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Bachelor Thesis

Analysis of various power generation technologies

Alejandra Gómez Ballester

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Examiner: Prof. Dr.-Ing. Martin Kaltschmitt

Second Examiner: Jerrit Hilgedieck

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Declaration of independence

I hereby certify that I have written this work independently and that I have not used any sources and aids other than those indicated, that all statements taken from other writings verbatim or in the same sense have been marked and that the work in the same or similar version was not yet part of a study or examination performance.

Hamburg at 11.09.2019

Alejandra Gómez Ballester

Preface

This Bachelor thesis was written at the Institute for Environmental Technology and Energy Economics at the Technical University of Hamburg.

Hamburg at 11.09.2019

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Nomenclature

Abbreviations

AEP	Annual Energy Production
AC	Alternating Current
CN	China
CO2	Carbon Dioxide
DC	Direct Current
e.g.	For example
GHG	Greenhouse Gas
GWP	Global Worming Potential
i.e.	that is to say
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kWp	kilowatts peak
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
PV	Photovoltaic
RER	Europe
RoW	Rest of the World

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1 Introduction

Environmental problem broke into the political agenda and public debate some decades ago. Late facts as Greta Thunberg's "Fridays for Future" are making increase the environmental awareness in response to the rather inefficient environmental measures and policies taken after climate summits as Copenhagen summit of 2009 or Paris agreements in 2016.

Climate change is nowadays a hot topic and it is generally sustained by scientific community. For instance, IPCC (Intergovernmental panel on climate change) published a report of 400 sheets that provide some data to help governments in taking decisions [1]. Their constate is clear: an augmentation of 1.5°C would be dramatic for the biodiversity and regarding major climates disasters in daily human's life.

In the graph it can be observed the reality of global warming with a significantly increase of 1 degree in only 1 century.

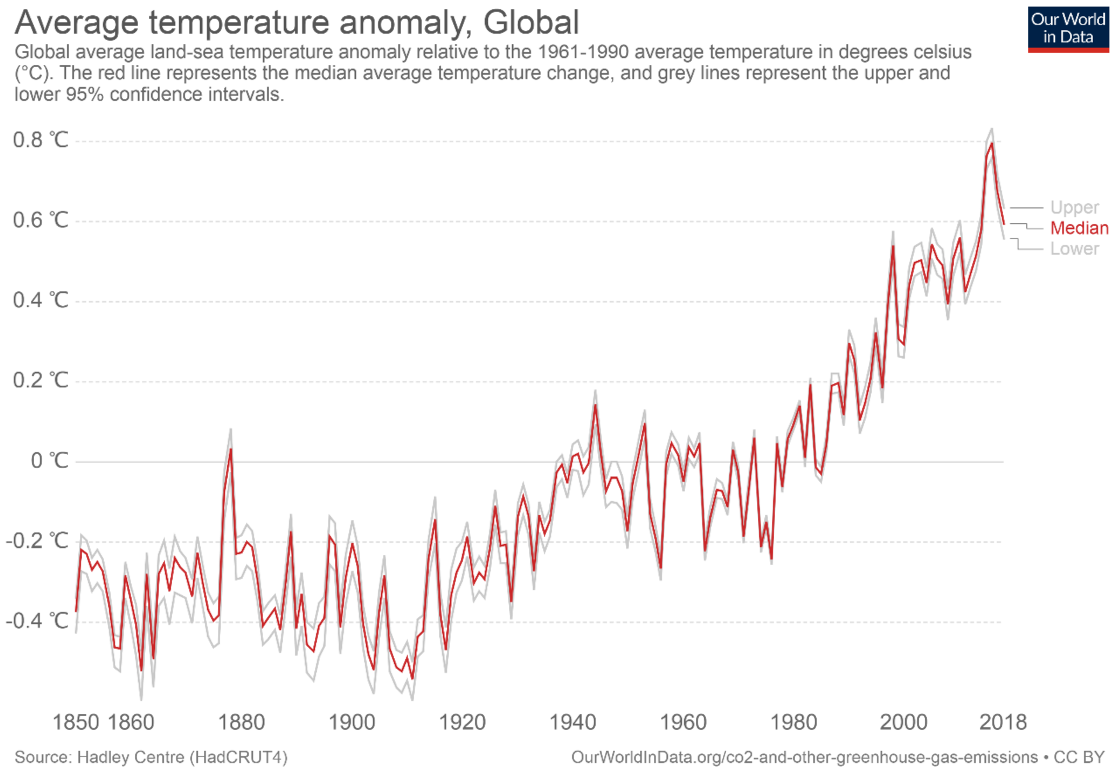


Figure 1: Average temperature anomaly Global

In any case, the less impact human activity causes the better for the environment and the less risk of bringing up environmental problems for the future generations.

