and can determine the most "clean" technology for the entire lifetime. The LCA method is used in various studies in order to compare the environmental impacts of fossil and non-fossil fuel electricity generation technologies.

According to the Energy Information Administration (EIA), renewable electricity generation technologies are globally increasing by the time and it is expected to increase significantly by 2035 [8], as it can be seen in Figure 1.2. In addition, renewable technologies can produce electricity in a clean and efficient way, but measuring the GHG emissions of the entire stages of their life is always important.

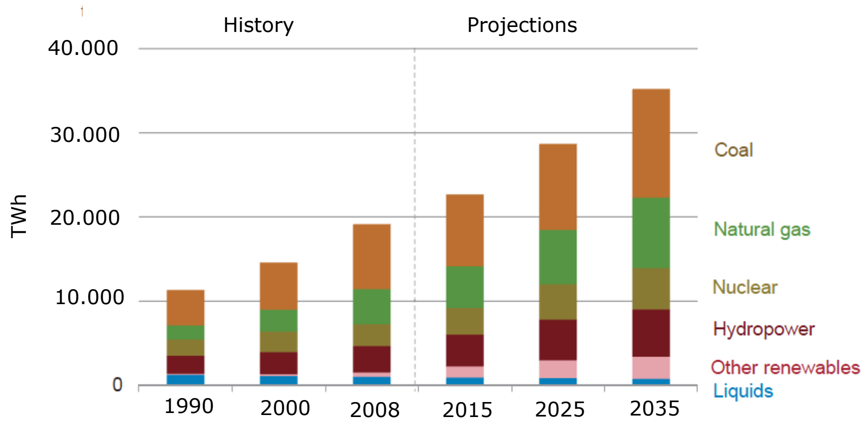


Figure 1.2: Electricity generation by fuel, EIA statistics history and projections, (Other renewables refer to wind and solar PV)[8].

Electricity generation using wind and solar PV is increasing rapidly the latest years. In 2014, wind installations increased 44%, reaching the number of 51,477 MW globally, according to the Global Wind Energy Council (GWEC) [16]. At the end of 2014, the total installed wind capacity in the world was 369,553 MW, as it ca be seen in Figure 4.2.

In European Union (EU), wind power installations increased 3.8% in 2014 compared to the year 2013 and it is expected to increase 64% more in 2020 [13]. Wind power is the electricity generation technology with the highest ratio of installations, 43.7% of the total installations in 2014. Currently, wind installed capacity in EU is 128.8 GW of which 120.6 GW, with 120,6 GW placed onshore and the rest 8 GW are offshore wind turbines [13].

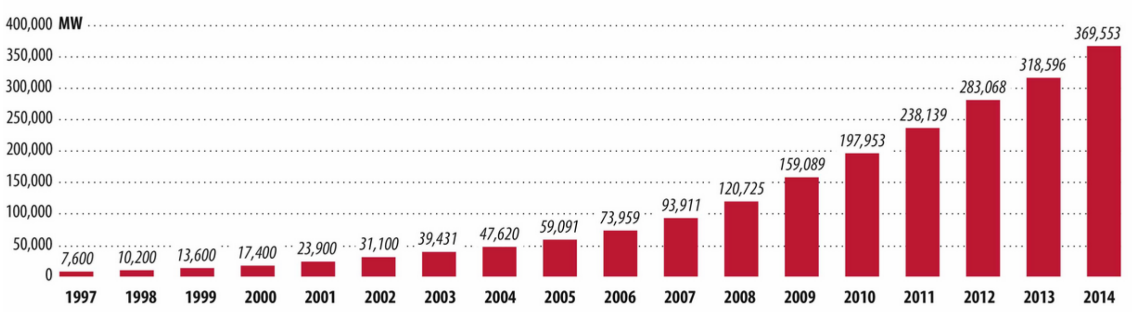


Figure 1.3: Global market for Wind power installations, 1997 – 2014, GWEC (2015) [16].

Wind market is expected to increase the next years. The most significant increase will be noticed outside the OECD, due to the intense policy support in these countries. The diversion in wind market among the OECD and non-OECD countries is due to the the absence of global climate policy, therefore wind market is based on national and regional policy supports [12]. According to the forecasts of GWEC, in the low scenario wind installations will be 712 GW in 2020 and 1,500 GW in 2013, while in the high scenario wind installations will reach the number of 800 GW in 2020 and nearly 2,000 GW in 2030 [12].

Solar Photovoltaic system is the second renewable technology after wind with an increased number of installations [12] (Figure 1.4). The global solar PV market in 2013 reached the number of 138,856 MW total installed capacity [12]. In European Union, the total installed capacity of solar PV was 81.5 GW in 2013, which is 11 GW higher than the previous year [12].

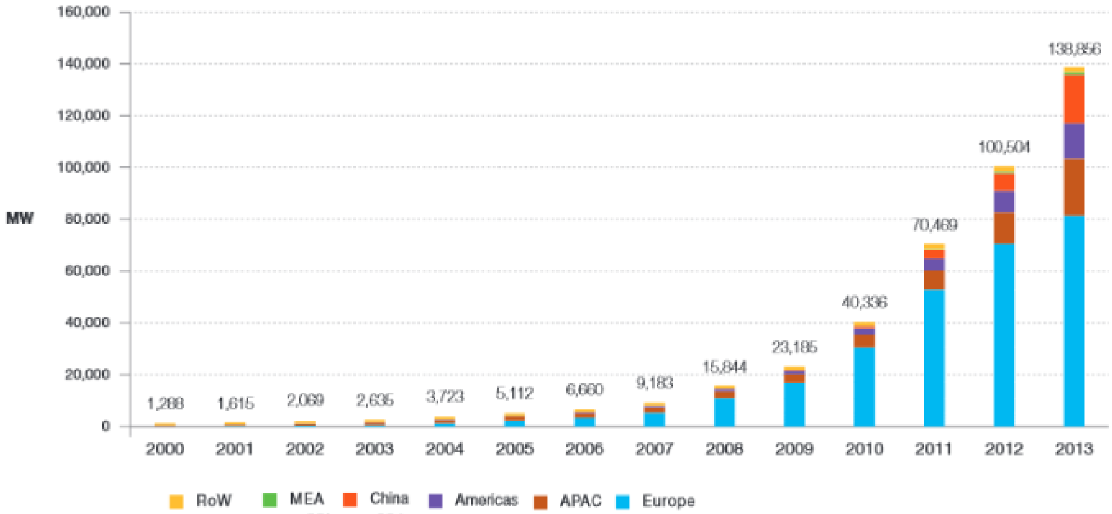


Figure 1.4: Global market for Solar Photovoltaic installed capacity 2000 – 2013, EPIA (2014) Row: Rest of world, MEA: Middle East and Africa, APAC: Acia Pecific [12].

In most countries the solar PV market is 'policy-driven', as in some countries the decrease in solar PV installations was related to the decline in political support for solar PV. As an example, in 2012 there was a considerable increase in solar PV installations in Denmark due to a new policy support. The next year, the policy support was declined, as a result of reducing the solar PV installations in Denmark. A similar situation was also in Spain, the expected support schemes were never introduced in 2013, so the PV installations were not as high as the previous years [12].

1.2 Case study

This study aims to assess the environmental impacts and measure the GHG emissions of 30 MW wind farm and 3 MW solar PV system in their entire life cycle. Wind and solar PV technologies are these with the fastest increase among all renewable energy technologies, therefore life cycle assessment is important for these technologies. The LCA method is used in order to carry out the analysis. It is a process of analyzing the materials and energy sources (inputs) of the selected technologies in order to calculate the environmental pollutant (outputs) [49]. The analysis and the input data are based on technical specification and land use of the analyzed technologies, therefore they may vary from country to country. The case study areas are Denmark and Spain, as both technologies are quite popular in these two countries. A lot of LCA studies have been carried out for wind and solar PV, but a comparison of these two technologies in Denmark and Spain has not analyzed yet.

1.2.1 Wind power

Denmark and Spain are both leading countries in wind power installations. According to the statistics from the European Wind Energy Association (EWEA), 4,845 MW are currently installed in Denmark and $22,986$ MW in Spain [13]. Spain is the second EU country with the highest number of wind capacity covering the 20.8% of the total electricity demand , while Denmark is the seventh with 39.1% of the Danish electricity demand covered by wind [10].

Wind energy is a clean and efficient electricity source but during the life cycle stages CO_2 is emitted, for this reason it is important to estimate the environmental impacts throughout their lifetime. LCA is an appropriate method for tracking the GHG emissions of the life cycle stages of a wind turbine: manufacturing, transport, installation, operation and dismantling.

1.2.2 Solar PV

Denmark is one of the countries with an unexpected rise in solar PV installations, reaching the number of 548 MW in 2013. On the other hand, Spain has remained a leading country in solar PV installations addressing the number of $5,340$ MW [12]. It can be concluded that both countries rely on solar PV for electricity production, with a higher installed capacity in Spain due to the appropriate weather conditions.

The electricity production from solar PV is clean and emission-free, however GHGs are emitted during the life cycle stages of the technology [44]. Considering the increased trend of PV installations the latest years, the estimation of the environmental pollutants in their lifetime is becoming more and more crucial. LCA is a proper technique for comparing and analyzing the environmental impacts in all life cycle stages, assessing the GHG emissions of a solar PV system.

1.3 Problem formulation

LCA method is important for analyzing the environmental impacts for both fossil and non-fossil fuel technologies in their entire lifetime. Renewable technologies are not completely 'clean' during their lifetime, so it is momentous a life cycle assessment during their life cycle stages.

In addition, renewable electricity generation technologies have an increased trend, with wind and solar PV installations being in high priority globally. Denmark and Spain are the leading countries for wind installations among the EU countries. Currently, the solar PV installations raised in Denmark, while Spain has remained one of the EU countries with the highest installations.

The scope of this study is to measure the environmental impacts of wind and solar PV technologies in their entire life cycle stages. The case study areas are chosen to be Denmark and Spain due to the reason that both technologies are quite popular in these countries. However, Denmark and Spain vary a lot in weather conditions, consequently it is more interesting to compare the LCA results for wind and solar PV in these two areas.

The LCA method, which is based on principles and guidelines of ISO standards $14040/14044$, is applied to this study and the SimaPro software is used for assessing the environmental impacts of wind and solar PV technologies and answering the research question:

"Analyzing the Life Cycle Assessment of wind and solar PV technologies in Denmark and Spain, what are the GHG emissions and the environmental impacts of both technologies in the selected areas?"

For a deeper LCA analysis the following sub questions arise:

- Which of wind and solar PV technologies has the best environmental performance?
- Which life cycle stage with in wind and solar PV technologies influence most the environmental performance?
- Does the geographical region affect the environmental performance of the technology?
- Which parameter can improve the environmental performance of the life cycle of wind and solar PV technologies?

Chapter 2

Methodology

Contents

This chapter introduces the methods used for the LCA of wind and solar PV technologies. The main methods for this study can be classified as following: LCA Methodology, LCA Modeling-SimaPro, Literature study and Data collection.

2.1 LCA Methodology

Life cycle assessment (LCA) is a method for calculating the potential environmental impacts of a product in the entire life cycle, starting from the extraction of the raw materials for the production to the final disposal of the product. The LCA process analyzes the materials and energy used in the life cycle stages of a product in order to define the environmental performance and the improvements opportunities in the entire lifetime of the product [22]. The LCA is described in two main standards:

- **ISO 14040**, which refers to the principles and framework of the LCA [22].
- **ISO 14044**, which refers to the requirements and guidelines for the LCA [23].

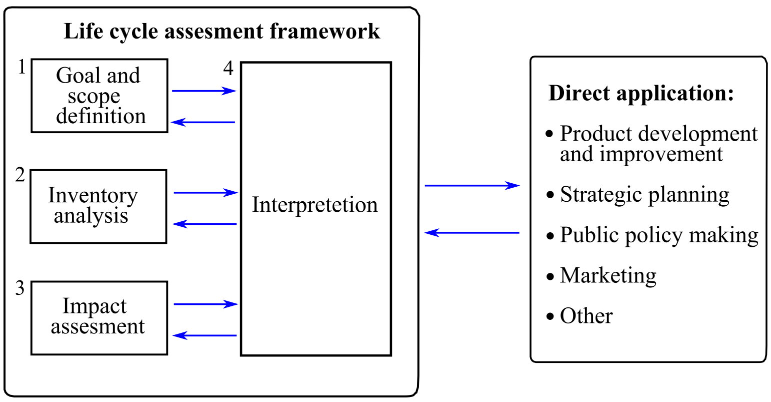


Figure 2.1: Phases of LCA process, based on [22].

According to the ISO standards, an LCA study is consisted of four main phases, as they are presented in Figure2.1.

2.1.1 Goal and scope definition

The first phase is the goal and scope definition. The goal definition presents the aim and the reason of the study, while the scope definition describes the relevant processes, the methods and assumptions of the study.

The object of the study is described in terms of a functional unit [30]. The functional unit must be carefully defined according to the product system and the scope of the LCA study. Furthermore, within the scope definition it is also included the system boundary which determines the unit processes of the LCA study. There are two main modeling approaches for conducting an LCA study, depending on the goal and scope of the analysis. These are the "Consequential modeling" and "Attributional modeling" [30].

- **Consequential modeling**: According to the United Nations Environment Programme, (UNEP), the consequential modeling is a "System modeling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit" [43]. Consequential modeling is describing the consequences of a decision and it is applied for examining the consequences of one additional product in the same product system. Consequential models are steady, linear and homogeneous models. This model system uses a market oriented approach to identify the change in demand of electricity [41].

- **Attributional modeling**: Attributional modeling is a "System modeling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule" [43]. In attributional approach, the environmental load is divided among the co- products, in case of more than one process. It is a modeling approach in which all the unit processes are included in a product system by linking the unit processes of the system according to a specific attributional rule. The electricity consumption is modeled as the market average supply and the allocation by product is necessary [41].

The main difference of these two approaches is that consequential modeling identifies the affected processes by using a market oriented approach, while the attributional modeling identifies the processes to be included by analyzing the bio-physical flows in the supply chain [30]. In this study, the consequential modeling it is applied, since it can better represent what is affected in the product system and can define the link between the purpose of the study and the modeling of the product system. The co-product allocation is avoided.

In addition, according to the ISO 14044 the selection of impact categories should include the environmental issues that are related to the analyzed product system and the goal and scope of the study" [23]

2.1.2 Life Cycle Inventory (LCI)

The second phase, life cycle inventory analysis, includes the modeling and data collection of the product system [30]. The data must be related to the functional unit and usually divided into two categories:

- Foreground data, which describes the modeling of the product system of the study,

- Background data, which includes everything else (i.e. energy, transport and waste management) and typical covered by database.

2.1.3 Life Cycle Impact Assessment (LCIA)

It is always important to choose an appropriate method according to the goal and scope of the analysis. For this analysis, it is chosen the "*Stepwise* 2006" method which has been based on the modifications of *EDIP*2003 and *IMPACT*2002+ methods [5]. The following steps for analyzing and presenting the results are included in an LCIA:
Characterization: The characterization results show how the different life cycle stages contribute to different impact categories. The emissions from the LCI are multiplied with an equivalent factor in order to define the impact potentials [30].
Normalization: It presents the results relative to a reference value, which is easier to understand and compare the results [30]. For the "*Stepwise* 2006" method the reference value is the impact per person in Europe for year 1995 [5].
Weighting: It is a way to evaluate each impact category and find the most important [30].
The category indicators for the "*Stepwise* 2006" has been defined as following:

- **Ecosystems**: This category has been defined as the Biodiversity Adjusted Hectare Year (BAHY), and measures as PDF*m2*years (PDF = Potentially Disappeared Fraction of species).

- **Human well-being**: This category has been defined as the Quality Adjusted Life Years (QALY), measured as the number of human life-years, multiplied by a quality adjustment between 0 and 1 (0 is for the death and 1 is for the perfect well-being).

- **Resource productivity**: It has been defined as a monetary unit of EUR2003 and measured as the future economic output derived from the resource [5].

2.1.4 Interpretation

The last phase in LCA is the Interpretation phase which includes:

- A conclusion and recommendations based on the results.

- Identification of the most significant issues, which refers to the presentation of key LCI and LCIA results.

- Evaluation, which includes completeness, sensitivity and consistency checks [30].

2.2 LCA Modeling- SimaPro

The SimaPro software was used for modeling the LCI and LCIA of this study. SimaPro is a professional LCA tool and designed to analyze the environmental performance of a product. It has been built according to the ISO 14040 and ISO 14044 standards. SimaPro software is used from consultancies, universities and research institutes in more than 80 countries [33].

The life cycle inventory dataset of SimaPro includes the Ecoinvent 3 database, which is the most recognized worldwide LCI database on the market. The data quality is maintained and validated by frequent updates [33]. In this LCA study, the Ecoinvent 3 database is used for modeling the background system for wind and solar PV scenarios.

2.3 Literature study and Data collection

Literature study is a significant method used throughout this study. It is a reliable way to gain knowledge for building a strong background and gather relevant information needed for the analysis of the study. Furthermore, it is a simple and common method for collecting all the relevant data from a variety of sources available online.

Data collection is also an important method, as using inaccurate data can affect the results of the analysis. Therefore, it is always necessary to be critical of the sources in order to limit the possibilities of inaccuracy. In this study the data collection for the inventory analysis is based on existing LCA studies. A validation of the data has been made through the sensitivity analysis, where different scenarios were analyzed in order to assess the uncertainties of the data.

Chapter 3

Goal and Scope Definition

Contents

The goal and scope of this study is to evaluate the environmental impacts of wind and solar PV technologies and measure the environmental performance of the life cycle stages of each component. It is a comparative LCA study, since the main goal of this study is to assess and compare the environmental performance of wind and solar PV in two different geographical regions. Two main scenarios are built for each technology, since the case study areas are chosen to be Denmark and Spain.

The four scenarios include the technical parameters of 30 MW onshore wind farm and 3 MW solar Photovoltaic power park in Denmark and Spain. The following tables can describe in detail the different scenarios for the analyzed technologies.

Table 3.1: Technical parameters of wind technologies, Wind$_{DK}$ and Wind$_{ES}$ scenarios.

	Onshore wind (Wind$_{\mathbf{DK}}$)	**Onshore wind (Wind$_{\mathbf{ES}}$)**
Technology	10x V90 − 3MW	15x G90 − 2MW
Capacity	30 MW	30 MW
Energy production over lifetime	2.1 TWh	1.88 TWh
Lifetime	20 yr	20 yr
Location	Denmark	Spain
Source	Vestas-2013 [51]	Gamesa-2013 [15]

Table 3.2: Technical parameters of solar PV systems, Solar$_{DK}$ and Solar$_{ES}$ scenarios.

	(Solar$_{DK}$) **Crystaline Silicon** **sc-Si /mc-Si**	**(Solar$_{ES}$)** **Crystaline Silicon** **sc-Si/ mc-Si**
Installed capacity	3 MW	3 MW
PV Module capacity	145 Wp	145 Wp
PV Modules amount	20, 689	20, 689
Cells per PV Module	38	38
PV system efficiency	14%/ 13.2%	14% /13.2%
Inverter efficiency	93.5%	93.5%
Energy production over lifetime	68, 040 MWh	105, 912 MWh
Lifetime	30 yr	30 yr
Location	Denmark	Spain
Source	[31], [45], [25], [46], [48]	[31], [45], [25], [46], [48]

3.1 Functional unit

It is necessary to define a functional unit (FU) in an LCA study in order to be able to relate the results with a given reference unit and compare them. The amount of energy produced (kWh) is a functional unit used in most LCA studies, but this does not take into account the reliability of electricity supply [26].

The reliability of electricity supply refers to the production of electricity exactly the same time it is consumed. This means that there must be a balance in production and consumption of electricity, otherwise fluctuations will result [26]. Wind and solar PV are intermittent systems with fluctuations in their production [26]. As shown in Figures 3.1 and 3.2, wind and solar PV power production is subject to short-term fluctuations, therefore they need a back up system, as it is difficult to store the electricity [26].

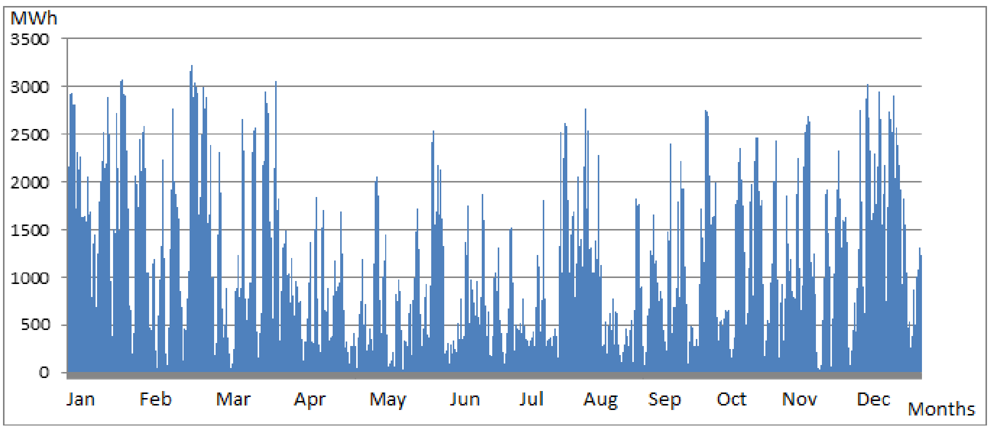


Figure 3.1: Hourly wind production per month for one year (2014) in Denmark, based on data from [11].

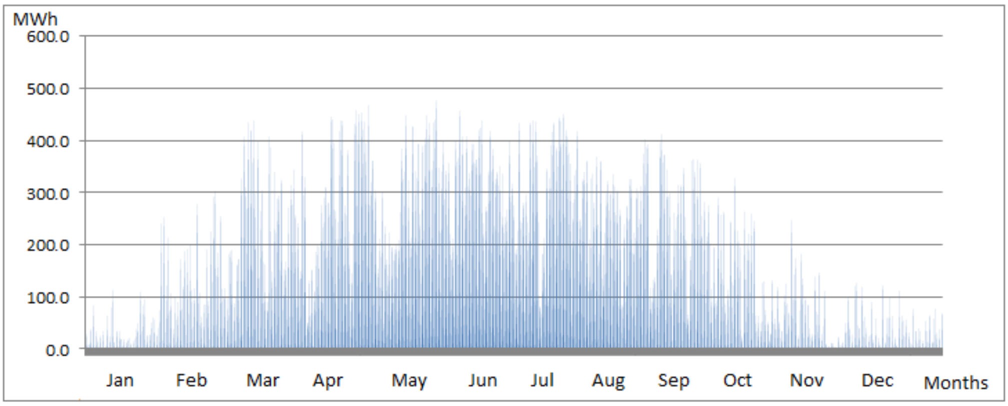


Figure 3.2: Hourly solar PV production per month for one year (2013) in Denmark, based on data from [11].

It is difficult to define a back up system as it is necessary to take into account a lot of considerations and model future energy scenarios.

The energy scenarios, which include implications for power system operation and appropriate methods, need to answer the following two questions:

- Is it technically possible to do this?
- What is necessary to make it possible? [32]

Answering these questions need to have knowledge and requirements for energy power system planning. The energy system is complex and difficult, therefore it is necessary to model it by using assumptions and alternative scenarios for evaluation. A power system is based on the control of generation and fluctuating demand [32]. As an example, the energy mix in Denmark is mainly based on wind power and also includes flexible demand options [32]. Therefore, the Danish energy power system requires control strategies for the generation and fluctuating demand.

However, the generation and fluctuating demand will not be the same in future and the need of resources will change, that means the control strategies need to take into account all these considerations. These strategies are included in future energy scenarios which aiming to the identification of the needs of the energy system and the allocation of the appropriate resources [32].

As already explained above, it is complicated to analyze future energy scenarios and as it is out of the scope of this study, an existing energy system analysis for Denmark will be used as an example for the Danish energy mix. The energy system analysis used for modeling the wind scenario in Denmark (Wind$_{DK}$) is based on an existing study [18] and it is described in the following Table (Table 3.3).

Table 3.3: Energy system analysis results of the change in demand for electricity by installing wind turbine capacity in Denmark, based on [18], (PP=Power Plant, CHP= Combined Heat and Power).

Energy system analysis with wind turbine installation	
Average change in electricity production (share)	
Wind turbine	0.98
PP-coal	0.08
PP-Ngas	0.09
Large-CHP coal	- 0.01
Small-CHP Ngas	- 0.1
Electric boiler	-0.04
Sum	1
Average change in heat production (share)	
Boiler coal	0.05
Boiler Ngas	0.04
Large-CHP coal	- 0.05
Small-CHP Ngas	- 0.08
Electric boiler	0.04
Sum	0

The described energy system in Table 3.3 refers to the changes in electricity demand by installing wind turbines. As it can be seen, the CHP plants have to decrease their production when the wind power production is higher than the demand. On the other hand, the power system has to increase the production of flexible resources, when the wind power production is smaller than the demand.

However, this energy mix refers to the years $2008 - 2009$ and a lot of changes will occur in the future. Nowadays, this energy system is not realistic and it used only as an example, since there is not other available source.

According to the "Coherent Energy and Environmental System Analysis (CEESA)" report the Danish future energy system will be based on:

- Geothermal
- Wind power
- Solar power
- Wave power
- Biomass
- Biogas
- Waste incineration [17].

A significant role will also play the central CHP plants and heat pumps for grid stability. In addition, electrolysers will be added to the system and wind turbines will be able to regulate the voltage and frequency of the electricity supply to the system [17]. On the other hand, coal and natural gas will phase out completely from the energy system.

For solar PV scenario in Denmark (Solar$_{DK}$), the same changes of electricity demand in energy system are assumed. This is due to the reason that solar is also an intermittent system and there is not other available data for changes in energy system with solar PV installations.

In addition, one more alternative scenario for meeting the electricity demand with wind capacity installations is analyzed, based on real current data [11]. Considering that the electricity production in Denmark will be based on wind power, the need for regulatory system is calculated. The regulatory system refers to a back up system in order to cover the demand of electricity when the production is lower that the consumption for one year. The results indicate the need for regulatory system is 31% for the total wind production per year. The following equation describes the calculation of the need for regulatory system:

$$\sum_{i=1}^{n} i = \frac{a_i}{a_i + a_{i+1} + ... + a_n} * 100 - \frac{b_i}{b_i + ... + b_n} * 100 = 31\% \tag{3.1}$$

where

i=1 hr

n=8760 hrs

α=hourly electricity consumption

b=hourly wind production

Two different scenarios are assumed for the regulatory system, Hydro reservoir and Natural gas. This means, the environmental impacts of 31% of Hydro reservoir or Natural gas will be added in the calculations.

Figure 3.3 presents the Danish electricity consumption and the wind production for one random month. The sum of the area under the consumption curve is considered to be equal to the area under the wind production, which is equal to 100%. In addition, it is important to be mentioned that the excess electricity production is not included in the calculations therefore, it is considered to have zero environmental impacts. In reality, the excess electricity production can either be exported to Nordic region or used in the heat distribution system. For the simplicity of this study, it is assumed that there are no impacts from the looses of wind production.

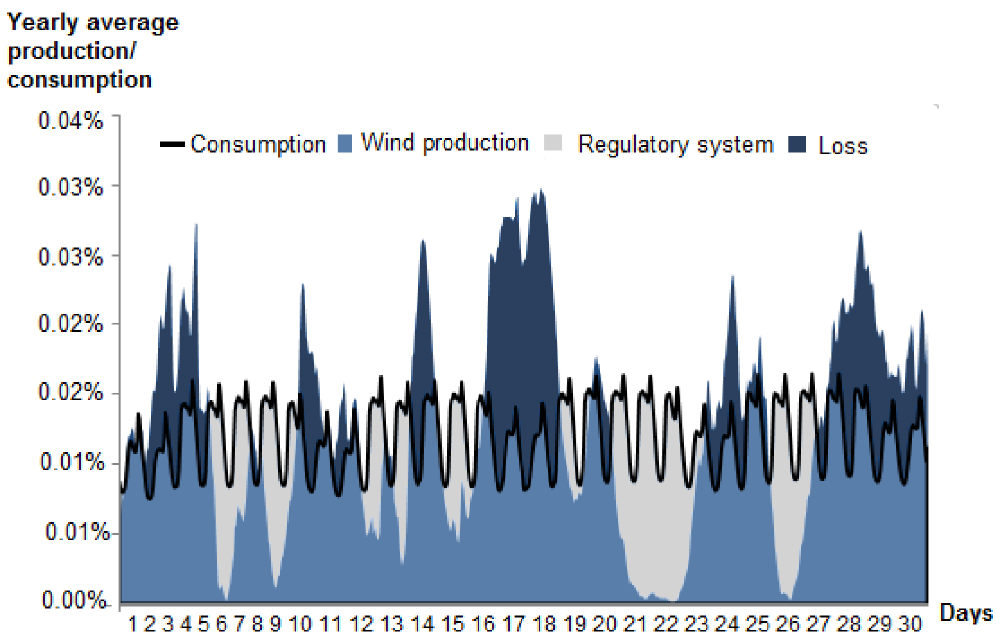


Figure 3.3: Calculations of need for regulatory system in wind production for one month in Denmark, based on data from [11]. Regulatory system refers to the wind production that is lower than the consumption, Loss refers to the wind production that is higher than the consumption.

The same considerations are also calculated for the solar PV production in Denmark for one year based on real current data [11]. The results appear that the need for regulatory system is 60% for the total solar PV production per year. The following equation explains the calculations for the share of the regulatory system:

$$\sum_{i=1}^{n} i = \frac{a_i}{a_i + a_{i+1} + ... + a_n} * 100 - \frac{c_i}{c_i + ... + c_n} * 100 = 60\% \tag{3.2}$$

where

i=1 hr

n=8760 hrs

α=hourly electricity consumption

c=hourly solar PV production

Hydro reservoir and Natural gas are also used as regulatory systems and 60% of their production will be added in the calculations.

To sum up, for Wind$_{DK}$ and Solar$_{DK}$ scenarios the following alternative scenarios for the changes in energy system are considered:

- Changes in energy system based on an existing study [18] (see Table 3.3).
- Use of Hydro reservoir as regulatory system (31% for Wind$_{DK}$ scenario and 60% Solar$_{DK}$ scenario).

- Use of Natural gas as regulatory system (31% for Wind_{DK} scenario and 60% Solar_{DK} scenario).

For Wind_{ES} and Solar_{ES} scenarios, it will not be included any changes of electricity demand in energy system, since there is not data available. Finally, the following functional unit has been defined:

"The production of 1 kWh, where the considered demand to be met is represented as a yearly average demand in terms of time of day (peak/low) and season."

The reference flow refers to a quantified amount related to the product system and it necessary in order to deliver the unit used as functional unit. The following reference flow has used in each scenario:
Wind_{DK} and Wind_{ES} scenarios: The reference flow refers to a wind mill.
Solar_{DK} and Solar_{ES} scenarios: The reference flow refers to a solar PV.

3.2 System boundaries

The life cycle of wind and solar PV power plants has been modeled using the life cycle stages shown in Figures 3.4 and 3.5. The description of the system is always necessary when the various life cycle stages have been analyzed individually. It is important to include all the life cycle stages and processes, as avoiding some of them may affect the results of the analysis.

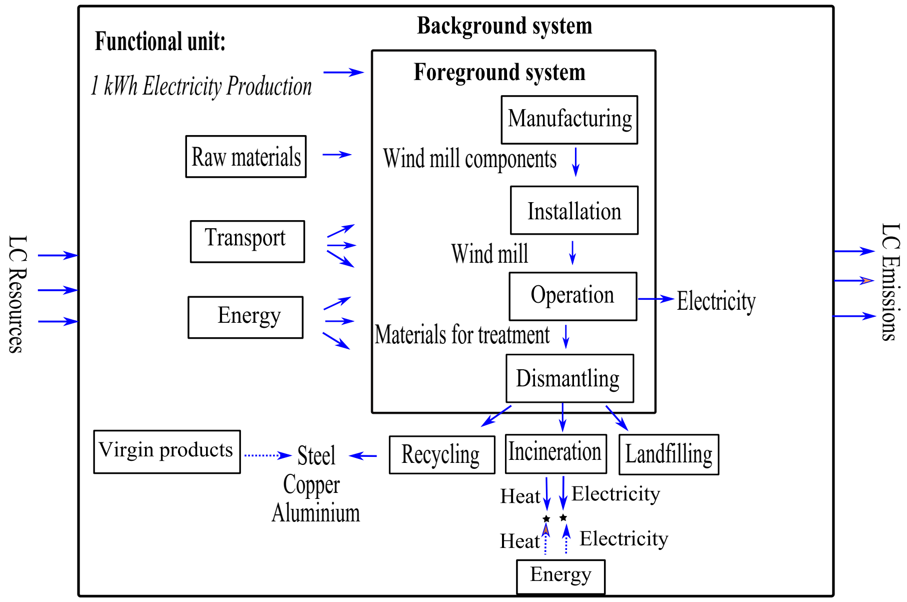


Figure 3.4: System boundaries for wind power plant, Wind_{DK} and Wind_{ES} scenarios.

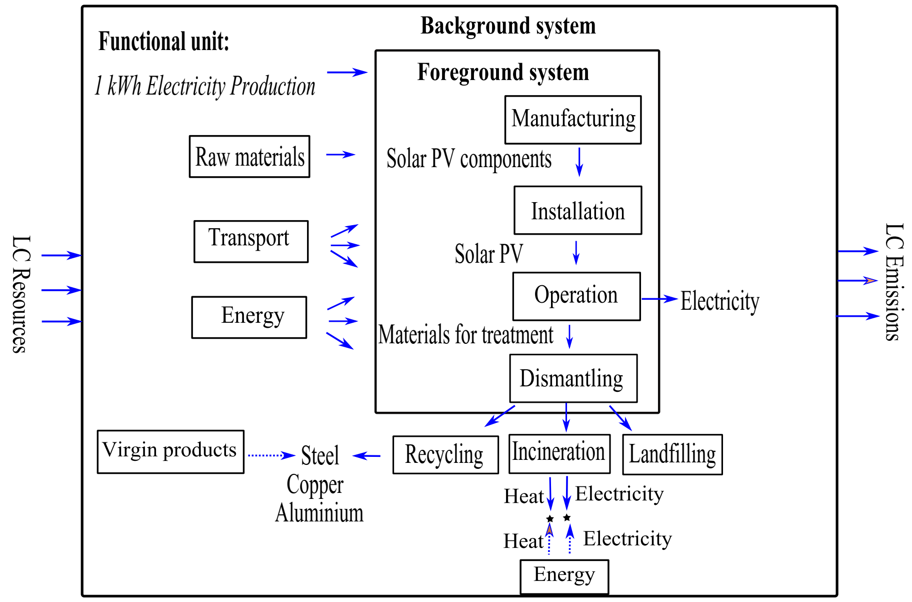


Figure 3.5: System boundaries of solar PV power plant, Solar$_{DK}$ and Solar$_{ES}$ scenarios.

The Figures 3.4 and 3.5 presents the background and the foreground system of wind and solar PV technologies respectively. The background system consists of processes on which no direct influence is exercised by the decision-maker [43]. In this study, the background system refers to the existing processes in Ecoinvent 3 dataset. The following background data was used in this study:

Raw materials
Raw materials refer to the extraction of raw materials used for the manufacturing of the wind and solar PV plant.

Transport
Transport includes transportation of raw materials to suppliers as well as transportation of components to the site, transportation for maintenance and transportation of the plant for waste treatment on the dismantling stage.

Energy
Energy refers to the energy used for the manufacturing, installation, operation and dismantling stages.

In Figures 3.6 and 3.7, it is presented the foreground system of the life cycle assessment of wind and solar PV scenarios. The foreground system consists of processes which are under the control of the decision-maker [43] and collected data is used.

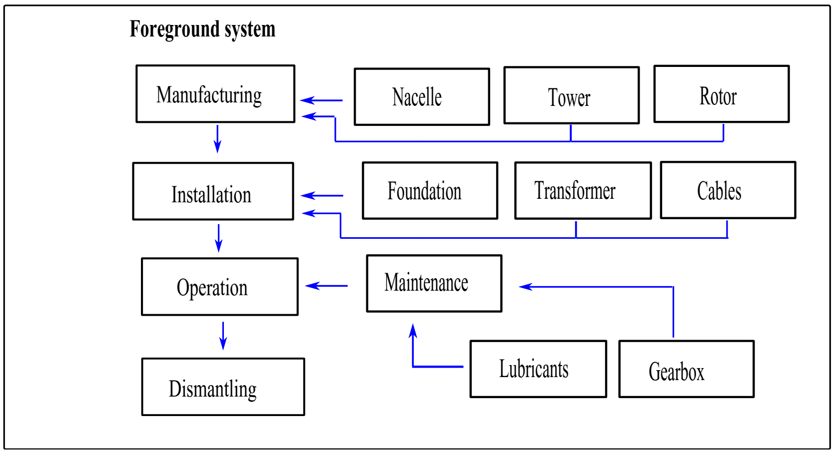


Figure 3.6: Foreground system of wind turbine for 20 years lifetime, Wind$_{DK}$ and Wind$_{ES}$ scenarios.

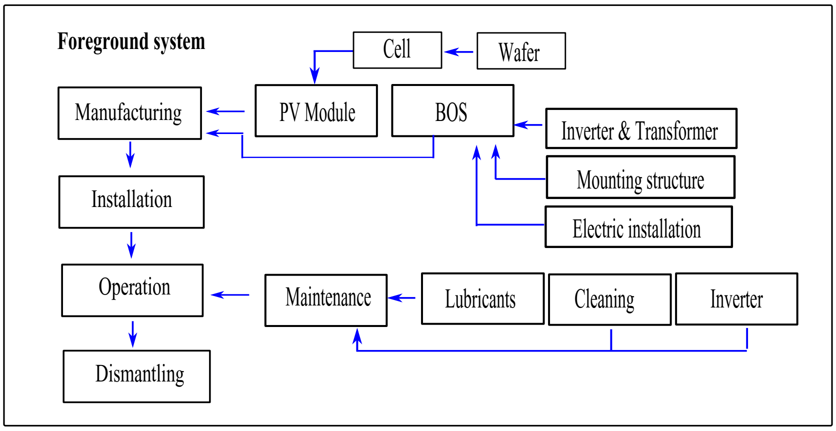


Figure 3.7: Foreground system of solar PV for 30 years lifetime, Solar$_{DK}$ and Solar$_{ES}$ scenarios.

Manufacturing

The manufacturing stage includes the manufacturing of wind and solar PV components. For wind scenarios (Figure 3.6), this stage includes the production of wind turbine's parts, which are the Nacelle, the Rotor, and the Tower. For solar scenarios (Figure 3.7), the manufacturing stage includes the manufacturing of the PV Modules and the Balance of the system (BOS). In the manufacturing stage of the PV Module, it is also included the manufacturing of wafers and cells.

Installation

The installation stage includes transport and installation of wind and solar PV components to the site respectively. Construction work is also included in this stage. The installation of the wind power plant also includes the installation of the Foundation, as well as the Transformer and the Cables. The installation of solar PV plant includes the installation of the PV Modules and the BOS.

Operation

The operation includes the general stage of running a wind or solar PV plant in order to generate electricity. It is also included the maintenance activities such as the replacement of components over the lifetime and the change of lubricants.

Dismantling

This stage includes the dismantling and waste treatment of the plant. Waste treatment options include recycling, incineration and landfilling.

Geographical coverage

In this study the geographical region refers to Denmark and Spain. For the wind scenarios (Wind$_{DK}$ and Wind$_{ES}$) all the components of wind turbine are considered to be produced in Denmark and Spain respectively. This consideration also includes the Foundation, the Transformer and the Cables. In solar scenarios (Solar$_{DK}$ and Solar$_{ES}$), it is considered that the wafers and the cells are produced in Germany(DE), as it is the only supplier in European Union. The rest components, which are the PV Module and the BOS are considered to be produced in Denmark and Spain respectively.