The energy industry plays a decisive role within this issue as it represented around 38% of the greenhouse gas emissions by 2016 (including electricity and heat).

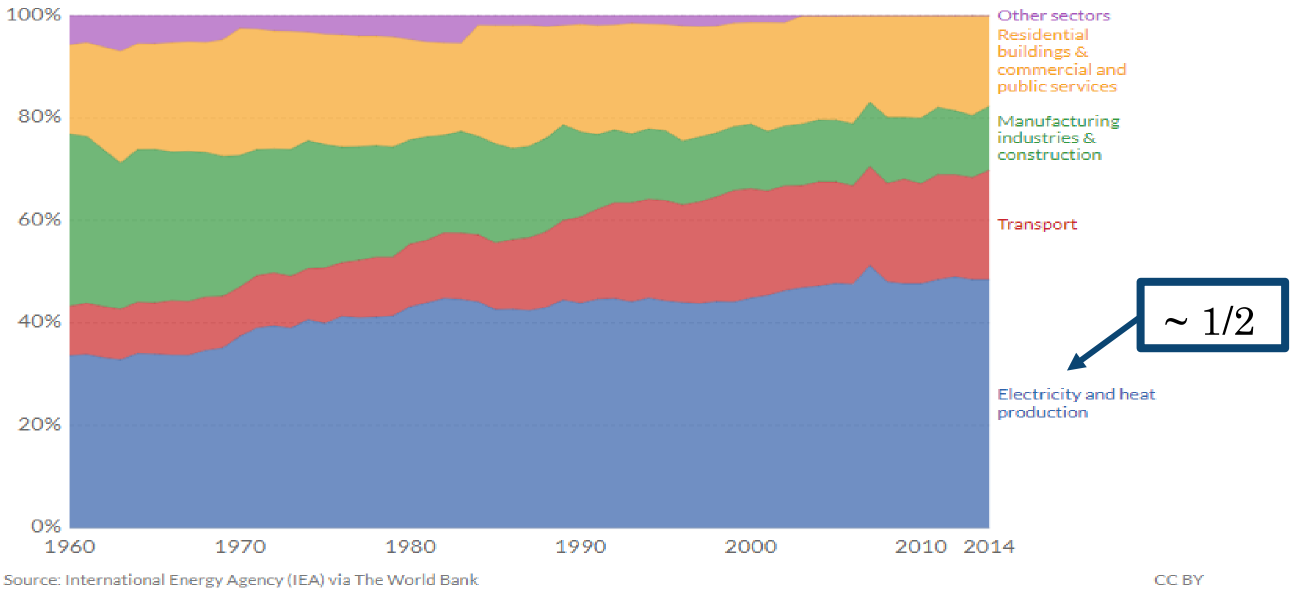


Figure 2: Carbon dioxide emissions from fuel combustion by sector, Germany

The predictions for rapid depletion of fossil fuels (coal, gas, oil) and climatological changes are making governments try to find an alternative scenario for their power generation and renewable technologies are the first option. For this reason, renewables have to rise to the circumstances of the energy transition.

This work will make an approach to find some solutions concerning the topic using the different energy productions technologies available right now.

The precise aim of this study is to maximize the benefits of wind and photovoltaic power for the environment. With this purpose, the main pollutant processes within the Life Cycle of wind and photovoltaic power are searched and possible solutions to reduce the ecological impact of this processes are given.

The bulk of the work will be developed around Life Cycle Assessment (LCA) technique. This technique goes all over the life cycle of a product, from cradle to grave, i.e. from the extraction of the raw materials for product manufacturing until the disposal or recycling of the waste generated at the end-of-life of the product. To have access to the data needed for this kind of analysis we chose to use the Suisse database Ecoinvent v3.5 . Ecoinvent offers a large life cycle inventory database for multitude of products, including energy production power plants, which is the aim of this work.

2 Work Methodology

2.1 Methodology and System Boundaries Definition

The ultimate goal pursued by an analysis of this kind is the production of electricity with low greenhouse gas emissions.

The biggest challenge of this work development was the definition of the study system as the transition to green energy of the energy system of a country is very complex and comprises from technical until geopolitical aspect. The setup of boundaries and definition of the level of detail have been carried out regarding the limited scope of this study.