Chapter 4

Life Cycle Inventory

Contents

The life cycle inventory (LCI) stage analyzes the materials and energy used (inputs) as well as the generated products and waste treatments (outputs) for the analyzed product system. This chapter analyzes two different technologies, wind and solar PV.

4.1 Life cycle Inventory- Background data

In this section it is described the background data for the inventory analysis. The "Ecoinvent 3, consequential, unit" dataset is used in this LCA study. The background data includes raw materials, transport, energy and waste treatment.

Raw materials

Raw materials refer to the materials used for the manufacturing of the components of the power plants. The extraction of raw materials and transportation to supplier are also included in this stage. The materials from "Ecoinvent 3" dataset is used as input data for this stage.

Transport

Transport refers to the transportation of raw materials to supplier and the components of power plants to the site. Furthermore, it is also included the transportation for maintenance and waste treatment.

Transportation of raw materials to the site is already included in the raw material stage. Transportation of power plants for waste treatment is also included in the waste treatment process. In addition, transportation of components to the site is considered by truck and the "Transport, lorry $16-32$ metric ton" is used from the "Ecoinvent 3" dataset. Furthermore, transportation for maintenance is considered once per year by car.

For the wind scenarios, the transport of wind components to the site is assumed to be 200 km for each part of the wind turbine for Wind$_{DK}$ scenario and 400 km for each part of the wind turbine for Wind_{ES} scenario. These assumptions are made, since there is not a specific location for the site. For the Foundation it is assumed that the the concrete will be delivered by local supplier, therefore 50 km distance for the foundation is considered for both cases. Tables 4.4 and 4.5 in the following section present the total tkm for the analyzed scenarios. Different scenarios are analyzed in the sensitivity analysis.

For Solar_{DK} scenario, the transport of solar PV components to the site is assumed to be 150 km for each component and 300 km for solar cells, since it is considered that the supplier is from Germany. For Solar_{ES} scenario , it is assumed 300 km for the components and 2, 100 km for the cells, as the supplier is also from Germany. The concrete used for the mounting of the system is delivered by local supplier, therefore the distance to the site is assumed to be 50 km for both scenarios. Tables 4.11 and 4.12 present the total tkm for each scenario. Different scenarios for transport distance are analyzed in the sensitivity analysis.

Energy

Energy refers to electricity and fuels consumed for manufacturing, installation, operation, and dismantling of the power plant.

- **Electricity**

  The "electricity country mixed" from "Ecoinvent 3" dataset is used as input data for electricity. For Wind_{DK} and Solar_{DK} scenarios it is used the "electricity medium voltage DK", while for Wind_{ES} and Solar_{ES} scenarios, the "electricity medium voltage ES" is used.

  The data for electricity consumption per wind turbine for Wind_{DK} and Wind_{ES} scenarios is provided by Vestas [51] and Gamesa [15] studies respectively. The electricity consumed in the life cycle stages of solar PV system (sc-Si and mc-Si) is based on existing LCI studies [31], [48] and [25]. Further details are presented in the following sections.

- **Fuels**

  Fuels refer to the fuels consumed for the manufacturing and installation of the power plant. Data from the "Ecoinvent 3" dataset was used for the amount of fuels consumed per wind turbine, since there was not other available source. In addition, the amount of fuels consumed for the manufacturing and installation of 3 MW solar PV system (sc-Si and mc-Si) was based on [31], [48] and [25].

Waste treatment

Waste treatment refers to waste scenarios for wind and solar PV plants at the dismantling stage. Three different waste treatments are used in this LCA study, recycling, incineration and landfilling. Recycling is important, as it is considered that the recycled materials will be utilized and reused. The non recyclable materials will be transported for landfilling or incineration. Table 4.1 presents the different waste scenarios for wind turbine and solar PV waste treatment based on existing LCA reports.

Table 4.1: Waste treatment scenarios for wind turbine.

Material	Recycling	Incineration	Landfilling	Sum	Sources
Steel and iron	90%		10%	100%	[51], [36], [9], [39]
Copper	90%		10%	100%	[51], [36], [9]
Aluminium	90%		10%	100%	[51], [36], [9]
Electronics	50%		50%	100%	[51], [15]
Plastics		50%	50%	100%	[51], [36], [9]
Glass		100%		100%	[36], [9], [15]
Lubricants		100%		100%	[51], [36], [9], [15]
Concrete			100%	100%	[51]
Painting			100%	100%	[51], [36], [15]
Silicon			100%	100%	[31], [48]

Steel, copper and aluminum can be recycled after the dismantling of power plant. It is considered only 90% recycling of metals and 10% losses, as there is much uncertainty of the recycling process, so there might be losses.

Steel is an important material input in this LCA study, for this reason focus has put on the recycling process of steel. The modeling of recycling is varying among three different modeling assumptions [39]. Therefore, the Ecoinvent process of recycling has been modeled in order to comply with the following modeling assumptions:

- **ISO** 14040/44: The material for treatment is the determining flow of all treatment activities and recovered material and by products are considered as co - products.

- **Attributional**: It is considered 0% allocation to material for treatment and 100% allocation for recovered material and by products.

- **PAS**2050: The same modeling as in ISO 14040/44 [39].

4.2 Life cycle Inventory-Wind

Wind turbines are designed to generate electricity from wind. The main components of a wind turbine are presented in the Figure 4.1. The wind turbine can rotate through a horizontal (HAWT) or vertical (VAWT) axis. The most common type of wind turbine is the HAWT, where the wind hits the blade and then hits the tower. The VAWT type is not as efficient as the HAWT. The differences are that the wind speed in VAWT is lower and the generator can be placed in the ground [7].

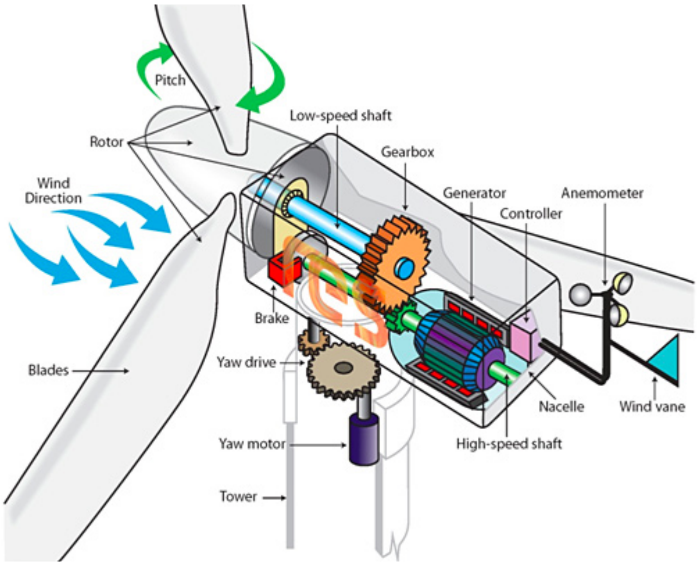


Figure 4.1: Main components of a wind turbine [35].

The main parts of a wind turbine are:

Nacelle

The nacelle is placed on the top of the tower and includes the generator and gearbox. The generator is used to produce electricity from the rotation of the rotor. The gearbox can amplify the energy output of the rotor. The gearbox is placed between the rotor and the generator. .

Rotor

The rotor is designed to capture the maximum surface area of wind. The rotor rotates around the generator through the low speed shaft and the gearbox. The rotor includes also the blades, which are designed to capture the energy from wind. The wind turbines usually have three blades.

Tower

The tower of the wind turbine is designed to support the nacelle and the rotor. The higher towers are better for the wind turbine. The size of the tower is usually 1 to 1.5 times the rotor diameter [7].

The main technical specifications of the two analyzed types of wind turbines are presented in the following Table (Table 4.2).

Table 4.2: Technical Specifications based on Vestas [51] and Gamesa[15]

Parameters	**Vestas V90-3 MW**	**Gamesa G90-2 MW**
Rotor		
Diameter	90 m	90 m
Swept area	6, 362 m2	6, 362 m2
Rotation speed	8.6 − 18.4 rpm	9 − 19 rpm
Blades		
Units	3	3
Length	44 m	44 m
Tower		
Height	105 m	78 m
Generator		
Nominal power	3 MW	2 MW
Total weight	256 ton	295 ton

4.2.1 LCA stages-Foreground system for wind

Manufacturing

Inventory data collection for the manufacturing of wind turbine has mainly gathered from the LCA reports of Vestas [51] and Gamesa [15] for the year 2013. However, it is difficult to collect data for all the life cycle stages of a wind turbine, for this reason more LCA reports are used and assumption are made. Table 4.3 presents the sources used for the LCI analysis of wind scenarios.

Table 4.3: Inventory data collection for Wind scenarios.

Inventory data	**Sources**
Materials inputs for wind turbines components:	
Nacelle, Tower and Rotor	Vestas [51], Gamesa [15]
Foundation	Vestas [51], [50] Gamesa [15]
Transformer	Vestas [51], Gamesa [15]
Cables	Vestas [51]
Electricity consumption in life cycle stages	Vestas [51], Gamesa [15]
Electricity production of wind turbine	Vestas [51], Gamesa [15]
Waste treatment scenarios	Vestas [51], Gamesa [15]
	and other LCA reports (see Table 4.1)
Land occupation	"Ecoinvent 3" dataset
Fuels consumption	"Ecoinvent 3" dataset

A detailed analysis of the material data for both scenarios (Wind$_{DK}$ and Wind$_{ES}$) is presented in Tables 4.4 and 4.5 respectively. Table 4.4 includes the material inputs and electricity consumed for one wind turbines V90 $-$ 3 MW, while Table 4.5 includes the material inputs and electricity consumed for one wind turbines G90 $-$ 2MW. In the LCA study, 10 wind turbines of V90 $-$ 3 MW were used for the Wind$_{DK}$ scenario and 15 wind turbines of G90 $-$ 2 MW were used for the Wind$_{ES}$ scenario.

Installation

The installation of wind power plant includes the installation of the components of the wind turbine, the Foundation as well as the Transformer and the Cables. Additionally, the installation stage includes the transportation of the components to the site and the fuels consumed during this stage. Construction work and land occupation are also considered, while road construction is not included in this study.

Table 4.4: LCI-data for "Installation" and "Manufacturing" of one wind turbine V90 $-$ 3 MW in Denmark (Wind$_{DK}$ scenario), (p=piece).

			Manufacturing						
	Unit	**Installation**	**Nacelle**	**Tower**	**Rotor**	**Foundation**	**Transformer**	**Cables**	**LCI data**
Reference flow									
Wind mill	p	1.00							Reference flow
Nacelle	p		1.00						Reference flow
Tower	p			1.00					Reference flow
Rotor	p				1.00				Reference flow
Foundation	p					1.00			Reference flow
Transformer	p						1.00		Reference flow
Cables	p							1.00	Reference flow
Material input									
Nacelle	p	1.00							[51]
Tower	p	1.00							[51]
Rotor	p	1.00							[51]
Foundation	p	1.00							[51]
Transformer	p	1.00							[51]
Cables	p	1.00							[51]
Low-alloyed steel	ton		10.00	163.00			1.00		Steel, low-alloyed GLO| market for | Conseq, U
High alloyed steel	ton		21.00						Steel, chromium steel 18/8 GLO| market for | Conseq, U
Reinforced steel	ton					36.00			Reinforcing steel GLO| market for | Conseq, U
Cast iron	ton		15.00		5.00				Cast iron GLO| market for | Conseq, U
Copper	ton		7.00				0.20	0.36	Copper GLO| market for | Conseq, U
Aluminium	ton		2.00				3.00E-3	3.00	Aluminium, cast alloy GLO| market for | Conseq, U
Plastics	ton							0.30	Polyethylene, high density GLO| market for | Conseq, U
Glass reinforced plastic	ton		4.00		22.50				Glass fibre reinforced plastic GLO| market for | Conseq, U
Painting	ton		0.10	0.60	0.70				Alkyd paint, white GLO| market for | Conseq, U
Zinc	ton			0.20					Zinc GLO| market for | Conseq, U
Concrete	ton					1,160.00			Concrete, 20MPa GLO| market for | Conseq, U
Electric/ electronic	ton		1.90						Electronics, for control units GLO| market for | Conseq, U
Lubricant	ton		0.70				0.40		Lubricating oil GLO| market for | Conseq, U
Processes									
Wire drawing	ton		7.00				0.20	0.36	Wire drawing, copper RER| processing | Conseq, U
Welding	m			296.00					Welding, arc, steel GLO| market for | Conseq, U
Zinc coating	m2			420.00					Zinc coat, pieces GLO| market for | Conseq, U
Excavation	m3					450.00			Excavation, hydraulic digger RER| processing | Conseq, U
Transport									
Transport	tkm		12,400.00	32,600.00	5,400.00	58,000.00			Transport, lorry 16-32 metric ton GLO| market for | Conseq, U
Fuels									
Diesel	MJ	30,000							Diesel, burned in building machine GLO| market for | Conseq, U
Energy									
Electricity	MWh	132.09	65.00	163.00	28.00				Electricity, medium voltage DK| market for | Conseq, U

Table 4.5: LCI-data for "Installation" and "Manufacturing" of one wind turbine G90 $-$ 2 MW in Spain (Wind$_{ES}$ scenario), (p=piece).

			Manufacturing						
	Unit	**Installation**	**Nacelle**	**Tower**	**Rotor**	**Foundation**	**Transformer**	**Cables**	**LCI data**
Reference flow									
Wind mill	p	1.00							Reference flow
Nacelle	p		1.00						Reference flow
Tower	p			1.00					Reference flow
Rotor	p				1.00				Reference flow
Foundation	p					1.00			Reference flow
Transformer	p						1.00		Reference flow
Cables	p							1.00	Reference flow
Material input									
Nacelle	p	1.00							[15]
Tower	p	1.00							[15]
Rotor	p	1.00							[15]
Foundation	p	1.00							[15]
Transformer	p	1.00							[15]
Cables	p	1.00							[51]
Low-alloyed steel	ton		21.80	188.00	3.30		1.00		Steel, low-alloyed GLO| market for | Conseq, U
High alloyed steel	ton		15.50		6.90				Steel, chromium steel 18/8 GLO| market for | Conseq, U
Reinforced steel	ton					14.50			Reinforcing steel GLO| market for | Conseq, U
Cast iron	ton		23.60		9.40				Cast iron GLO| market for | Conseq, U
Copper	ton		0.50		0.10		0.20	0.30	Copper GLO| market for | Conseq, U
Aluminium	ton		1.00	0.20	0.10			3.00	Aluminium, cast alloy GLO| market for | Conseq, U
Plastics	ton		1.10		0.10			0.50	Polyethylene, high density GLO| market for | Conseq, U
Fiberglass	ton				15.10				Glass fibre GLO| market for | Conseq, U
Glass reinforced plastic	ton		1.70		0.20				Glass fibre reinforced plastic GLO| market for | Conseq, U
Painting	ton		0.10	0.60	0.70				Alkyd paint, white GLO| market for | Conseq, U
Epoxy	ton				1.50				Epoxy resin, liquid GLO| market for | Conseq, U
Concrete	ton					1,056.00			Concrete, 20MPa GLO| market for | Conseq, U
Electric/ electronic	ton		0.90						Electronics, for control units GLO| market for | Conseq, U
Lubricant	ton		0.60				0.40		Lubricating oil GLO| market for | Conseq, U
Processes									
Wire drawing	ton		0.50		0.10		0.20	0.30	Wire drawing, copper RER| processing | Conseq, U
Welding	m			296.00					Welding, arc, steel GLO| market for | Conseq, U
Excavation	m3					450.00			Excavation, hydraulic digger RER| processing | Conseq, U
Transport									
Transport	tkm		26,800.00	75,200.00	15,200.00	52,800.00			Transport, lorry 16-32 metric ton GLO| market for | Conseq, U
Fuels									
Diesel	MJ	30,000.00							Diesel, burned in building machine GLO| market for | Conseq, U
Energy									
Electricity	MWh	173.25	76.05	219.96	49.14				Electricity, medium voltage ES| market for | Conseq, U

The Foundation of wind turbines has a typical size of 15 x 15 m and 2 m deep. The main material of the Foundation is the reinforced concrete [50]. The Transformer is used in order to collect the energy produced from the wind plant and transfer it to the grid. The distance to the grid is assumed to be 20 km. The Cables refer to internal and external cables. The internal cables are used in the wind turbine, for connecting the wind turbines between them and between the Transformer. It is assumed that internal cables are 10 km and 36 kV. External cables include the cables used for connecting the wind plant to the grid. These cables are assumed to be 20 km high voltage 110 kV [51].

For both scenarios, Wind$_{DK}$ and Wind$_{ES}$, the same assumptions for cables and distance to the grid are used, since there was not data available for cables (external and internal) for the G90 $-$ 2 MW wind turbine. The same material inputs for cables from V90 $-$ 3 MW are used for both cases.

Operation

Operation includes the maintenance of wind turbines, which is considered to be the change of lubricants and the replacement of the gearbox once in the entire lifetime of

20 years. Transport to the site for maintenance once per year is also included in this stage. For the simplicity of the analysis it is assumed one replacement of the gearbox for each wind turbine based on Vestas [51] and Gamesa [15] reports. In sensitivity analysis different scenarios of maintenance are analyzed.

Dismantling

The dismantling stage includes the dismantling of the wind turbine and the transport of the components for waste treatment. The different waste treatment scenarios have already presented in Table 4.1. The same waste treatments are used for both wind scenarios ($Wind_{DK}$ and $Wind_{ES}$). The Tables 4.6 and 4.7 present the operation and dismantling stages for $Wind_{DK}$ and $Wind_{ES}$ scenarios respectively.

Table 4.6: LCI-data for "Operation" and "Dismantling" of 30 MW wind farm ($Wind_{DK}$ scenario) in Denmark, 20 years lifetime, (p=piece).

	Unit	Operation	Dismantling	LCI data
Reference flow				
Wind mill	MWh	2,108,000.00		Reference flow
Dismantling	p		1.00	Reference flow
Material inputs				
Installation	p	10.00		Reference flow
Materials for treatment				
Dismantling	p	10.00		Reference flow
Recycling				
Steel and iron	ton		224.00	see section 4.1 *Waste treatment*
Aluminium	ton		9.00	Aluminium GLO| recycling| Conseq, U
Electronics	ton		0.95	Electronics scrap RER| treatment of | Conseq, U
Incineration				
Lubricant oil	ton		1.10	Waste mineral oil GLO| market for | Conseq, U
Plastics	ton		13.30	Waste plastic, mixture GLO| market for | Conseq, U
Glass	ton		13.30	Waste glass GLO| Conseq, U
Landfilling				
Electronics	ton		0.95	Electronics scrap RER| treatment of | Conseq, U
Steel and iron	ton		24.90	Inert waste, for final disposal GLO| market for | Conseq, U
Painting	ton		1.40	Waste paint GLO| market for | Conseq, U
Aluminium	ton		1.00	Waste aluminium GLO| market for | Conseq, U
Plastics	ton		0.30	Waste polyethylene GLO| market for | Conseq, U
Concrete	ton		1,160.00	Waste reinforced concrete GLO| market for | Conseq, U
Energy				
Electricity	MWh		66.04	Electricity, medium voltage DK| market for | Conseq, U

Table 4.7: LCI-data for "Operation" and "Dismantling" of 30 MW wind farm (Wind$_{ES}$ scenario) in Spain, 20 years lifetime, (p=piece).