The first step is to choose the energy technologies which would be included in the study. Between all the electricity generation technologies, just wind power and photovoltaic power have been deeply developed. The choice of these two technologies is justified because they are currently the most relevant renewables in the energy mix . See *3.1 Germany Energy Scenario*. They are also the ones in which more expectations are being placed on and due to the major role they are expected to play in the future energy supply. The advantage of these two technologies is that they offer a cheap and clean option to generate power. Furthermore, they are relatively easy to build and they can be placed near the consumer.

In order to go through the study of the chosen energy technologies, a model need to be defined.

The work is developed specifically for Germany as is the country of interest for TUHH University. Latest data available for German energy scenario have been used.

The characterization of the technology's models is made below. The most representative scenarios have been chosen in each case.

- Wind Power:

  Onshore wind power plant
  1-3 MW wind turbines
  Located in Germany
  (Further description and justification of this choice can be red in 3.3.1 Technical Aspects. Wind Power)

- Photovoltaic Power:
  Rooftop slanted installation
  3 kWp
  Located in Germany
  (Further description and justification of this choice can be red in 3.3.2 Technical Aspects. Photovoltaics)

The LCA of a product is built based on a "Functional unit" which represents the aspects that wants to be studied. All the inputs and outputs data and factors are set in reference to this functional unit. In our case the functional unit is 1 kWh of electricity at the point of connection to the grid.

Due to the limited scope of this work, we will just focus but on the GWP impact category, ignoring the rest impact categories. More specifically the GWP100, i.e. the Global Worming Potential in a 100-year time horizon.
The indicator that characterize the greenhouse gas emissions to the atmosphere for the energy produced is the *g CO2 equivalent/kWh*, also known as "carbon intensity" or "emission factor".

Global warming potential

Global Warming Potentials (GWP) are calculated as the ratio of the radiative forcing of one kilogramme greenhouse gas emitted to the atmosphere to that from one kilogramme CO2 over a period of time (e.g., 50 years, 100 years). [2]

Carbon dioxide equivalent emission

The amount of carbon dioxide (CO2) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. Most typically, the CO2-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP) for a 100-year time horizon. [2]

A Database has been resorted to obtain the LCIA results for equivalent CO2 emissions.

Next, data has been processed and analysed in order to highlight the most environmentally pollutant processes within the energy technology life cycle.

For the analysis, some of the influencing factors to the studied system have been simplified.
Aspects, as it can be for example iron extraction from the ground, can be mentioned but they will not be studied in depth as they are out of this field of knowledge.

Once the analysis of the data is completed, a set of solutions will be suggested with the objective of reducing the emissions in the life cycle of the future facilities. The feasibility of the purposed improvements will be analysed.