	Unit	Operation	Dismantling	LCI data
Reference flow				
Wind mill	MWh	1,887,600.00		Reference flow
Dismantling	p		1.00	Reference flow
Material inputs				
Installation	p	15.00		Reference flow
Materials for treatment				
Dismantling	p	15.00		Reference flow
Recycling				
Steel and iron	ton		257.00	see section 4.1 *Waste treatment*
Aluminium	ton		3.80	Aluminium GLO| recycling| Conseq, U
Electronics	ton		0.45	Electronics scrap RER| treatment of | Conseq, U
Incineration				
Lubricant oil	ton		1.00	Waste mineral oil GLO| market for | Conseq, U
Plastics	ton		1.00	Waste plastic, mixture GLO| market for | Conseq, U
Glass	ton		16.10	Waste glass GLO| Conseq, U
Landfilling				
Electronics	ton		0.45	Electronics scrap RER| treatment of | Conseq, U
Steel and iron	ton		28.50	Inert waste, for final disposal GLO| market for | Conseq, U
Painting	ton		1.40	Waste paint GLO| market for | Conseq, U
Aluminium	ton		0.40	Inert waste, for final disposal GLO| market for | Conseq, U
Plastics	ton		1.70	Waste polyethylene GLO| market for | Conseq, U
Concrete	ton		1,056.00	Waste reinforced concrete GLO| market for | Conseq, U
Energy				
Electricity	MWh		86.62	Electricity, medium voltage ES| market for | Conseq, U

Lifetime

It is assumed that the lifetime of a wind turbine is 20 years. This is based on the design lifetime of the $V90-3$ MW and $G90-2$ MW wind turbines. In sensitivity analysis different scenarios of wind turbine's lifetime are analyzed.

Electricity generation

A medium average wind speed of 8 m/s is considered for Denmark. The $V90-3$ wind turbine is designed to run with medium to high wind speed per year in Denmark [51]. For the baseline scenario it is assumed a medium wind speed of 8 m/s, while in sensitivity analysis the high wind speed conditions are also analyzed. The electricity generation for the Wind$_{DK}$ scenario is 2.1 TWh for the 20 years lifetime with a capacity factor of 40%.

The $G90-2$ MW wind turbine is designed to run from low to medium wind speed, consequently an average low wind speed of 7 m/s is considered for this scenario [15]. The electricity generation for the Wind$_{ES}$ scenario is 1.88 TWh for the 20 years lifetime with a capacity factor of 35.8%.

4.2.2 Assumptions

Assumptions are made in this study, since it is difficult to collect exact data for all the LCA stages. The following assumptions are made for this analysis:

Lifetime
The lifetime of the wind turbine is assumed to be 20 years. It is difficult to forecast the exact lifetime of the wind turbine, for this reason the design life of the wind turbine is included in this study. This assumption is a general for all the LCA studies for wind turbines, however this study is based on two different geographical regions with different weather conditions. Denmark's weather is wet and rainy, which can wear out the wind turbine and reduce its performance. In reality, the capacity factor of the wind turbine is not the same in its entire lifetime. A lot of studies have proved that the capacity factor of wind turbine is decreasing after the age of $12 - 15$ years for a wind turbine in Denmark due to wear and tear [20]. A more realistic scenario of the lifetime of the wind turbine is presented in the sensitivity analysis.

Location and wind speed
It is important to define the wind conditions, as they contribute significantly in the results of the analysis. In this study, it is assumed that the wind plant will be placed at a site with an average wind speed of 8 m/s for Denmark (Wind_{DK}) and an average wind speed of 7 m/s for Spain (Wind_{ES}). This assumption is based on wind-class of each wind turbine and on average wind speed of the area. It is a general assumption, but in reality wind turbines are chosen to be placed in locations with extreme wind speed (i.e. in mountains for the Spanish case). Different scenarios for the location of the wind farm are analyzed in the sensitivity analysis.

Distance to the grid
The distance to the grid is assumed to be 20 km for both scenarios, which is based on Vestas and Gamesa reports. This is a common distance to the grid, however there are cases with less or more than 20 km distance. In the baseline scenario it is chosen an average distance, while in the sensitivity analysis it is presented how this assumption can affect the environmental performance of the plant.

Transport
An average transport distance is assumed for the simplicity of the study, since there is not specific location for the wind farms. For the WF1 scenario it is assumed 200 km distance from the supplier and for the WF2 scenario 400 km distance. These assumptions have been verified from maps, however transport has proved that it is not a significant factor for the life cycle analysis.

4.3 Life cycle Inventory- Solar PV

Solar Photovoltaic converts sunlight directly into electricity. A solar PV system consists of solar cells that are grouped together to a PV Module, and the balance of the system (BOS) which includes the Inverter, the Transformer,the Mounting structures and the electric installation (Figure 4.2). The BOS of open ground PV systems also includes office facilities, fence and grid connections [46], [25].

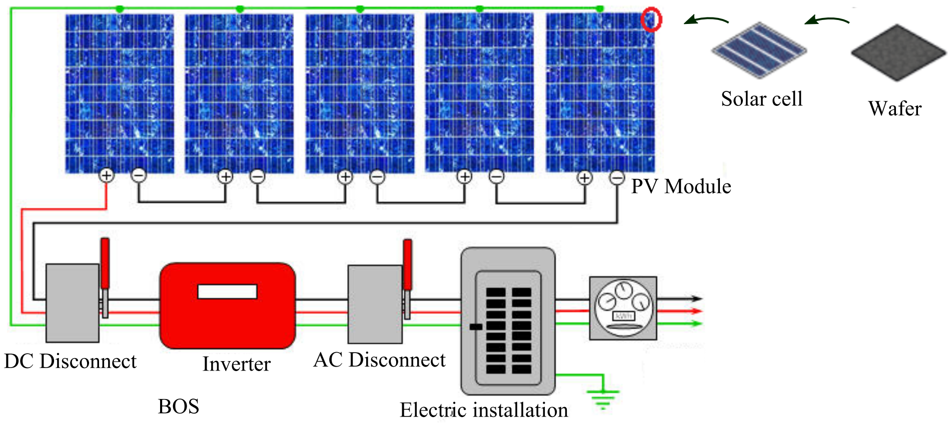


Figure 4.2: Main components of a solar PV system based on [3].

PV module
A number of solar cells are connected to each other and mounted in a support structure, which is called PV Module. Multiple PV Modules can be wired together to form an array. PV Modules are designed to produce direct-current (DC) electricity. Currently, there is a wide range of different types of solar cell technologies on the market. They can be classified into two main categories:

- **Crystalline silicon**

Silicon is an abundant elements in the earth and crystalline silicon has dominated the PV market for several decades. The wafer of the cell can be mono-crystalline silicon (sc-Si), multi-crystalline silicon (mc-Si) or ribbon cast multi-crystalline technology. These are the most common PV technologies in the market and also referred to as first generation technologies [31]. Sc- Si PV Modules have a higher efficiency than mc- Si PV Modules, but mc- Si PV Modules have a lower cost production. The main difference between them is that Sc- Si wafers are from a single silicon, while mc-Si wafers are from different crystals of silicon [31].

The sc-Si wafers have a typical size of $156x156$ mm2 (0.0243 m2) and a thickness of 270 μm. The mc-Si wafers have a typical size of $156x156$ mm2 (0.0243 m2) and a thickness of 240 μm. Each PV Module has 38 cells of $156x156$ mm2. The production of PV Modules with sc-Si or mc-Si are similar [31].

- **Thin film**

Thin-film PV technologies include the amorphous (a-Si) and micromorph silicon ($a - Si/\mu c - S$), Cadmium-Telluride (CdTe), Copper Indium-Selenide (CIS) and Copper Indium-Gallium-Diselenide (CIGS) technologies. These technologies are early developed, not so common in the market and also referred to as second generation technologies [31].

Nowadays, PV market is growing rapidly with crystalline silicon technologies being the predominant PV technology ($85 - 90\%$ of the global annual market). Efficiencies of crystalline silicon PV modules range from $13 - 20\%$ [40]. In addition, considerable progress has been achieved in thin-film (CdTe) PV technologies ($10 - 15\%$ of the global annual market) with an efficiency of $9 - 11\%$ [40]. However, this study put focus only on crystalline silicon technologies (sc-Si and mc-Si), since thin film technologies are not common for open ground solar PV systems in the case study areas.

Balance of the system (BOS)

The balance of system (BOS) includes all components of a photovoltaic system other than the PV Module. These are the Inverter, Transformer, Mounting structures, Electric installation, office facilities, fence, concrete and grid connections [25].

The Inverter is used to convert incoming direct current (DC) electricity from the solar PV Module into to alternating current (AC) electricity used in the grid. The Electric installation is used in order to utilize and distribute the converted electricity to the grid. It is included in a junction box, which is a PV connector system that includes the cables of the PV Modules and the cables of the Inverter. The Mounting structure is used in order to mount the PV Module on the ground [25], [31].

4.3.1 LCA stages-Foreground system for Solar PV

Manufacturing

Inventory data collection for solar PV scenarios has been gathered from existing LCA reports. Assumption are also made, as it is difficult to collect data for all the life cycle stages. In Table 4.8, it is presented the sources used for the LCI analysis of solar PV scenarios. The material inputs for the manufacturing stage of wafer and cell are presented in Tables 4.9 and 4.10.

Table 4.8: Inventory data collection for solar PV scenarios.

Inventory data	**Sources**
Materials inputs for PV System:	
PV Module	[48], [31], [45]
Cell	[48], [31]
Wafer	[48], [31]
Inverter	[48]
Transformer	[48]
Electric installation	[48], [31]
Mounting structure	[48], [31], [25]
Electricity consumption in life cycle stages	[48], [31], [25]
Electricity production of solar PV system	[21]
Waste treatment scenarios	LCA reports (see Table 4.1)
Land occupation	[48], [31]
Fuels consumtion	[48], [31]

Table 4.9: LCI-data for sc-Si and mc-Si Wafer used in manufacturing of solar PV system.

	Unit	sc-Si Wafer	mc-Si Wafer	LCI data
Reference flow				
sc-Si Wafer	m2	1.00		Reference flow
mc-Si Wafer	m2		1.00	Reference flow
Material input				
Silicon carbide	kg	0.49	0.49	Silicon carbide GLO| market for | Conseq, U
Silicon si	kg	1.00		Silicon, single crystal, photovoltaics GLO| market for | Conseq, U
Silicon multi-Si	kg		1.14	Silicon, multi-Si, casted GLO| market for | Conseq, U
Polyethylene	kg	0.30		Polyethylene terephthalate, granulate, GLO| market for | Conseq, U
Dipropylene glycol	kg	0.30	0,30	Dipropylene glycol GLO| market for | Conseq, U
Polystyrene	kg	0.20	0.20	Polystyrene, high impact RER| production | Conseq, U
Sodium hydroxide	kg	0.015	0.01	Sodium hydroxide, without water GLO| market for | Conseq, U
Acetic acid	kg	0.04	0.04	Acetic acid, without water,GLO| market for | Conseq, U
Hydrochloric acid	kg	2.70E-3	2.70E-3	Hydrochloric acid, without water,RER| market for | Conseq, U
Argon	kg	6.20		Argon, liquid GLO| market for | Conseq, U
Triethylene glycol	kg	0.11	2.61	Triethylene glycol GLO| market for | Conseq, U
Glass wool mat	kg	0.01	0.01	Glass wool mat GLO| market for | Conseq, U
Alkylbenzene	kg	0.24	0.24	Alkylbenzene sulfonate, GLO| market for | Conseq, U
Acrylic binder	kg	2.00E-3	2.00E-3	Acrylic binder, without water, GLO| market for | Conseq, U
Packaging film	kg	0.10	0.10	Packaging film, low density polyethylene RER| production | Conseq, U
Low-alloyed Steel	kg	1.48	1.48	Steel, low-alloyed GLO| market for | Conseq, U
Processes				
Wire drawing steel	kg	1.49	1.49	Wire drawing, steel GLO| market for | Conseq, U
Wafer factory	p	4.00E-6	4.00E-6	Wafer factory GLO| market for | Conseq, U
Tap water	kg	6.00E-3	6.00E-3	Tap water RER| market for | Conseq, U
Water deionised	kg	65.00	65.00	Water, deionised, from tap water, at user GLO| market for | Conseq, U
Energy				
Electricity	kWh	8.00	8.00	Electricity, medium voltage DE| market for | Conseq, U
Fuel				
Natural gas	MJ	4.00	4.00	Heat, central or small-scale, natural gas RER| market for| Conseq, U
Emissions to water				
Phosphate	kg	5.00E-4	5.00E-4	Phosphate river
Nitrogen	kg	9.90E-3	9.90E-3	Nitrogen river
Copper	kg	6.00E-5	6.00E-5	Copper river
Lead	kg	3.00E-5	3.00E-5	Lead river
DOC	kg	0.01	0.01	DOC, Dissolved Organic Carbon river
Cadmium	kg	6.00E-6	6.00E-6	Cadmium river
AOX	kg	5.00E-5	5.00E-5	AOX, Adsorbable Organic Halogen as Cl river
BOD5	kg	0.03	0.03	BOD5, Biological Oxygen Demand river
Mercury	kg	6.00E-6	6.00E-6	Mercury river
TOC	kg	0.01	0.01	TOC, Total Organic Carbon river
COD	kg	0.02	0.02	COD, Chemical Oxygen Demand river
Chromium	kg	3.00E-5	3.00E-5	Chromium river
Nickel	kg	6.00E-5	6.00E-5	Nickel river

Table 4.10: LCI-data for sc-Si and mc-Si cell (156x156 mm2) used in manufacturing of solar PV system.

	Unit	sc-Si Cell	mc-Si Cell	LCI data
Reference flow				
sc-Si Cell	p	1.00		Reference flow
mc-Si Cell	p		1.00	Reference flow
Material input				
Silicone	kg	2.90E-5	2.90E-5	Silicone product GLO| market for | Conseq, U
Ethanol	kg	1.60E-5	1.60E-5	Ethanol, without water, from ethylene GLO| market for | Conseq, U
Metallization paste, front side	kg	2.00E-4	2.00E-4	Metallization paste, front side GLO| market for | Conseq, U
Metallization paste, back side	kg	1.00E-4	1.00E-4	Metallization paste, back sideGLO| market for | Conseq, U
Metallization aluminium	kg	1.70E-3	1.70E-3	Metallization paste, back side, aluminium GLO| market for | Conseq, U
Phosphorous chloride	kg	4.00E-5	4.00E-5	Phosphorous chloride GLO| market for | Conseq, U
Ammonia	kg	2.00E-4	2.00E-4	Ammonia, liquid RER| market for | Conseq, U
Nitric acid	kg	6.00E-4	6.00E-4	Nitric acid, without water, GLO| market for | Conseq, U
Calcium chloride	kg	5.00E-4	5.00E-4	Calcium chloride GLO| market for | Conseq, U
Oxygen	kg	2.40E-3	2.40E-3	Oxygen, liquid RER| market for | Conseq, U
Polystyrene	kg	1.00E-5	1.00E-5	Polystyrene, expandable GLO| market for | Conseq, U
Sodium hydroxide	kg	3.60E-3	3.60E-3	Sodium hydroxide, without water GLO| market for | Conseq, U
Acetic acid	kg	7.00E-5	7.00E-5	Acetic acid, without water,GLO| market for | Conseq, U
Phosphoric acid	kg	2.00E-4	2.00E-4	Phosphoric acid, without water, GLO| market for | Conseq, U
Hydrochloric acid	kg	1.10E-3	1.10E-3	Hydrochloric acid, without water,RER| market for | Conseq, U
Fluorine	kg	2.00E-6	2.00E-6	Fluorine, liquid RER| production | Conseq, U
Sodium silicate	kg	1.80E-3	1.80E-3	Sodium silicate, spray powder,GLO| market for | Conseq, U
Titanium	kg	3.00E-8	3.00E-8	Titanium dioxide RER| market for | Conseq, U
Hydrogen fluoride	kg	9.00E-4	9.00E-4	Hydrogen fluoride GLO| market for | Conseq, U
Argon	kg	6.00E-4	6.00E-4	Argon, liquid GLO| market for | Conseq, U
Solvent, organic	kg	3.00E-5	3.00E-5	Solvent, organic GLO| market for | Conseq, U
Nitrogen	kg	0.04	0.04	Nitrogen, liquid RER| market for | Conseq, U
Tetrafluoroethylene	kg	8.00E-5	8.00E-5	Tetrafluoroethylene GLO| market for | Conseq, U
Processes				
Photovoltaic factory	p	2.00E-10	2.00E-10	Photovoltaic panel factory GLO| market for | Conseq, U
sc-Si Wafer	m2	2.43E-2		Table 4.9
mc-Si Wafer	m2		2.43E-2	Table 4.9
Water deionised	kg	0.08	0.08	Water, deionised, from tap water, at user GLO| market for | Conseq, U
Energy				
Electricity	kWh	0.70	0.70	Electricity, medium voltage DE| market for | Conseq, U
Fuel				
Oil	MJ	0.02	0.02	Heat, central or small-scale, other than natural gas RER| Conseq, U
Natural gas	MJ	0.10	0.10	Heat, central or small-scale, natural gas RER| market for| Conseq, U
Emissions to air				
Aluminium	kg	2.00E-5	2.00E-5	Aluminium high. pop.
Hydrogen chloride	kg	6.00E-6	6.00E-6	Hydrogen chloride high. pop.
Hydrogen fluoride	kg	4.80E-8	4.80E-8	Hydrogen fluoride high. pop.
Lead	kg	7.00E-4	7.00E-4	Lead high. pop.
Particulates	kg	2.00E-3	2.00E-3	Particulates, unspecified high. pop.
Silicon	kg	7.00E-5	7.00E-5	Silicon high. pop.
Silver	kg	7.00E-4	7.00E-4	Silver high. pop.
Sodium hydroxide	kg	4.80E-5	4.80E-5	Sodium hydroxide high. pop.
Tin	kg	7.70E-5	7.70E-5	Tin high. pop.
VOC	kg	0.19	0.19	VOC, volatile organic compounds high. pop.

A more detailed analysis of the material inputs and energy used for the manufacturing of PV Module and BOS for both scenarios (Solar$_{DK}$ and Solar$_{ES}$) is presenting in Tables 4.11 and 4.12. It is used $20,689$ PV Modules of 145 WP each for the manufacturing of 3 MW solar PV system. The total area of one PV Module is 1 m2 and includes 38 cells. The total amount of cells used is $786,206$.

The Mounting structure refers to open ground PV systems and includes fence, office facilities and concrete for the mounting of $20,689$ m2 solar PV system. Three Inverters of 1 MW capacity each is used for the manufacturing of the BOS. Furthermore, it is assumed that the cables used for the electric connections are 2.5 mm2. For the connections of the PV Modules it is assumed 1 m cabling for each PV Module and 20 m cabling to connect the PV Modules to the Inverter and to the meter.

Installation

The installation of the solar PV plant includes the installation of the PV Modules and the BOS. Additionally, it is also included the transport of the components to the site and the fuels consumed during this stage. Construction work and land occupation are also included in this stage. The material data is presented in detail in Tables 4.11 and 4.11 for Solar$_{DK}$ and Solar$_{ES}$ scenarios respectively.

Table 4.11: LCI-data for "Installation" and "Manufacturing" of 145 WP sc-Si and mc-Si PV Module in Denmark (Solar$_{DK}$). The BOS has scaled to 1 m2 equal to one PV Module, (p=piece).

	Unit	Installation	Manufacturing sc-Si PV Module	mc-Si PV Module	BOS	LCI data
Reference flow						
Solar PV	p	1.00				Reference flow
sc-Si PV Module	p		1.00			Reference flow
mc-Si PV Module	p			1.00		Reference flow
BOS	p				1.00	Reference flow
Material input						
PV module (sc-Si or mc-Si)	p	1.00				[48], [31], [45]
BOS	p	1.00				[48], [31], [25]
Nickel	kg		1.60E-4	1.60E-4		Nickel, 99.5% GLO| market for | Conseq, U
Copper	kg		0.11	0.11	188.00	Copper GLO| market for | Conseq, U
Silicone	kg		0.12	0.12		Silicone product GLO| market for | Conseq, U
Corrugated board box	kg		1.10	1.10	0.08	Corrugated board box GLO| market for | Conseq, U
Polyethylene	kg		0.30	0.30	0.20	Polyethylene, granulate
Polycarbonate	kg				3.50E-5	Polycarbonate GLO| market for | Conseq, U
Polyvinylchloride	kg				0.01	Polyvinylchloride GLO| market for | Conseq, U
Polystyrene	kg				5.00E-3	Polystyrene, high impact GLO| market for | Conseq, U
Ethylvinylacetate	kg		1.00	1.00		Ethylvinylacetate, foil GLO| market for | Conseq, U
Polyvinylfluoride	kg		0.10	0.10		Polyvinylfluoride, film GLO| market for | Conseq, U
Solar glass	kg		10.00	10.00		Solar glass, low-iron GLO| market for | Conseq, U
Acetone	kg		1.30E-2	1.30E-2		Acetone, liquid GLO| market for | Conseq, U
Lead	kg		5.00E-3	5.00E-3		Lead GLO| market for | Conseq, U
Aluminium	kg		2.60	2.60	4.20	Aluminium alloy, AlMg3 GLO| market for | Conseq, U
Brazing	kg		8.60E-3	8.60E-3		Brazing solder, cadmium free RER| production | Conseq, U
Glass fibre	kg		0.18	0.18	6.00E-3	Glass fibre reinforced plastic GLO| market for | Conseq, U
Lubricating oil	kg		1.60E-3	1.60E-3	0.80	Lubricating oil RER| production | Conseq, U
Vinyl acetate	kg		1.60E-3	1.60E-3		Vinyl acetate GLO| market for | Conseq, U
Methanol	kg		2.11E-3	2.11E-3		Methanol GLO| market for | Conseq, U
1-propanol	kg		8.10E-3	8.10E-3		1-propanol GLO| market for | Conseq, U
Section bar	kg				3.90	Section bar extrusion GLO| market for | Conseq, U
Epoxy	kg				3.50E-5	Epoxy resin, liquid GLO| market for | Conseq, U
Low -alloyed Steel	kg				7.50	Steel, low-alloyed GLO| market for | Conseq, U
Concrete	kg				1.30	Concrete, normal CH| production | Conseq, U
Nylon	kg				0.04	Nylon 6 GLO| market for | Conseq, U
Brass	kg				3.00E-5	Brass GLO| market for | Conseq, U
Alkyd paint	kg				3.00E-3	Alkyd paint, without solvent GLO| market for | Conseq, U
Capacitor	kg				8.40E-6	Capacitor, film type GLO| market for | Conseq, U
Transistor	kg				5.00E-6	Transistor, wired, small size GLO| market for | Conseq, U
Inductor	kg				5.00E-5	Inductor, ring core choke type GLO| market for | Conseq, U
Diode glass	kg				6.00E-6	Diode, glass GLO| market for | Conseq, U
Processes						
Wire drawing copper	kg		0.11	0.11	0.11	Wire drawing, copper GLO| market for | Conseq, U
Section bar rolling	kg				6.10	Section bar rolling, steel GLO| market for | Conseq, U
Zinc coat	m2				0.15	Zinc coat, pieces GLO| market for | Conseq, U
Wire drawing steel	kg				7.50	Wire drawing, steel GLO| market for | Conseq, U
Sheet rolling	kg				0.20	Sheet rolling, steel GLO| market for | Conseq, U
Photovoltaic factory	p		4.00E-6	4.00E-6		Photovoltaic panel factory GLO| market for | Conseq, U
sc-Si Cell	p		38.00			Table 4.10
mc-Si Cell	p			38.00		Table 4.10
Tempering flat glass	kg		10.00	10.00		Tempering, flat glass GLO| market for | Conseq, U
Tap water	kg		21.00	21.00		Tap water RER| market for | Conseq, U
Transport						
Transport	tkm		59,809.00	59,809.00	101,804.00	Transport, lorry 16-32 metric ton GLO| market for | Conseq, U
Energy						
Electricity	kWh	0.01	4.70	4.70	0.60	Electricity, medium voltage DK| market for | Conseq, U
Fuel						
Diesel	MJ	1.90				Diesel, burned in building machine GLO| market for | Conseq, U

Table 4.12: LCI-data for "Installation" and "Manufacturing"of 145 WP sc-Si and mc-Si PV Module in Spain (Solar$_{ES}$). The BOS has scaled to 1 m2 equal to one PV Module, (p=piece).

	Unit	Installation	Manufacturing sc-Si PV Module	mc-Si PV Module	BOS	LCI data
Reference flow						
Solar PV	p	1.00				Reference flow
sc-Si PV Module	p		1.00			Reference flow
mc-Si PV Module	p			1.00		Reference flow
BOS	p				1.00	Reference flow
Material input						
PV module (sc-Si or mc-Si)	p	1.00				[48], [31], [45]
BOS	p	1.00				[48], [31], [25]
Nickel	kg		1.60E-4	1.60E-4		Nickel, 99.5% GLO| market for | Conseq, U
Copper	kg		0.11	0.11	188.00	Copper GLO| market for | Conseq, U
Silicone	kg		0.12	0.12		Silicone product GLO| market for | Conseq, U
Corrugated board box	kg		1.10	1.10	0.08	Corrugated board box GLO| market for | Conseq, U
Polyethylene	kg		0.30	0.30	0.20	Polyethylene, granulate
Polycarbonate	kg				3.50E-5	Polycarbonate GLO| market for | Conseq, U
Polyvinylchloride	kg				0.01	Polyvinylchloride GLO| market for | Conseq, U
Polystyrene	kg				5.00E-3	Polystyrene, high impact GLO| market for | Conseq, U
Ethylvinylacetate	kg		1.00	1.00		Ethylvinylacetate, foil GLO| market for | Conseq, U
Polyvinylfluoride	kg		0.10	0.10		Polyvinylfluoride, film GLO| market for | Conseq, U
Solar glass	kg		10.00	10.00		Solar glass, low-iron GLO| market for | Conseq, U
Acetone	kg		1.30E-2	1.30E-2		Acetone, liquid GLO| market for | Conseq, U
Lead	kg		5.00E-3	5.00E-3		Lead GLO| market for | Conseq, U
Aluminium	kg		2.60	2.60	4.20	Aluminium alloy, AlMg3 GLO| market for | Conseq, U
Brazing	kg		8.60E-3	8.60E-3		Brazing solder, cadmium free RER| production | Conseq, U
Glass fibre	kg		0.18	0.18	6.00E-3	Glass fibre reinforced plastic GLO| market for | Conseq, U
Lubricating oil	kg		1.60E-3	1.60E-3	0.80	Lubricating oil RER| production | Conseq, U
Vinyl acetate	kg		1.60E-3	1.60E-3		Vinyl acetate GLO| market for | Conseq, U
Methanol	kg		2.11E-3	2.11E-3		Methanol GLO| market for | Conseq, U
1-propanol	kg		8.10E-3	8.10E-3		1-propanol GLO| market for | Conseq, U
Section bar	kg				3.90	Section bar extrusion GLO| market for | Conseq, U
Epoxy	kg				3.50E-5	Epoxy resin, liquid GLO| market for | Conseq, U
Low -alloyed Steel	kg				7.50	Steel, low-alloyed GLO| market for | Conseq, U
Concrete	kg				1.30	Concrete, normal CH| production | Conseq, U
Nylon	kg				0.04	Nylon 6 GLO| market for | Conseq, U
Brass	kg				3.00E-5	Brass GLO| market for | Conseq, U
Alkyd paint	kg				3.00E-3	Alkyd paint, without solvent GLO| market for | Conseq, U
Capacitor	kg				8.40E-6	Capacitor, film type GLO| market for | Conseq, U
Transistor	kg				5.00E-6	Transistor, wired, small size GLO| market for | Conseq, U
Inductor	kg				5.00E-5	Inductor, ring core choke type GLO| market for | Conseq, U
Diode glass	kg				6.00E-6	Diode, glass GLO| market for | Conseq, U
Processes						
Wire drawing copper	kg		0.11	0.11	0.11	Wire drawing, copper GLO| market for | Conseq, U
Section bar rolling	kg				6.10	Section bar rolling, steel GLO| market for | Conseq, U
Zinc coat	m2				0.15	Zinc coat, pieces GLO| market for | Conseq, U
Wire drawing steel	kg				7.50	Wire drawing, steel GLO| market for | Conseq, U
Sheet rolling	kg				0.20	Sheet rolling, steel GLO| market for | Conseq, U
Photovoltaic factory	p		4.00E-6	4.00E-6		Photovoltaic panel factory GLO| market for | Conseq, U
sc-Si Cell	p		38.00			Table 4.10
mc-Si Cell	p			38.00		Table 4.10
Tempering flat glass	kg		10.00	10.00		Tempering, flat glass GLO| market for | Conseq, U
Tap water	kg		21.00	21.00		Tap water RER| market for | Conseq, U
Transport						
Transport	tkm		192,121.00	192,121.00	204,643.00	Transport, lorry 16-32 metric ton GLO| market for | Conseq, U
Energy						
Electricity	kWh	0.01	4.70	4.70	0.60	Electricity, medium voltage ES| market for | Conseq, U
Fuel						
Diesel	MJ	1.90				Diesel, burned in building machine GLO| market for | Conseq, U

Operation

Operation includes the maintenance of the solar PV system, which is considered to be the change of lubricant oils, cleaning and 10% replacement of the inverter every 10 years [46], [48]. Transport to the site for maintenance twice per year is also included in this stage.

Dismantling

The dismantling stage refers to the dismantling of the solar PV system and the transport of the components for waste treatment, according to the waste scenarios presented in Table 4.1. The operation and dismantling stages are presented in Tables 4.13 and 4.14 for Solar$_{DK}$ and Solar$_{ES}$ scenarios respectively.

Table 4.13: LCI-data for "Operation" and "Dismantling" of 3 MW solar PV system (sc-Si and mc-Si PV Module) in Denmark, Solar$_{DK}$ scenario, (p=piece).

	Unit	Operation	Dismantling	LCI data
Reference flow				
Solar PV	MWh	68,040.00		Reference flow
Dismantling	p		1.00	Reference flow
Material inputs				
Installation	p	20,689.00		Reference flow
Material for treatment				
Dismantling	p	20,689.00		Reference flow
Recycling				
Steel and iron	kg		3.00	see section 4.1 *Waste treatment*
Aluminium	kg		6.00	Aluminium GLO| recycling| Conseq, U
Incineration				
Lubricant oil	kg		0.80	Waste mineral oil GLO| market for | Conseq, U
Plastics	kg		0.90	Waste plastic, mixture GLO| market for | Conseq, U
Glass	kg		10.60	Waste glassGLO| recycling | Conseq, U
Landfilling				
Steel and iron	kg		0.30	Inert waste, for final disposal GLO| market for | Conseq, U
Painting	kg		6.00E-3	Waste paint GLO| market for | Conseq, U
Aluminium	kg		0.90	Waste aluminium GLO| market for | Conseq, U
Glass	ton		0.60	Waste glass GLO| landfill | Conseq, U
Plastics	kg		0.90	Waste polyethylene GLO| market for | Conseq, U
Silicon	kg		1.40	Waste, from silicon wafer production GLO| market for | Conseq, U
Concrete	kg		1.30	Waste reinforced concrete GLO| market for | Conseq, U
Energy				
Electricity	kWh		9.00E-4	Electricity, medium voltage DK| market for | Conseq, U

Table 4.14: LCI-data for "Operation" and "Dismantling" of 3 MW solar PV system (sc-Si and mc-Si PV Module) in Spain, Solar$_{ES}$ scenario, (p=piece).

	Unit	Operation	Dismantling	LCI data
Reference flow				
Solar PV	MWh	105, 912.00		Reference flow
Dismantling	p		1.00	Reference flow
Material inputs				
Installation	p	20,689.00		Reference flow
Material for treatment				
Dismantling	p	20,689.00		Reference flow
Recycling				
Steel and iron	kg		3.00	see section 4.1 *Waste treatment*
Aluminium	kg		6.00	Aluminium GLO| recycling| Conseq, U
Incineration				
Lubricant oil	kg		0.80	Waste mineral oil GLO| market for | Conseq, U
Plastics	kg		0.90	Waste plastic, mixture GLO| market for | Conseq, U
Glass	kg		10.60	Waste glassGLO| recycling | Conseq, U
Landfilling				
Steel and iron	kg		0.30	Inert waste, for final disposal GLO| market for | Conseq, U
Painting	kg		6.00E-3	Waste paint GLO| market for | Conseq, U
Aluminium	kg		0.90	Waste aluminium GLO| market for | Conseq, U
Glass	kg		0.60	Waste glass GLO| landfill | Conseq, U
Plastics	kg		0.90	Waste polyethylene GLO| market for | Conseq, U
Silicon	kg		1.40	Waste, from silicon wafer production GLO| market for | Conseq, U
Concrete	kg		1.30	Waste reinforced concrete GLO| market for | Conseq, U
Energy				
Electricity	kWh		9.00E-4	Electricity, medium voltage ES| market for | Conseq, U

Lifetime

Lifetime of solar PV system in this study is assumed to be 30 years, according to "*Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*" [46]. The lifetime of the different photovoltaic components is:
Modules: 30 years for mature module technologies (i.e. sc-Si and mc-Si).
Inverters: 30 years with 10% part replacement every 10 years.
Transformers: 30 years lifetime.
Mounting structure: 30 to 60 years life expectancy for ground mount installations.
Cables: 30 years lifetime [46].
However, different scenarios of solar PV systems by varying the lifetime expectancy are analyzed in the sensitivity analysis.

Degradation

The degradation refers to the PV Module efficiency over the life time. In this study, a degradation rate of 80% of the initial efficiency for the 30 years lifetime is used [46].

Electricity generation

The annual specific yield in Denmark is 945 kWh/kWp [21], consequently the electricity production of a 3 MW solar PV system is $68,040$ MWh for the 30 years lifetime. For Spain, the annual specific yield is $1,471$ kWh/kWp [21], which can be translated to $105,912$ MWh electricity production of a 3 MW solar PV system over the lifetime. A degradation rate of 80% is also considered in both scenarios.

4.3.2 Assumptions

The following assumptions are made for the Solar$_{DK}$ and Solar$_{ES}$ scenarios:

Lifetime
Lifetime of solar PV is assumed to be 30 years, as it is used in most LCA studies [46]. However, lifetime is considered to be a significant parameter in the LCA studies for this reason alternative scenarios for lifetime of solar PV systems are included in the sensitivity analysis.

Location
Location is important as it can affect the LCA results. In the baseline scenario an average specific yield is used in both scenarios, while locations with an increased specific yield have been analyzed in the sensitivity analysis.

Transport
Assumptions are made for the transport distance, since there is not a specific location. For the Solar$_{DK}$ scenario an average distance of 150 km is used, while for the Solar$_{ES}$ scenario 300 km distance is used. Different scenarios for transport distance of solar PV scenarios are analyzed in the sensitivity analysis.

Chapter 5

Life Cycle Impact Assessment

Contents

This chapter presents the results from the life cycle impact assessment (LCIA) of the generation of 1 kWh electricity from a 30 MW wind farm and a 3 MW solar PV park in Denmark and Spain. The described results are identified as the most important.

5.1 Main LCA results

The most important impact categories that have been analyzed in this study are presented in Table 5.1.

Table 5.1: Main impact categories, the definition is based on [4], (UES= unprotected ecosystem).

Main Impact categories	Unit	Definition
Human toxicity	kg equivalent	The amount of chloroethylene emitted into air.
Ecotoxicity, aquatic	kg equivalent	The amount of triethylene glycol emitted into water.
Ecotoxicity, terrestrial	kg equivalent	The amount of triethylene glycol emitted into soil.
Eutrophication, aquatic	kg NO3 equivalent	A body of water that exceed the critical load for aquatic. eutrophication (enrichment of a body of water with chemical nutrients).
Eutrophication, terrestrial	m2 UES	The ecosystem area that exceed the critical load for terrestrial. eutrophication (enrichment of a ecosystem with chemical nutrients).
Acidification	m2 UES	The ecosystem area that exceed the critical load for acidification.
Global warming	kg CO2 equivalent	Total contribution to global warming resulting from the emission of one unit of gas relative to one unit of carbon dioxide, 100 years time horizon.
Nature occupation	m2 arable land	The impact on biodiversity from the occupation of one m2 of arable land during one year.
Mineral extraction	MJ extra energy	The future energy requirement for extraction from lower grade ores.
Non-renewable energy	MJ total primary	Total primary non-renewable energy.
Ozone layer depletion	kg eq of CFC-11	The amount of degradation to the ozone layer caused by trichlorofluoromethane.
Photochemical ozone impacts on vegetation	m2*ppm*hours	The product of area of vegetation exposed to the 40 ppb threshold the annual duration of exposure over the threshold, and the accumulated hourly mean ozone concentration over the threshold.
Respiratory inorganics	kg eq PM2.5	The amount of PM 2 .5 into air.
Respiratory organics	pers*ppm*hours	The product of the number of people exposed above the 60 ppb threshold, the annual duration of the exposure above the threshold, and the accumulated hourly mean ozone concentration over the threshold.

As already mentioned in Section 3.1, the functional unit for Wind$_{DK}$ scenario has been defined including the changes of electricity demand in energy system and by using two alternative back up systems, Hydro reservoir and Natural gas. The same assumptions have been considered for Solar$_{DK}$ scenario, since it is also an intermittent system. For Wind$_{ES}$ and Solar$_{ES}$scenarios, the changes in energy system have not taken into account, since there was not data available. The environmental impact results from the whole life cycle stages for the described technologies in Table 3.3, Hydro reservoir and Natural gas technologies have been taken directly from the Ecoinvent 3 dataset. Furthermore, it is assumed that the electricity from Hydro reservoir is imported from Norway (alpine region), as there is not available in Denmark.

In Table 5.2, it is presented the main impact categories for 30 MW wind farm in Denmark and Spain. The Wind$_{ES}$ scenario generally presents higher results compared to the Wind$_{DK}$ scenario. This is due to the reason that wind production is lower in Spain compared to Denmark and the analyzed wind turbine technologies differ in manufacturing materials. In addition, Wind$_{DK}$ scenario including the changes in energy system and Wind$_{DK}$ using Natural gas as regulatory system present significantly higher results compared to the baseline scenario. This can be explained due to the reason that it is also considered the environmental impacts of coal and Natural gas technologies, which have considerable high impacts. On the other hand, Wind$_{DK}$ scenario with Hydro reservoir as regulatory system presents slightly increased results compared to the baseline scenario.

Table 5.2: Main characterized results for Wind$_{DK}$ and Wind$_{ES}$ scenarios.

		Wind$_{DK}$scenario				Wind$_{ES}$scenario
Impact category	**Unit**	**Wind**	**Wind considering changes in energy system**	**Wind with Hydro reservoir as regulatory system**	**Wind with Natural gas as regulatory system**	**Wind**
Global warming	gr CO2-eq/kWh	6.66	118.93	8.83	170.71	8.01
Human toxicity carc.	gr C2H3Cl-eq/kWh	0.27	0.07	0.31	0.62	0.24
Human toxicity, non-carc.	gr C2H3Cl-eq/kWh	0.41	0.30	0.44	0.69	0.33
Ecotoxicity, aquatic	kg TEG-eq w/kWh	0.36	0.76	0.39	2.3	0.35
Ecotoxicity, terrestrial	kg TEG-eq s/kWh	0.29	0.19	0.31	0.31	0.31
Resp1ratory inorganics	gr PM2.5-eq/kWh	0.01	0.05	0.01	0.04	0.01
Ozone layer depletion	mg CFC-11-eq/kWh	4.74E-4	4.18E-3	6.01E-4	0.01	6.81E-4
Nature occupation	m2a/kWh	2.15E-4	7.72E-4	2.58E-4	3.06E-4	3.34E-4
Acidification	m2 UES/kWh	2.91E-4	7.62E-3	4.24E-4	1.87E-3	5.77E-4
Eutrophication, aquatic	gr NO3-eq/kWh	0.11	0.09	0.11	0.14	0.18
Eutrophication, terrestrial	m2 UES/kWh	6.16E-4	4.35E-3	8.3E-4	6.14E-3	8.99E-4
Non-renewable energy	MJ primary/kWh	0.08	1.57	0.01	3.31	0.11
Mineral extraction	MJ extra/kWh	0.01	4.06E-3	0.01	0.01	0.01
Respiratory organics	pers*ppm*h/kWh	7.71E-6	2.10E-5	9.23E-6	3.68E-5	7.81E-6
Photochemical ozone, vegetat.	m2*ppm*h/kWh	0.07	0.25	0.09	0.42	0.08

Tables 5.3, 5.4 and 5.5 present the LCA results for solar PV scenarios in Denmark and Spain. Solar$_{ES}$ scenario has a better performance in all impact categories, especially the CO2 emissions are much lower compared to the Solar$_{DK}$ scenario. In addition, mc-Si solar PV is performing better compared to sc-Si solar PV in both scenarios. Considering the changes in energy system for Solar$_{DK}$ scenario the results are considerable increased compared to the baseline scenario. This is due to the high environmental impacts of the selected regulatory systems. Only Solar$_{DK}$ scenario with Hydro reservoir as regulatory system presents slightly higher results compared to the baseline scenario, since Hydro reservoir has a better environmental performance compared to the others regulatory systems.