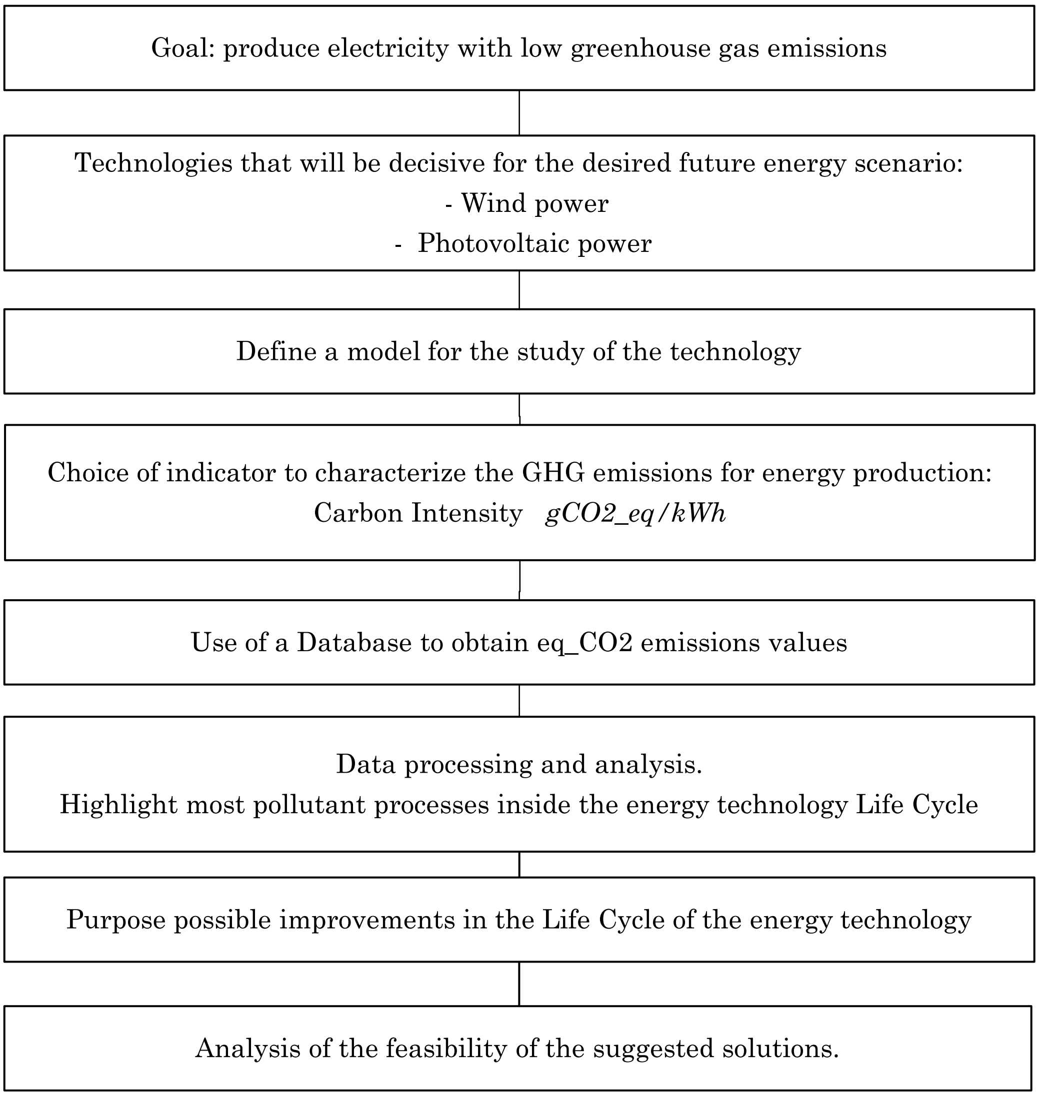


Figure 3: Work Methodology

2.2 LCA

Life Cycle Assessment methodology was first started to be developed in the 1960s in the United States by some private companies with the purpose of managing the materials and energy resources [3]. Now a days, LCAs are regulated by International Organization of Standardization (ISO) within the standards:

ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework [4]

ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines [5] and they are performed with multiple aims [6]:

- Product process improvement
- Cost reduction
- Decision making
- Proactive environmental concerns
- Customer requirements
- Optimization
- Product comparison
- Others

According to ISO 14040:2006 definition, Life Cycle Assessment (LCA) is the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* [4].

Studying a product through LCA allows us to have a global overview of its environmental impact "from cradle to grave", i.e. through its whole life cycle. That comprises :

In the case of renewable energies, the two first, extraction of raw materials and production, have the biggest impact. Meanwhile, the distribution and service life are minor, and End of Life is still not very developed as renewables have been introduced in the market relatively recently and first facilities are starting to be dismantled currently.

An LCA consists in 4 phases:

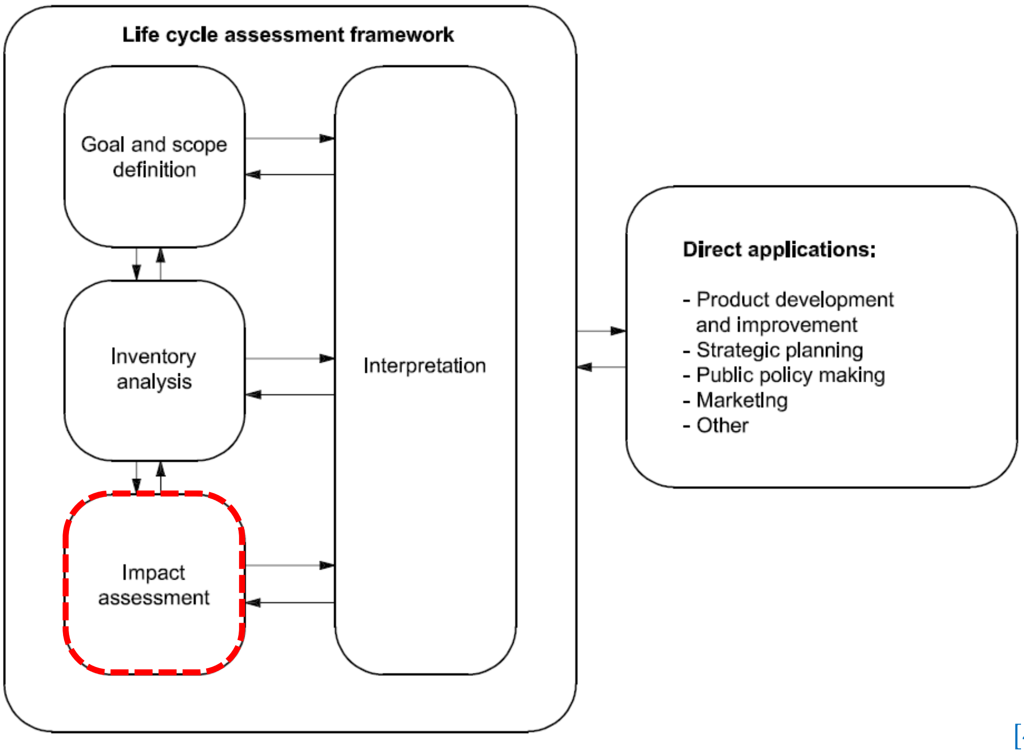
1. Goal and Scope

2. Life Cycle Inventory (LCI)

3. Life Cycle Impact Assessment (LCIA)

4.Interpretation

This work is focused on the Impact Assessment phase.



[4]

Figure 4: Stages of an LCA

LCIA assigns LCI results to impact categories. The collection of indicators LCIA results or the LCIA profile provides information on the environmental issues associated with the inputs and outputs of the product system. [4]

There are different Environmental Impact Assessment Methods (CML, eco-indicator 99, ILCD and others). An LCIA method is understood as a set of LCIA impact categories

When carrying the analysis calculation in OpenLCA software "CML (baseline) [v4.4, January 2015]" has been applied as impact assessment method.

The most used LCIA methods include commonly the following impact category indicators:

- Acidification
- Climate change
- Resource depletion
- Ecotoxicity
- Energy Use
- Eutrophication
- Human toxicity
- Ionising Radiation
- Land use
- Odour
- Ozone layer depletion
- Particulate matter/ Respiratory inorganics
- Photochemical oxidation

From between the above-mentioned impact categories, just climate change indicator is useful for the aim of this work.

When working with LCA, at least the following concepts should be understood:

Product system: collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

Process: set of interrelated or interacting activities that transforms inputs into outputs.

Unit process: smallest element considered in the life cycle inventory analysis for which input and output data are quantified.

Output: product, material or energy flow that leaves a unit process

Releases: emissions to air and discharges to water and soil.

In the development of this work the Product Systems will be the electricity production from wind and photovoltaic energy.
The numerical results will be obtained for every unit process inside the studied product systems. The releases to air will be analysed.

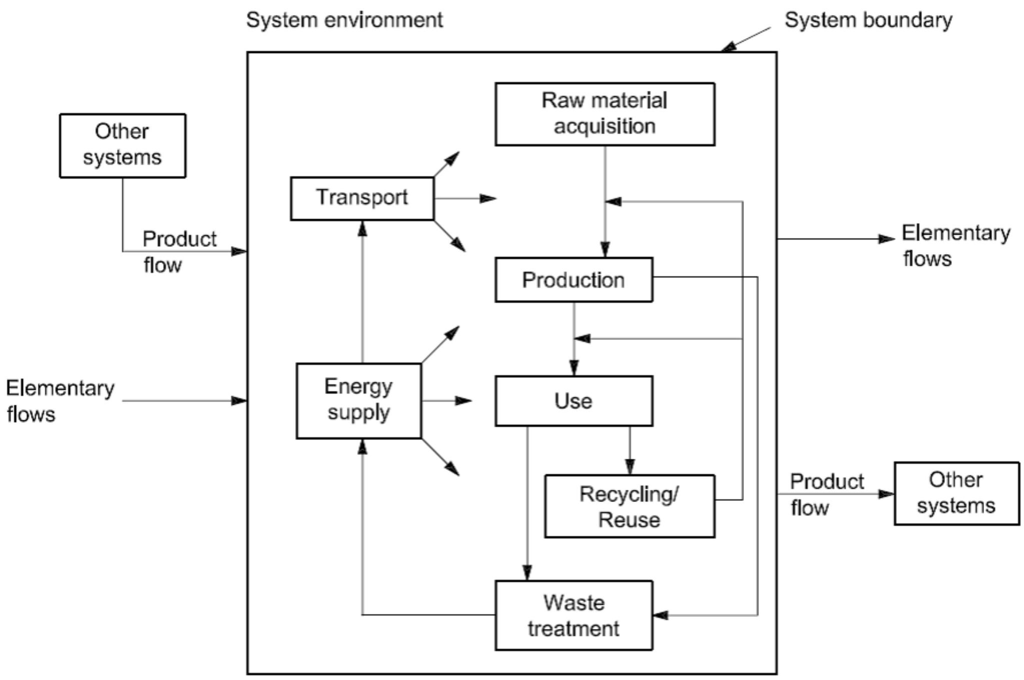


Figure 5: Example of a product system for LCA including processes, inputs and outputs.