Table 5.3: Main characterized results for sc-Si Solar$_{DK}$ scenario, (sc-Si=single crystalline silicon).

Solar$_{DK}$ scenario					
Impact category	**Unit**	**sc-Si PV**	**sc-Si PV considering changes in energy system**	**sc-Si PV with Hydro reservoir as regulatory system**	**sc-Si PV with Natural gas as regulatory system**
Global warming	gr CO2-eq/kWh	75.22	185.67	79.68	392.56
Human toxicity carc.	gr C2H3Cl-eq/kWh	1.70	1.49	1.78	2.4
Human toxicity, non-carc.	gr C2H3Cl-eq/kWh	2.34	2.21	2.42	2.84
Ecotoxicity, aquatic	kg TEG-eq w/kWh	21.81	21.39	21.81	25.39
Ecotoxicity, terrestrial	kg TEG-eq s/kWh	0.98	0.89	1.04	1.05
Respiratory inorganics	gr PM2.5-eq/kWh	0.10	0.14	0.11	0.16
Ozone layer depletion	mg CFC-11-eq/kWh	0.01	0.01	0.01	0.04
Nature occupation	m2a/kWh	0.01	0.01	0.01	0.01
Acidification	m2 UES/kWh	8.57E-3	1.58E-2	8.85E-3	0.01
Eutrophication, aquatic	gr NO3-eq/kWh	0.29	0.16	0.31	0.37
Eutrophication, terrestrial	m2 UES/kWh	7.31E-3	0.01	7.73E-3	0.02
Non-renewable energy	MJ primary/kWh	0.92	2.4	0.96	7.18
Mineral extraction	MJ extra/kWh	0.02	0.02	0.03	0.03
Respiratory organics	pers*ppm*h/kWh	4.92E-5	6.21E-5	5.26E-5	1.06E-4
Photochemical ozone, vegetat.	m2*ppm*h/kWh	0.52	0.70	0.56	1.22

Table 5.4: Main characterized results for mc-Si Solar$_{DK}$ scenario, (mc-Si=multi crystalline silicon).

Solar$_{DK}$ scenario					
Impact category	**Unit**	**mc-Si PV**	**mc-Si PV considering changes in energy system**	**mc-Si PV with Hydro reservoir as regulatory system**	**mc-Si PV with Natural gas as regulatory system**
Global warming	gr CO2-eq/kWh	68.17	178.57	72.75	387.66
Human toxicity carc.	gr C2H3Cl-eq/kWh	1.78	1.57	1.88	2.48
Human toxicity, non-carc.	gr C2H3Cl-eq/kWh	2.31	2.37	2.29	2.86
Ecotoxicity, aquatic	kg TEG-eq w/kWh	21.81	21.39	21.81	25.59
Ecotoxicity, terrestrial	kg TEG-eq s/kWh	0.99	0.89	1.05	1.06
Respiratory inorganics	gr PM2.5-eq/kWh	0.09	0.11	0.09	0.15
Ozone layer depletion	mg CFC-11-eq/kWh	0.01	0.01	0.01	0.04
Nature occupation	m2a/kWh	0.01	0.01	0.01	0.01
Acidification	m2 UES/kWh	7.33E-3	0.01	7.61E-3	0.01
Eutrophication, aquatic	gr NO3-eq/kWh	0.54	0.41	0.56	0.62
Eutrophication, terrestrial	m2 UES/kWh	6.52E-3	0.01	6.94E-3	1.72E-2
Non-renewable energy	MJ primary/kWh	0.87	2.31	0.87	7.12
Mineral extraction	MJ extra/kWh	0.03	0.02	0.03	0.03
Respiratory organics	pers*ppm*h/kWh	4.72E-5	6.01E-5	5.05E-5	1.04E-4
Photochemical ozone, vegetat.	m2*ppm*h/kWh	0.49	0.53	0.49	1.18

Table 5.5: Main characterized results for Solar$_{ES}$ scenario, (sc-Si=single crystalline silicon, mc-Si=multi crystalline silicon).

Solar$_{ES}$ scenario			
Impact category	**Unit**	**sc-Si PV**	**mc-Si PV**
Global warming	gr CO2-eq/kWh	47.74	41.89
Human toxicity carc.	gr C2H3Cl-eq/kWh	1.09	1.10
Human toxicity, non-carc.	gr C2H3Cl-eq/kWh	1.49	1.45
Ecotoxicity, aquatic	kg TEG-eq w/kWh	13.17	13.15
Ecotoxicity, terrestrial	kg TEG-eq s/kWh	0.65	0.65
Respiratory inorganics	gr PM2.5-eq/kWh	0.07	0.05
Ozone layer depletion	mg CFC-11-eq/kWh	7.75E-3	7.71E-3
Nature occupation	m2a/kWh	6.93E-3	6.88E-3
Acidification	m2 UES/kWh	5.51E-3	4.58E-3
Eutrophication, aquatic	gr NO3-eq/kWh	0.19	0.34
Eutrophication, terrestrial	m2 UES/kWh	4.69E-3	4.1E-3
Non-renewable energy	MJ primary/kWh	0.59	0.54
Mineral extraction	MJ extra/kWh	0.01	0.01
Respiratory organics	pers*ppm*h/kWh	3.16E-5	2.95E-5
Photochemical ozone, vegetat.	m2*ppm*h/kWh	0.33	0.31

The results presented in Tables 5.2, 5.3, 5.4 and 5.5 for wind and solar PV scenarios are weighted in order to identify the most significant impact categories. The results have been compiled into the monetary unit of EUR2003 according to the weighting methodology of Stepwise method [5], as already explained in Section 2.1.3.

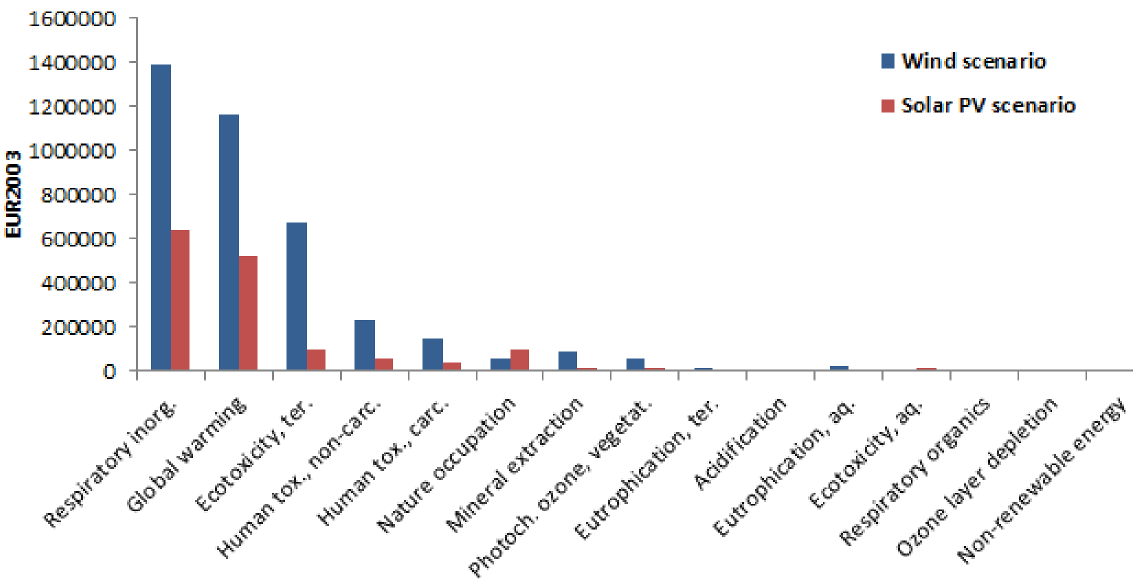


Figure 5.1: Results of Weighting comparison of wind and solar PV scenarios. The most significant impact categories start from the left side and end to the most insignificant.

Figure 5.1 presents the most significant impact categories of wind and solar PV scenarios. The weighting results presented in Table 5.1 refer to Wind$_{DK}$ and Solar$_{DK}$ scenarios respectively, while the same significant impact categories have been also defined with the weighting method for Wind$_{ES}$ and Solar$_{ES}$ scenarios. The most important categories that will be analyzed in detail in the following section are the Respiratory inorganic, Global warming and Ecotoxicity terrestrial.

5.2 Detailed LCA results

This section describes in detail the results of the most significant impact categories for the life cycle stages of wind and solar PV scenarios. A comparison of the different scenarios is also presented.

Respiratory inorganic

Figure 5.2 presents the Respiratory inorganic results for wind and solar PV system scenarios. As it can be see, the Respiratory inorganic is much lower in wind scenarios (0.01 gr PM$2.5eq$/kWh) compared to solar PV scenarios. Considering the changes in energy system, the results for Wind$_{DK}$ scenario can reach the 0.05 gr PM2.5 eq/kWh.

In Solar$_{DK}$ scenario the results are 0.10 gr PM2.5 eq/kWh for sc-Si and 0.09 gr PM2.5 eq/kWh for mc-Si. Furthermore, considering the scenarios with the changes in energy system and with the regulatory systems, the results are in the range of $0.11 - 0.16$ gr PM$2.5eq$/kWh for sc-Si and $0.09 - 0.15$ gr PM$2.5eq$/kWh for mc-Si. For Solar$_{ES}$ scenario, the Respiratory inorganic results are 0.07 gr PM$2.5eq$/kWh for sc-Si and 0.05 gr PM$2.5eq$/kWh for mc-Si.

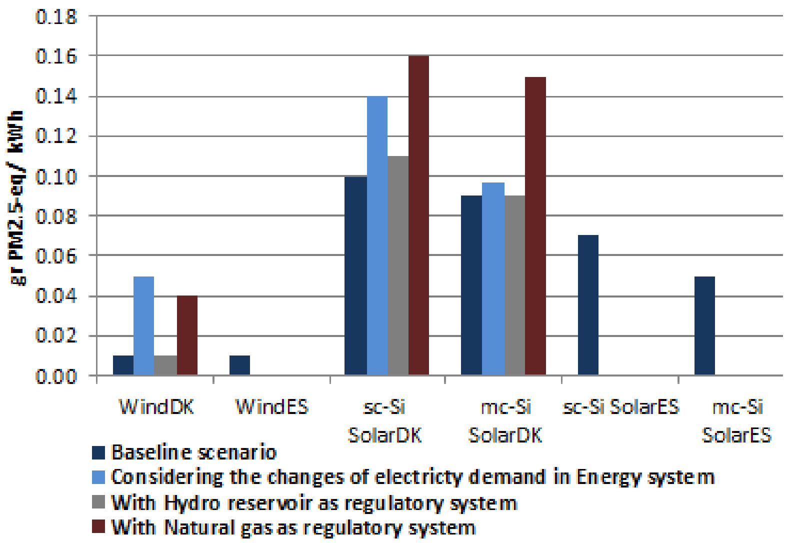


Figure 5.2: Respiratory inorganic for 30 MW wind farm (Wind$_{DK}$ and Wind$_{ES}$ scenarios) and 3 MW solar PV system (Solar$_{DK}$ and Solar$_{ES}$ scenarios) in Denmark and Spain. It is also presented the scenarios with the inclusion of the changes of electricity demand in energy system and the regulatory systems for Denmark. The results are presented per kWh electricity generation.

Global Warming Potential

As it can be seen in Figure5.3, the results for wind scenarios are 6.66 gr CO2eq/kWh for Wind$_{DK}$ and 8.00 gr CO2eq/kWh for Wind$_{ES}$ scenario. Considering the changes in Danish energy system, the results increase at 118.93 gr CO2eq/kWh for Wind$_{DK}$ scenario.

Including the Hydro reservoir as regulatory system, the results are 8.83 gr CO2$eq/$kWh and 170.71 gr CO2$eq/$kWh for using Natural gas as regulatory system.

The solar PV scenarios present generally higher results. In sc-Si Solar$_{DK}$ scenario the CO2 emissions are 75.22 gr CO2$eq/$kWh. Furthermore, including the scenarios with the changes in energy system, Hydro reservoir and Natural gas as regulatory system, the results increase at 185.67 gr CO2$eq/$kWh, 79.68 gr CO2$eq/$kWh for sc-Si and 392.56 gr CO2$eq/$kWh respectively. For mc-Si Solar$_{DK}$ scenario the CO2 emissions are slightly lower than the sc-Si Solar$_{DK}$ scenario (68.17 gr CO2$eq/$kWh).

On he other hand, Solar$_{ES}$ scenario presents significantly better environmental performance compared to Solar$_{DK}$ scenario. The CO2 emissions for Solar$_{ES}$ are $47,74$ gr CO2$eq/$kWh for sc-Si and $41,89$ gr CO2$eq/$kWh for mc-Si solar PV.

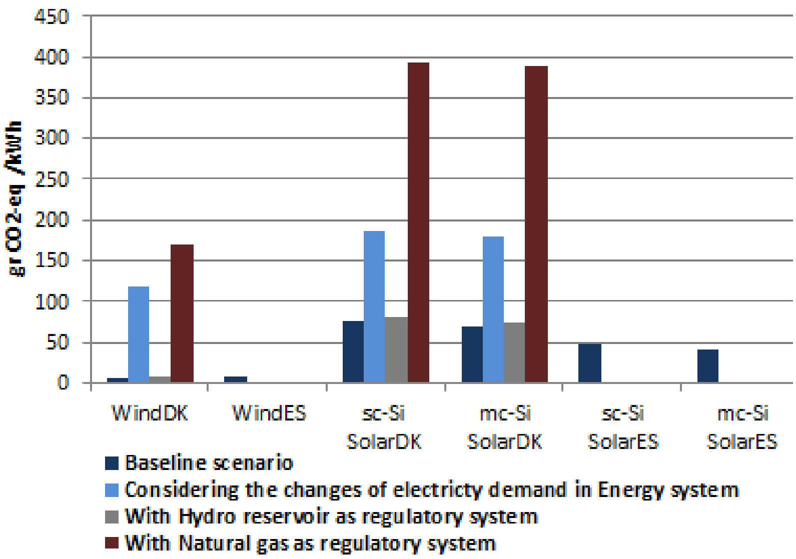


Figure 5.3: Global Warming Potential for 30 MW wind farm (Wind$_{DK}$ and Wind$_{ES}$ scenarios) and 3 MW solar PV system (Solar$_{DK}$ and Solar$_{ES}$ scenarios) in Denmark and Spain. It is also presented the scenario with the inclusion of the changes of electricity demand in energy system the regulatory systems for Denmark for Denmark. The results are presented per kWh electricity generation.

Ecotoxicity terrestrial

Ecotoxicity terrestrial for wind scenarios are almost the same, 0.29 and 0.31 kg TEG-eq/kWh for Wind$_{DK}$ and Wind$_{ES}$ scenarios respectively. Only the Wind$_{DK}$ scenario with the change in energy system presents lower results (0.19 kg TEG-eq/kWh). In Solar$_{DK}$ and Solar$_{ES}$ scenarios, the results are significantly higher. For Solar$_{DK}$ scenario the results are in the range of $0.89 - 1.06$ kg TEG-eq/kWh, while for Solar$_{ES}$ scenarios, the results are 0.65kg TEG-eq/kWh.

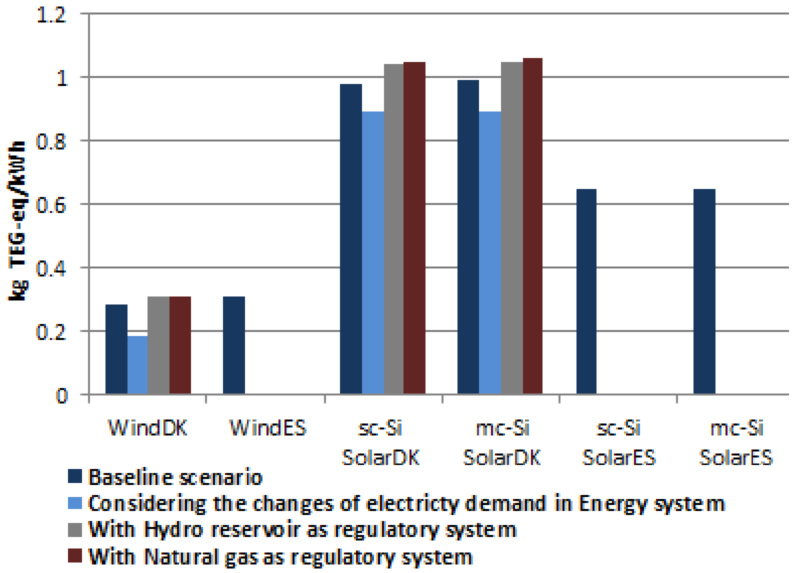


Figure 5.4: Ecotoxicity terrestrial for 30 MW wind farm (Wind$_{DK}$ and Wind$_{ES}$ scenarios) and 3 MW solar PV system (Solar$_{DK}$ and Solar$_{ES}$ scenarios) in Denmark and Spain. It is also presented the scenario with the inclusion of the changes of electricity demand in energy system the regulatory systems for Denmark for Denmark. The results are presented per kWh electricity generation.

LCIA of life cycle stages

According to the goal and scope of this study, the environmental impacts of life cycle stages are important to be analyzed. As it can be seen from Figure 5.5, the life cycle stage with the major impact is the manufacturing stage for both technologies. The installation stage is considerable only for wind scenarios.

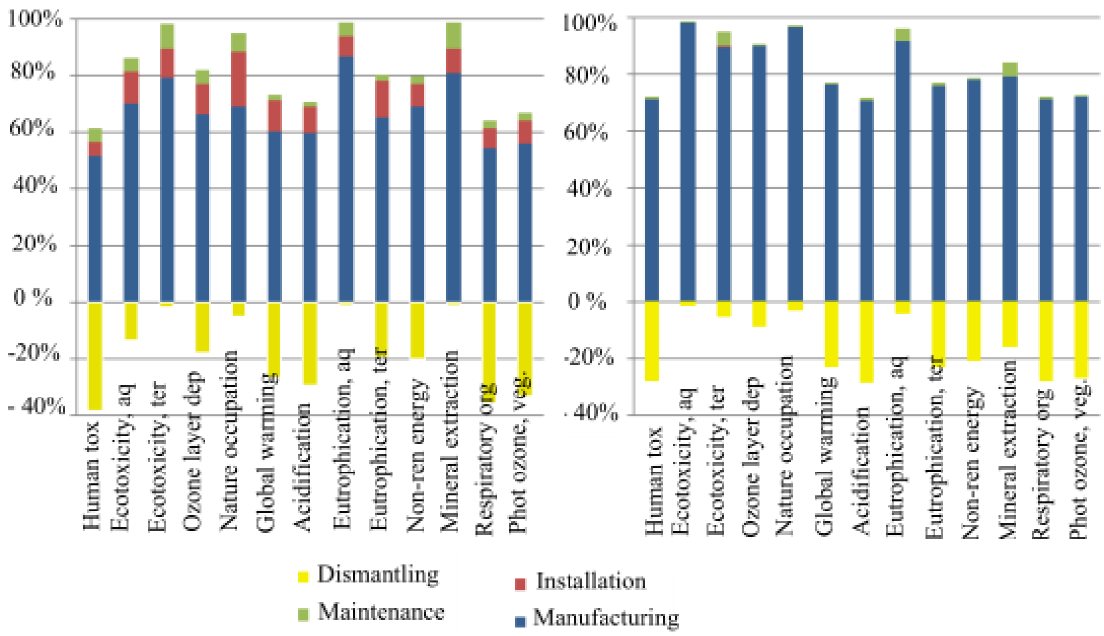


Figure 5.5: LCA results for life cycle stages of 30 MW wind farm (left) and 3 MW solar PV system (right).