It should be taken into account that:

- An LCA study does not encompass the economic or social domain.
- An LCA doesn't provide absolute accurate environmental impact data. It works with approaches.
- Comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent [4].

2.3 Software tools

For the development of this work the swiss database *"Ecoinvent version3.5"* has been employed. It provided complete LCI dataset for a huge number of products among which we have made use of the ones referring to energy production.

Besides, the software *"Open LCA v1.7"* was used in order to open the *Ecoinvent v3.5* database, visualize, extract and process the data of our interest.

3 Theoretical background

3.1 Germany Energy Scenario

This section is intended to give a brief overview of German energy context to help the reader to place himself. For more detailed knowledge go to *Appendix 1 – German Energy Context*.

For the development of this work we have regarded the present energy share of Germany in the last completed year (2018). See Figure 6.

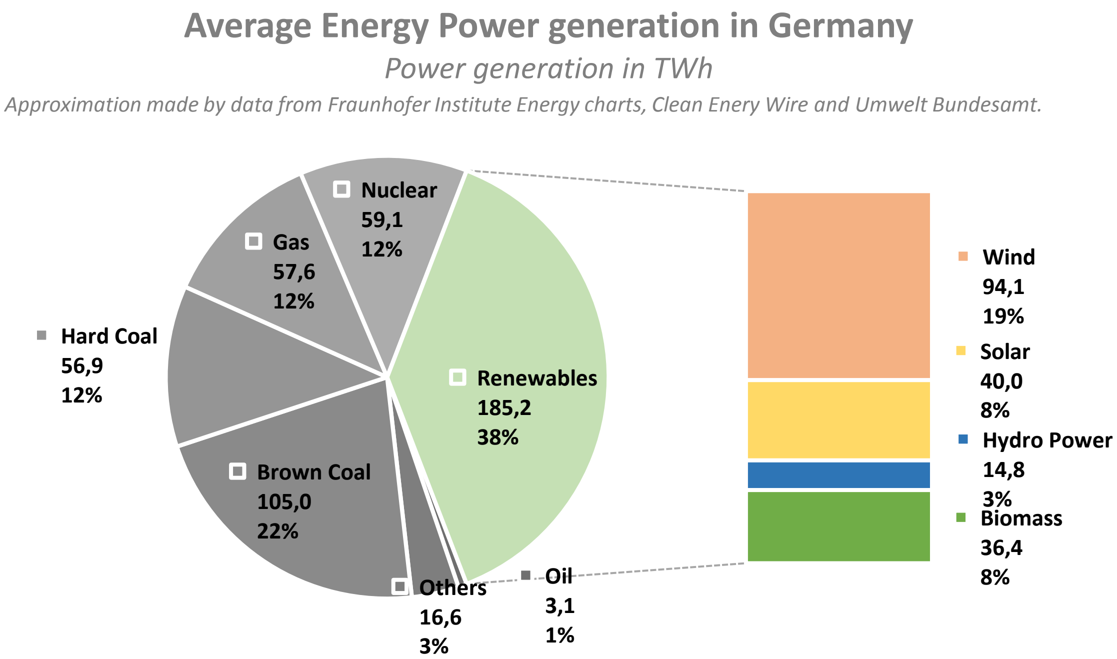


Figure 6: Share of energy sources in gross German power production in 2018.

As we can see, now a days, in 2018 , Brown Coal (22 %), referring mainly to lignite, is leading the power energy mix, followed by wind power (19%). Fossil fuels (brown coal, hard coal, natural gas and mineral oil) still represent almost half (~47%) of the German electric generation.

This is sustained because Germany is rich in lignite reservoirs.

Although Germany is on its way towards a goal of 50% renewables in 2030 and 80-90% for 2050 with the support of the German law for energy transition which took effect in 2000.

3.2 Economic Aspects

This section addresses the power generation from another relevant angle. The economical expenses incurred by the energy facilities are decisive in the competitiveness of a technology in the energy mix.

In this study the representative economic indicator chosen is the Levelized Cost of Energy (LCOE).

LCOE is the present value of the unit-cost (per kWh) of a payment stream that is equal to the present value of the total expenses of building and operating a generation power plant during its entire economical lifetime.

It is usually expressed in the units €cents/ kWh.