Contribution analysis for wind

The contribution analysis of wind scenarios aims to analyze the different components of wind turbine and define the materials that most contribute to the environmental impacts. Figure 5.6 presents the impacts of manufacturing stage of each component for Wind$_{DK}$ scenario. It is notable that Tower is responsible for the high emissions of Global Warming, while Nacelle has higher results in Respiratory inorganic and Ecotoxicity terrestrial. The materials that are responsible for these high environmental impacts are steel and irons, concrete and glass reinforced plastic.

As it can be seen in Figure 5.7, the manufacturing stage of Wind$_{ES}$ scenario presents almost the same performance with Wind$_{DK}$ scenario. Tower has the highest results in Global Warming and Respiratory inorganic, while the results for Nacelle are also considerable in Ecotoxicity terrestrial. The materials with the highest environmental impacts are also steel and concrete.

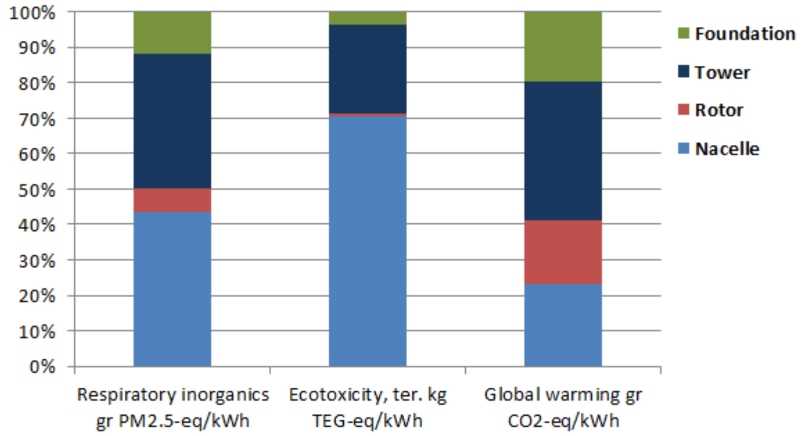


Figure 5.6: Main impact categories for manufacturing stage of wind turbine in Denmark, Wind$_{DK}$ scenario.

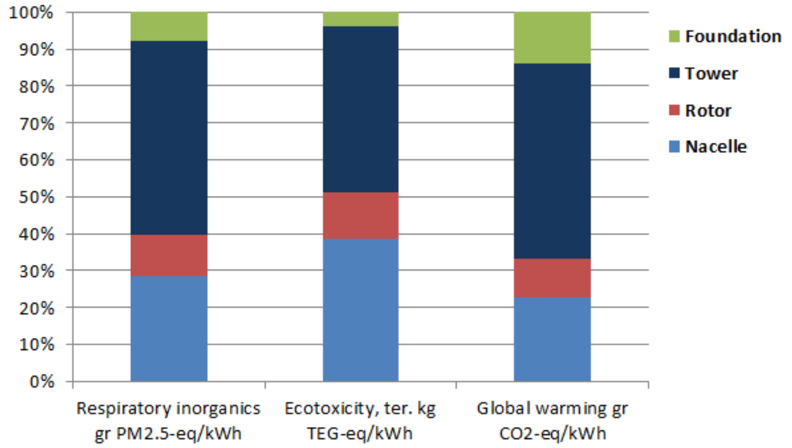


Figure 5.7: Main impact categories for manufacturing stage of wind turbine in Spain, Wind$_{ES}$ scenario.

Contribution analysis for solar PV

The contribution analysis of solar scenarios aims to analyze the solar PV system and present the materials that contribute to low environmental performance of the system. Figures 5.8 and 5.9 present the impacts of manufacturing stage of each component of Solar$_{DK}$ and Solar$_{ES}$ scenario respectively. The PV Module is the component with the highest impact in Global Warming and Respiratory inorganic, while the Mounting structure is also considerable in Ecotoxicity terrestrial. The results of the rest components present insignificant impacts. In addition, the mc-Si PV Module has generally lower results compared to sc-Si PV Module. The materials which present the highest environmental impacts are silicon and aluminium.

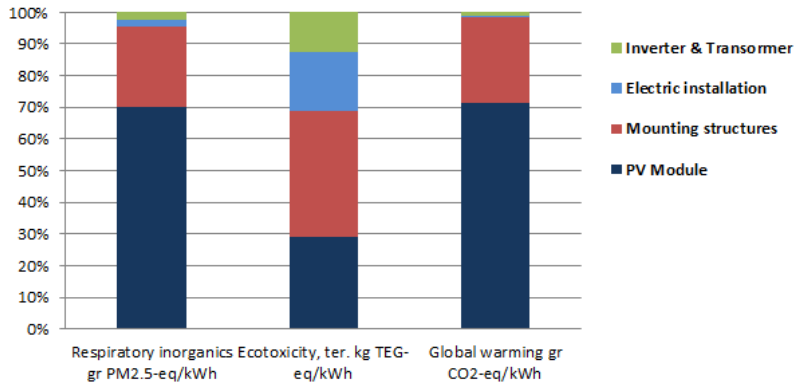


Figure 5.8: Main impact categories for manufacturing stage of solar PV system in Denmark, Solar$_{DK}$ scenario.

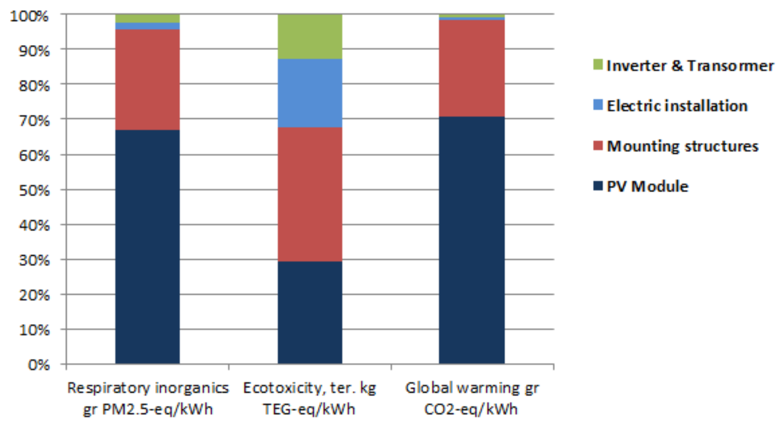


Figure 5.9: Main impact categories for manufacturing stage of solar PV system in Spain, Solar$_{ES}$ scenario.

In conclusion, wind scenarios are performing better than solar PV scenarios. Comparing Wind$_{DK}$ and Wind$_{ES}$ scenarios, the Wind$_{DK}$ presents lower results in all impact categories which means that wind production has a better performance in Denmark than in Spain. The manufacturing stage of wind turbine is mainly responsible for the low environmental performance of wind turbine and especially Tower has the highest environmental impacts.

Furthermore, Solar$_{ES}$ scenario presents a better environmental performance compared to the Solar$_{DK}$ scenario due to the better solar conditions in Spain. The manufacturing stage of solar PV system has the highest emissions and it is responsible for the low environmental performance of solar PV system. The PV Module has the highest results and then follows the Mountain structure, while the rest components present an insignificant environmental impact. In addition, mc-Si solar PV technology presents a considerable better environmental performance compared to sc-Si solar PV technology .

Chapter 6

Sensitivity Analysis

Contents

Sensitivity analysis aims to evaluate the assumptions made throughout the goal and scope definition and LCI analysis. It is always important to contact a sensitivity analysis in order to assess the importance of possible uncertainties in data and how these uncertainties can affect the results. In this study, the sensitivity analysis is based on two main categories:

- Evaluation of assumptions made in LCI analysis, which aims to define in what extent the results can be affected.

- Assessment of different parameters in the analyzed scenarios, which aims to present the differences among the different geographical regions.

6.1 Sensitivity analysis for wind scenarios

The sensitivity analysis for wind power plant is based on the following scenarios:

1. Lifetime of wind turbine
2. Distance to the grid
3. Transport
4. Maintenance of wind turbine
5. Wind farm location and wind conditions
6. Waste treatment-recycling

Lifetime of wind turbine

In the baseline scenario, it is assumed 20 years lifetime of wind turbine based on the designed lifetime. In reality, the lifetime of the turbine can reach the 30 years. Figure 6.1 presents how the lifetime can affect the environmental performance of wind turbine. It is notable that all impact categories have a significant reduction, especially the CO2 emissions. Considering 30 years lifetime, the CO2 emissions reduce at 4.49 gr CO2eq/kWh for Wind$_{DK}$ scenario and 5.39 gr CO2eq/kWh for Wind$_{ES}$ scenario.

Furthermore, for Wind$_{DK}$ scenario it is also considered an alternative scenario with a reduction of capacity factor after the age of 15 years. It has been proved that due to weather conditions in Denmark wind turbines wear and tear after the age of 15 years [20], therefore their efficiency will not be the same in their entire lifetime of 30 years.

However, the results present insignificant changes compared to the alternative scenario with 30 years lifetime (Figure 6.1).

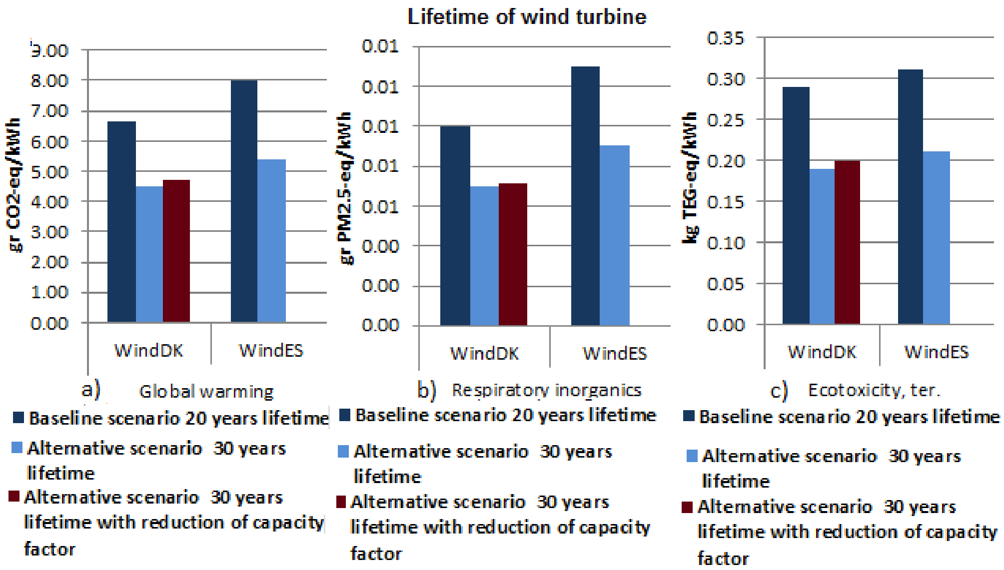


Figure 6.1: (Left) a) Global warming results for 20 (baseline scenario) and 30 (alternative scenario) years lifetime of wind turbine, **(Middle) b)** Respiratory inorganics results for 20 and 30 years lifetime of wind turbine, **(Right) c)** Ecotoxicity terrestrial results for 20 and 30 years lifetime of wind turbine for Wind_{DK} and Wind_{ES} scenarios.

Distance to the grid

Two alternative scenarios were analyzed for the distance to the grid, as it can be seen in Figure 6.2. In the baseline scenario, it is considered 20 km distance, while considering 10 km distance the results present an insignificant change. On the other hand, considering 50 km distance to the grid the results are slightly higher.

Transport

Different scenarios for transport distance were also analyzed. The results are not presented, since they do not appear any considerable change compared to the baseline scenario. Insignificant changes in the results appear by considering more than 600 km transport distance. Therefore, it can be assumed that transport is not a significant factor for this LCA study.

Maintenance of wind turbine

For the wind turbine's maintenance, two different scenarios were analyzed (Figure 6.3). The first one refers to change of only the lubricant oils in the entire lifetime and the results were slightly lower. The second scenario refers to the chance of the lubricant oils, 1 Gearbox and 1 Transformer resulting to no changes compared to the baseline scenario.

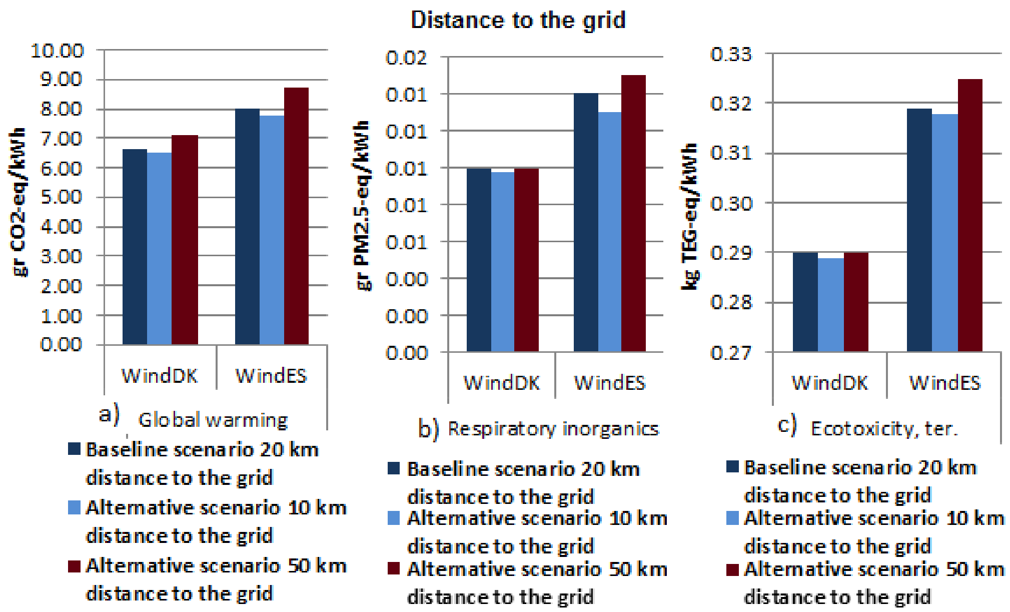


Figure 6.2: (Left) a) Global warming results for 20 km (baseline scenario), 10 km (alternative scenario) and 50 km (alternative scenario) distance to the grid, **(Middle) b)**Respiratory inorganics results for 20 km, 10 km and 50 km distance to the grid, **(Right) c)** Ecotoxicity terrestrial results for 20 km, 10 km and 50 km distance to the grid for Wind$_{DK}$ and Wind$_{ES}$ scenarios.

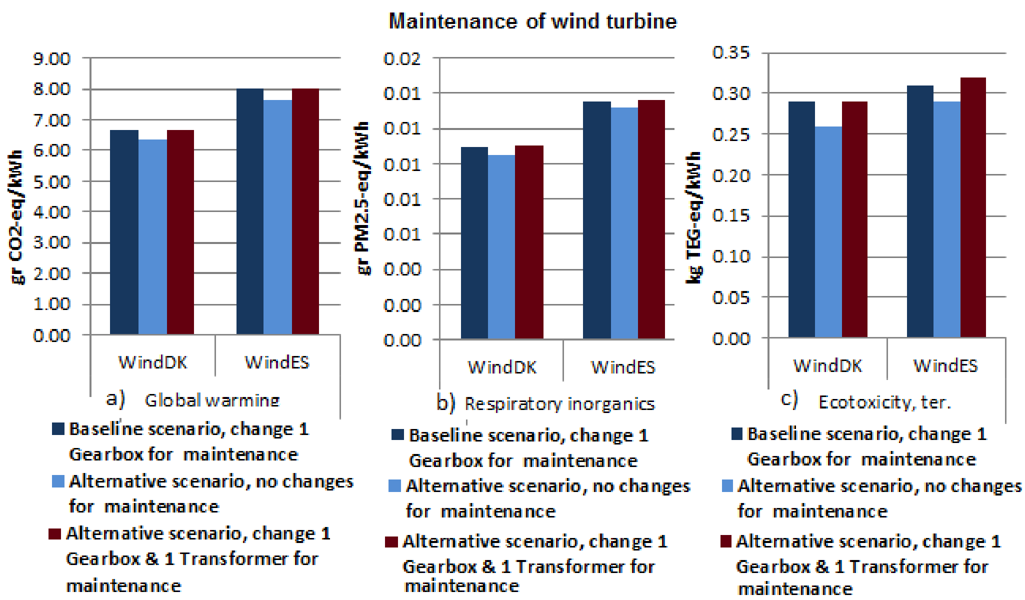


Figure 6.3: (Left) a) Global warming results for change of 1 Gearbox for maintenance (baseline scenario), no changes for maintenance (alternative scenario) and change of 1 Gearbox and 1 Transformer for maintenance (alternative scenario), **(Middle) b)**Respiratory inorganics results for change of 1 Gearbox for maintenance, no changes for maintenance and change of 1 Gearbox and 1 Transformer for maintenance, **(Right) c)** Ecotoxicity terrestrial results for change of 1 Gearbox for maintenance, no changes for maintenance and change of 1 Gearbox and 1 Transformer for maintenance for Wind$_{DK}$ and Wind$_{ES}$ scenarios.

Location and wind speed

The location of the wind turbine is important as it defines the wind speed and therefore, it can affect the results. In Figure 6.4 it is presented the baseline scenario with an average wind speed of 8 m/s for $Wind_{DK}$ and 7m/s for $Wind_{ES}$ scenario. In Spain, it is also possible to place wind turbines in mountains where the wind speed can reach the 14m/s (3.5m/s -14m/s) [28]. Therefore, as alternative scenario it is considered a wind speed of 9m/s (average of 3.5m/s -14m/s) for $Wind_{ES}$ scenario. The same consideration is also made for $Wind_{DK}$ scenario, assuming that the wind turbine is placed in West, which is the most windy part of the country [11]. The results presented in Figure 6.4 show a significant reduction in $Wind_{ES}$ scenario, while in $Wind_{DK.0}$ scenario there is a slightly decrease of the results.

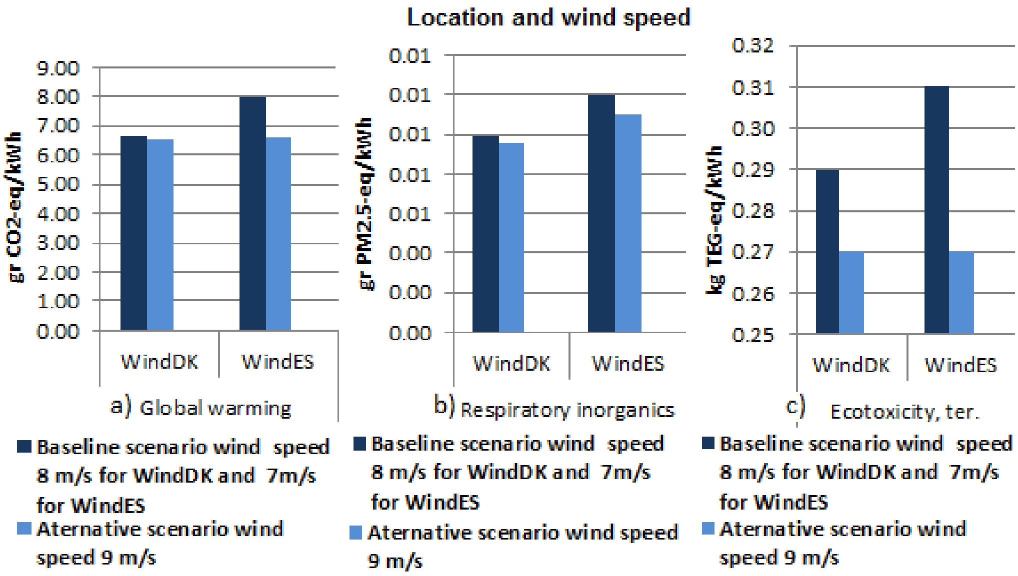


Figure 6.4: (Left) a) Global warming results for wind speed 8 m/s for $Wind_{DK}$ and 7m/s for $Wind_{ES}$ (baseline scenario), 9 m/s (alternative scenario), **(Middle) b)**Respiratory inorganics results for wind speed 8 m/s for $Wind_{DK}$ and 7m/s for $Wind_{ES}$, 9 m/s, **(Right) c)** Ecotoxicity terrestrial results for wind speed 8 m/s for $Wind_{DK}$ and 7m/s for $Wind_{ES}$, 9 m/s for $Wind_{DK}$ and $Wind_{ES}$ scenarios.