It can be approximated as follows:

$$LCOE = \frac{\text{total plant´s building and operating costs over the life time}}{total\ electrical\ output\ over\ the\ life\ time}$$

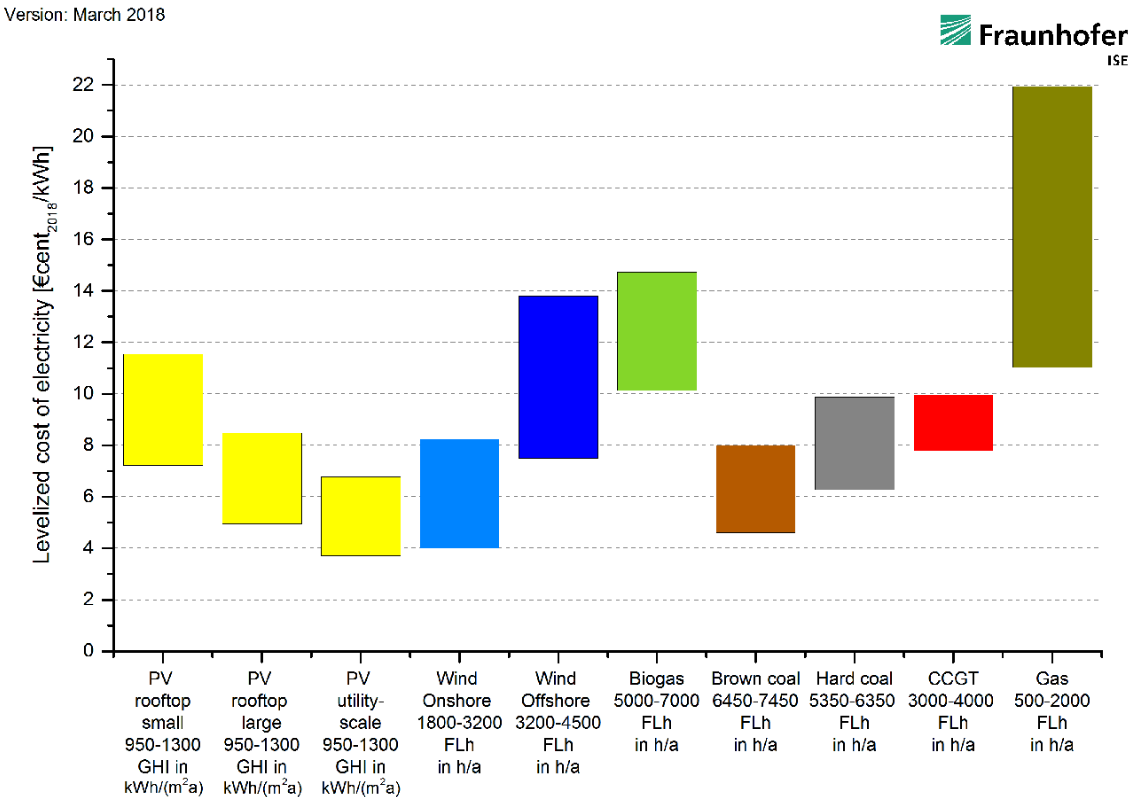


Figure 7: Levelized cost of electricity in €/kWh for Germany. 2018

It can be seen that, in 2018, the production of wind onshore power came to be the second cheapest energy generation technology, while small PV installations was economically competitive with fossil fuels just in some cases. In the other hand, the production of PV power for self-consuming avoids the costs overrun of electricity market and distributors.

The previous LCOEs are settled for Germany but the value can vary from one region to another depending on multiple factors as labour costs or land availability.

According to IEA statements, the global average LCOE of photovoltaic and onshore wind has dropped "significantly" by 65 and 15 percent, respectively, over the past five years.

Wind Power

Wind is a mature technology in the German market and is competitive by itself. First non-subsidized projects were launched in 2017.

The distribution of costs in a wind onshore project are shown below. The major costs are in the drivetrain, rotor and tower.
In the case of substituting some components of the turbine, the substitution of the blades and nacelle will entail high costs of more than 50% of the cost of building a new project. This can lead to questioning the substitution is worthwhile.