Waste treatment-recycling

Different scenarios for waste treatment are also analyzed. The different scenarios refer to 98% and 80% waste treatment of recycled materials (metals). The results presented in Figure 6.5 show insignificant changes for $Wind_{DK}$ scenario, while for $Wind_{ES}$ scenario the results are slightly increased by considering 80% waste treatment of recycled materials. Furthermore, one more alternative scenario considering 100% recycling of plastics is analyzed. However, the results do not appear any important change, for this reason they are not presented.

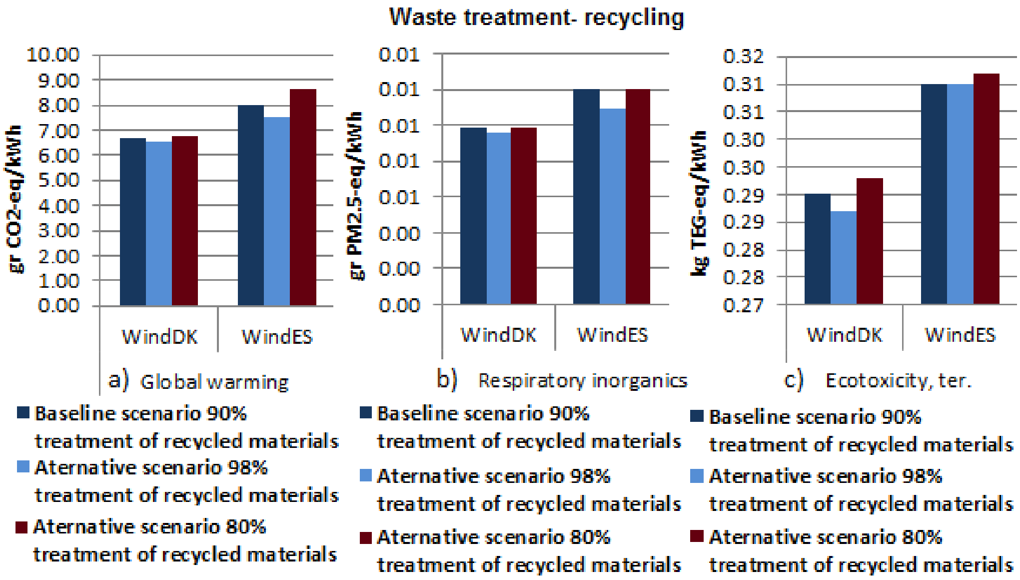


Figure 6.5: (Left) a) Global warming results for 90% treatment of recycled materials (baseline scenario), 98% treatment of recycled materials (alternative scenario) and 80% treatment of recycled materials (alternative scenario), **(Middle) b)** Respiratory inorganics results for 90% treatment of recycled materials, 98% treatment of recycled materials and 80% treatment of recycled materials, **(Right) c)** Ecotoxicity terrestrial results for 90% treatment of recycled materials, 98% treatment of recycled materials and 80% treatment of recycled for Wind$_{DK}$ and Wind$_{ES}$ scenarios.

6.2 Sensitivity analysis for solar PV scenarios

The sensitivity analysis for solar PV system is based on the following scenarios:

1. Lifetime of solar PV.
2. Degradation rate.
3. Maintenance of solar PV.
4. Transport.
5. Location and annual specific yield.
6. Waste treatment-recycling.

Lifetime of solar PV

For the baseline scenario it is considered 30 years lifetime of solar PV system. In this section different scenarios of 40 and 25 years lifetime are analyzed. Figure 6.6 presents the results of the different scenarios. Considering 40 years lifetime, the CO2 emissions reduce considerable at 56.41 and 51.13 gr CO2eq/kWh for sc-Si and mc-Si Solar$_{DK}$ scenario respectively. For the Solar$_{ES}$ the results reduce at 35.81 gr CO2eq/kWh for sc-Si and 31.42 gr CO2eq/kWh for mc-Si. The Respiratory inotganics and Ecotoxicity terrestrials have also a significant decrease. On the other hand, considering 25 years lifetime, the CO2 emissions increase at 90.27 and 81.81 gr CO2eq/kWh for sc-Si and mc-Si Solar$_{DK}$ scenario respectively. In Solar$_{ES}$ the results reach the number of 57.27 and 50.27 gr CO2eq/kWh for sc-Si and mc-Si respectively. The rest analyzed impact categories have also a considerable increase compared to the baseline scenario.

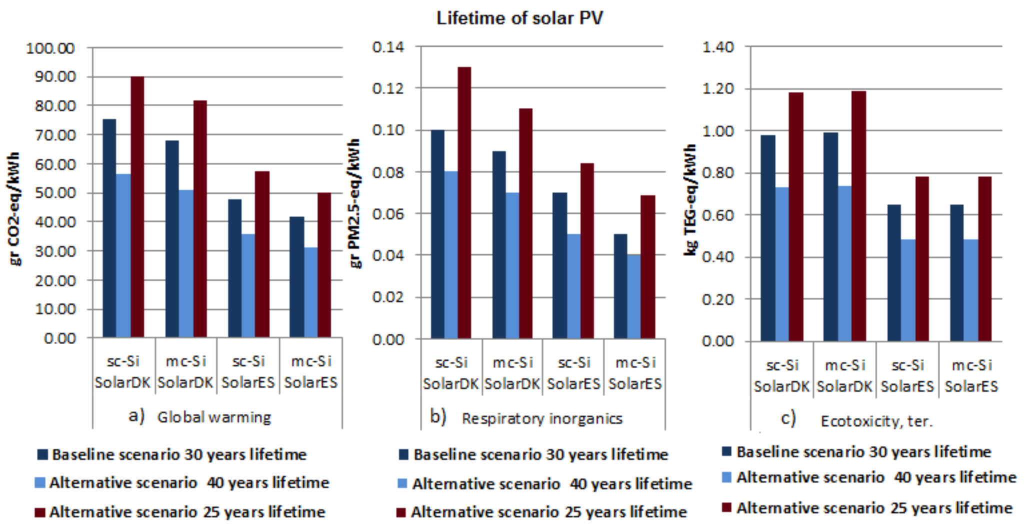


Figure 6.6: (Left) a) Global warming results for 30 (baseline scenario), 40 (alternative scenario) and 25 (alternative scenario) years lifetime of solar PV system, **(Middle) b)** Respiratory inorganics results for 30, 40 and 25 years lifetime of solar PV system, **(Right) c)** Ecotoxicity terrestrial results for 30, 40 and 25 years lifetime of solar PV system for Solar$_{DK}$ and Solar$_{ES}$ scenarios.

Degradation rate

The degradation rate refers to the efficiency of solar PV system in the entire lifetime. The alternative analyzed scenarios are assumed to be 90% and 70% degradation rate of solar PV system. Considering 90% degradation rate, the results presented in Figure 6.7 are slightly lower compared to the 80% in the baseline scenario. On the other hand, considering 70% degradation rate the results increase significantly, as it can be seen in Figure 6.7.

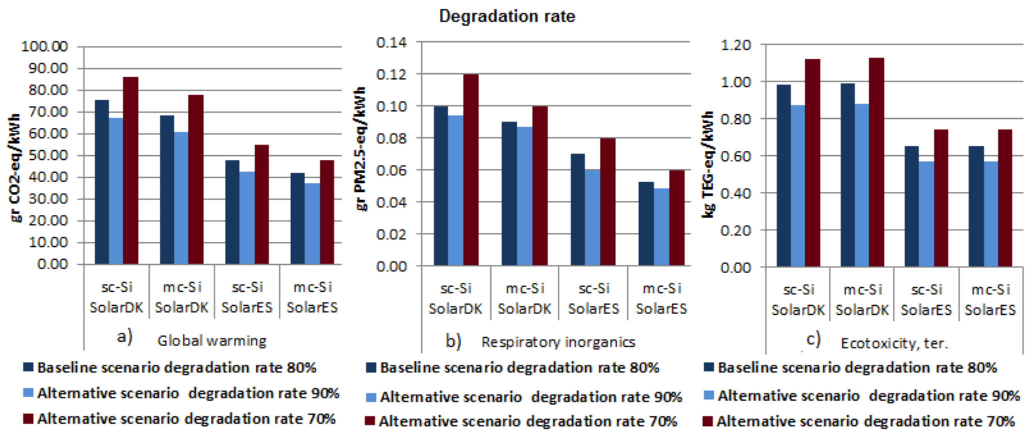


Figure 6.7: (Left) a) Global warming results for 80% (baseline scenario), 90% (alternative scenario) and 70% (alternative scenario) degradation rate of solar PV system, **(Middle) b)** Respiratory inorganics results for 80%, 90% and 70% degradation rate of solar PV system, **(Right) c)** Ecotoxicity terrestrial results for 80%, 90% and 70% degradation rate of solar PV system for Solar$_{DK}$ and Solar$_{ES}$ scenarios.

Maintenance of solar PV

Two different scenarios were analyzed for the solar PV system's maintenance, as it can be seen in Figure 6.8. The first one refers to no change of the inverter in the entire lifetime and the results present an insignificant decrease compared to the baseline scenario. The second scenario refers to the chance of 1 inverter, while the baseline scenario refers to 10% change of the inverter every 10 years. The results in this case are slightly increased compared to the baseline scenario.

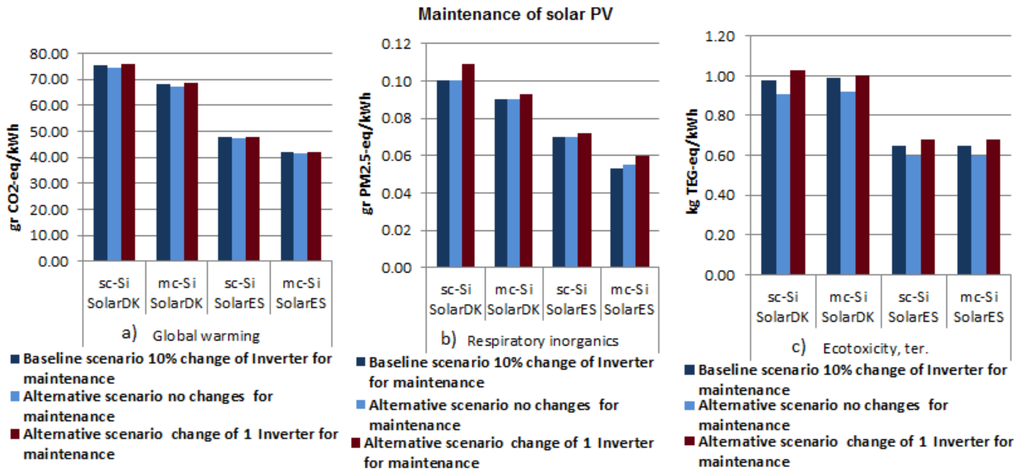


Figure 6.8: (Left) a) Global warming results for 10% change of Inverter for maintenance (baseline scenario), no changes for maintenance (alternative scenario) and change of 1 Inverter for maintenance (alternative scenario), **(Middle) b)**Respiratory inorganics results for 10% change of Inverter for maintenance, no changes for maintenance and change of 1 Inverter for maintenance, **(Right) c)** Ecotoxicity terrestrial results for 10% change of Inverter for maintenance, no changes for maintenance and change of 1 Inverter for maintenance for Solar$_{DK}$ and Solar$_{ES}$ scenarios.

Transport

The alternative scenarios for transport distance in solar PV scenarios do not present any important changes. The results can only be affected by increasing the transport distance more than 600 km. This can conclude that transport is not an important factor in this LCA study, as already mentioned in the previous section (Section 6.1).

Location and annual specific yield

For Solar$_{ES}$ scenarios, two different locations for the solar PV system are analyzed. The first one refers to a solar PV system in the South part of the country, where the annual specific yield is higher compared to the baseline scenario. The second scenario refers to a solar PV system in the North part of the country, where the annual specific yield is significant lower. The results presented in Figure 6.9 are considerable higher for the second alternative scenario in North Spain, while the alternative scenario in South Spain presents a slightly better environmental performance compared to the baseline scenario.

The annual specific yield in Denmark for different locations does not present any considerable change. Therefore, the results for alternative locations for Solar$_{DK}$ scenario are not presented, since the changes are insignificant.

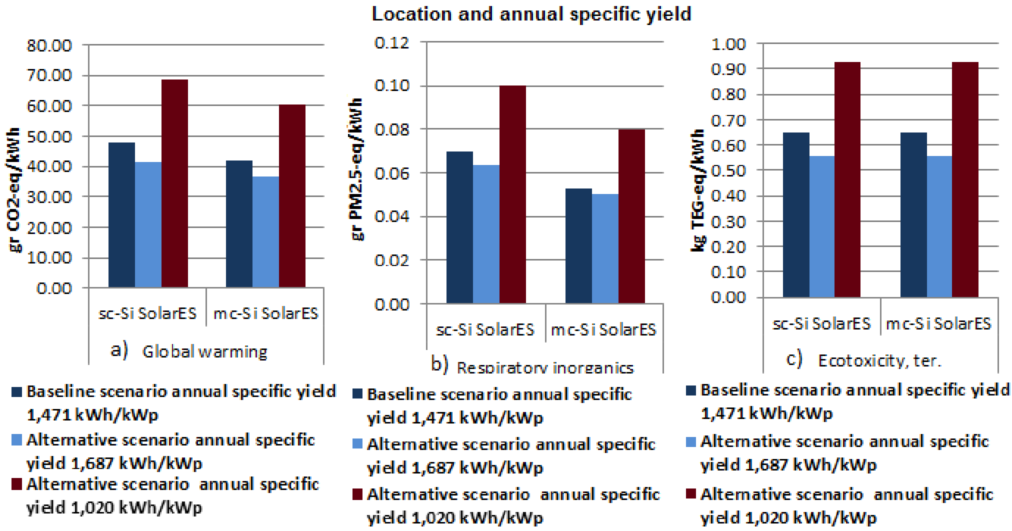


Figure 6.9: (Left) a) Global warming results for annual specific yield 1,471 kWh/kWp (baseline scenario), 1,687 kWh/kWp (alternative scenario) and 1,020 kWh/kWp (alternative scenario), **(Middle) b)** Respiratory inorganics results for annual specific yield 1,471 kWh/kWp, 1,687 kWh/kWp and 1,020 kWh/kWp, **(Right) c)** Ecotoxicity terrestrial results for annual specific yield 1,471 kWh/kWp, 1,687 kWh/kWp and 1,020 kWh/kWp based on [42] for Solar$_{ES}$ scenarios.

Waste treatment-recycling

The different scenarios for waste treatment refer to 98% and 80% treatment of recycled materials (metals), as well as 100% recycling of plastics. The results appear insignificant changes, for this reason they are not presented.

6.3 Conclusion on the sensitivity analysis

The sensitivity analysis results show that in general Wind$_{DK}$ scenario is performing better compared to Wind$_{ES}$ scenario. On the other hand, the sensitivity analysis results for solar PV scenarios appear that Solar$_{ES}$ scenario presents lower environmental impacts compared to Solar$_{DK}$ scenario. In addition, most assumptions and uncertainties affect the results insignificantly. The most important parameters that can improve the environmental performance of wind and solar PV technologies are:

- Lifetime
- Location for Wind$_{ES}$ and Solar$_{ES}$ scenarios.

Chapter 7

Evaluation

Contents

In the interpretation phase it is also included the sensitivity, completeness and consistency check in order to evaluate the LCA results.

7.1 Sensitivity check

The sensitivity check includes a sensitivity analysis in order to evaluate how assumptions, uncertainties and LCIA methods can affect the results [22]. As already mentioned in Section 6.3, the parameters that can affect significantly the results are:

- Lifetime, and
- Location for Wind$_{ES}$ and Solar$_{ES}$ scenarios.

7.2 Completeness check

The completeness check aims to ensure if all the required data used in the LCA processes is sufficient for the interpretation of the results [22]. In this study, the processes that are not included in the calculations can be considered to be the indirect land use change (iLUC) and the services. Due to the occupied land, the demand for crops need to be covered from other regions. The indirect land use change (iLUC) refers to the link between the demand for crops in one region and the environmental impacts in other regions [24]. In addition, Services can be considered as the marketing, sales, cleaning and in general all the energy system services. Furthermore, uncertainties in transport distance and location of the power plant can also be considered, therefore assumptions are made. However, it is concluded from the sensitivity analysis that transport is not a significant factor, while location is important only for Wind$_{ES}$ and Solar$_{ES}$ scenarios.

7.3 Consistency check

The consistency check aims to verify if the assumptions, methods and data are consistent with the goal and scope of the LCA [22]. This LCA study has followed the methodology framework explained in Section2.1, based on ISO14044 standards. This study can be characterized as a consistent, since high quality data has been used throughout the study, taken from only one dataset (Ecoinvent 3). Furthermore, the consequential modeling approach has been applied, where the consequences of the co-products are also included.

Chapter 8

Conclusion

Life cycle Assessment is important for measuring the environmental performance of a product system. This study aims to analyze the life cycle stages of wind and solar PV technologies in two different geographical regions, Denmark and Spain. The goal and scope of this study is to assess the life cycle stages of these technologies, compare their environmental impacts into the different geographical regions and define which parameters can improve their performance.

The LCIA results indicate that wind is performing better than solar PV. In addition, wind turbine technology in Spain appears higher environmental impacts compared to Denmark. The CO2 emissions for wind scenario in Spain are 21% higher than in Denmark. This can be explained due to Denmark's higher wind potential compared to Spain. On the other hand, solar PV in Spain appears significantly better performance compared to solar PV in Denmark, which is also based on different weather conditions. The CO2 emissions of solar PV in Denmark are almost 60% higher than in Spain.

For the scenarios in Denmark, the changes of electricity demand in order to cover the demand of consumption is also included. The alternative scenarios analyzed refer to the inclusion of the changes of electricity demand based on danish energy mix and the use of Hydro reservoir or Natural gas as regulatory system. The results of these scenarios present considerably higher environmental impacts. This can be explained due to the increased environmental impacts of coal and Natural gas. It is also important to mention that solar PV scenario with Natural gas as regulatory system appears extremely high CO2 emissions due to the fact that the need of regulatory system for solar PV production in Denmark is high (60%). Only the use of Hydro reservoir as regulatory system can slightly affect the environmental impacts on the baseline scenario.

The contribution analysis for wind turbine, indicates that the manufacturing stage has the highest environmental impacts and specifically, Tower is the component with the highest environmental impact. On the other hand, the contribution analysis for solar PV shows that the PV Module in the manufacturing stage is responsible for the increased environmental impacts.

Sensitivity analysis assesses how the assumptions and uncertainties of the study can affect the result. The most important parameters are defined to be:

- Lifetime - Extended lifetime can significantly reduce the environmental impacts.
- Location - Considering ideal locations for wind turbines and solar PV systems, the environmental performance of the power plant can be improved considerably.

Finally, the most significant issues that can be concluded from this study are defined to be the following:

- Wind turbine has better environmental performance than solar PV.
- The manufacturing stage is responsible for the increased environmental impacts.

- Geographical region can affect significantly the environmental performance of the power plant.
- Lifetime and location are the parameters that can improve the performance of the power plant.
- The influence of using Hydro reservoir as a regulatory system is relatively smaller in comparison to the use of Natural gas.

Future work

The work could be improved in many directions, if there was not time limitation. The suggestions for future work which can be investigated are:

- **Energy system modeling:** A detailed analysis of the changes of electricity demand in energy system with current data is not made, due to the time limitation. The energy system modeling including the changes of electricity demand by installing wind or solar PV capacity, would be interesting for both geographical regions. This would result to a better reflection and comparison of the environmental performance of the analyzed technologies.
- **Processes that are not included:** Processes that are not included in the LCA analysis and would be interesting to be included is the indirect land use change (iLUC). In addition, services and office facilities would be also possible to be included in the analysis.

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