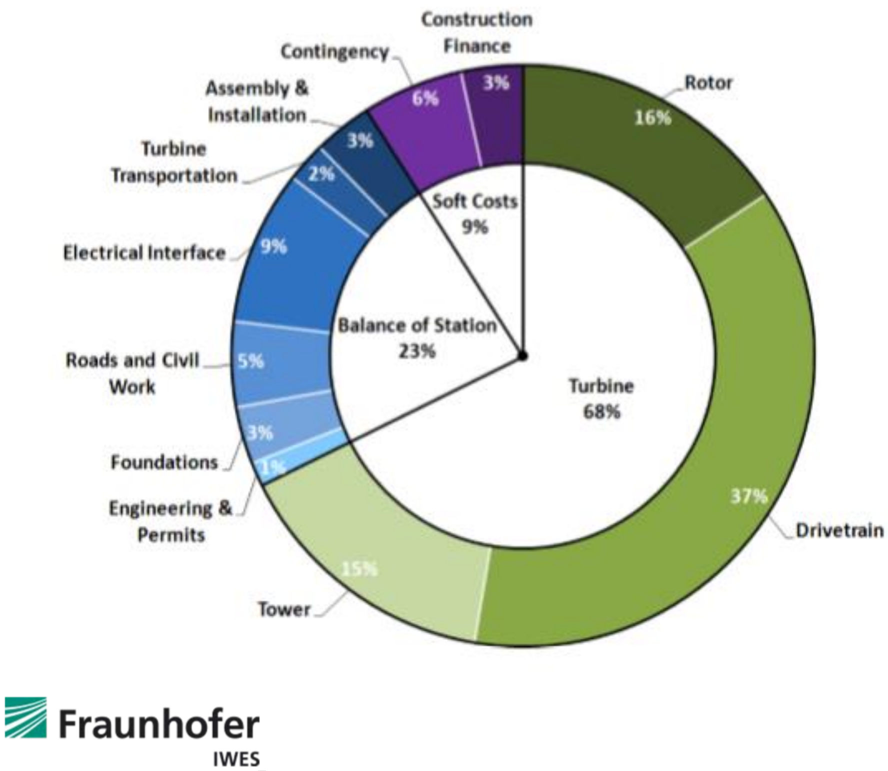


Figure 8: Costs of tower and support structures onshore

Photovoltaic Power

Regardless of its extremely quick development in the last decade, photovoltaic is still not a mature technology in the market. Photovoltaic installations are not a secure investment by themselves for multiple factors.
That's why at the present, the economic viability of photovoltaic energy installations in Germany are closely linked to the supporting feed-in tariffs approved by the German´s Renewable Energy Act (EEG) (2000).

It is different in the case of household or small installations. There, the decision of investing is made regarding more the needs of a particular than the competitivity of the power generated in the electricity market. In this case the financial conditions are not present and operational costs are almost inexistent. In the other hand economy of scales is not applied.

It is worth mentioning that for all renewables, including solar, there exist in Germany the "Feed-in tariffs", which means that any power producer receives a compensation, by grid operator, for every kWh of renewable electricity putted into de grid. The support rates (€cts/kWh) follow a degression mechanism, remuneration drops with time, and prescribe in 20 years horizon since the start of energy producing. In the case of small PV facilities (<100kWp), they are not affected by the phase-out of feed-in tariffs and they continue to receive the support rates. [7]

The costs of a PV project are distributed approximately as follows:

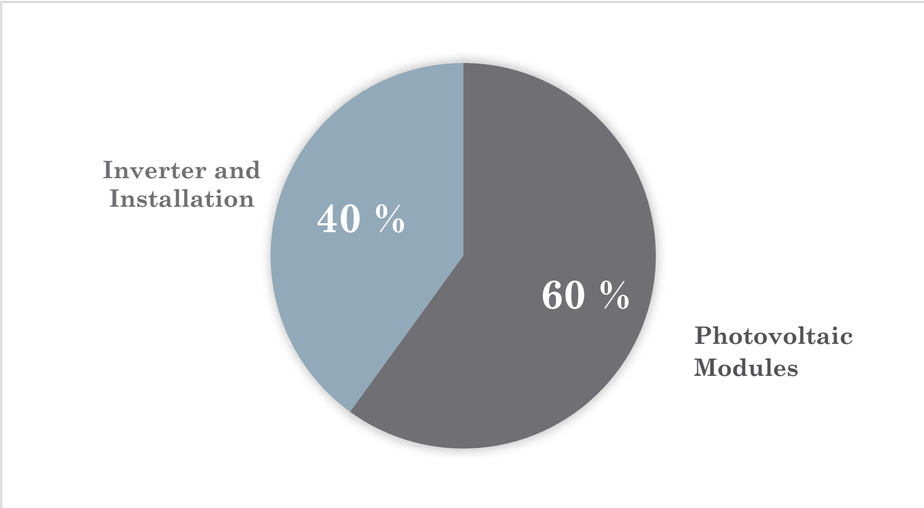


Figure 9: Cost distribution in PV facilities [14]

Even the PV panels represent more than half of the price of the installation, the prices of the PV modules continue to fall rapidly following the learning curve thanks to development of the technology.

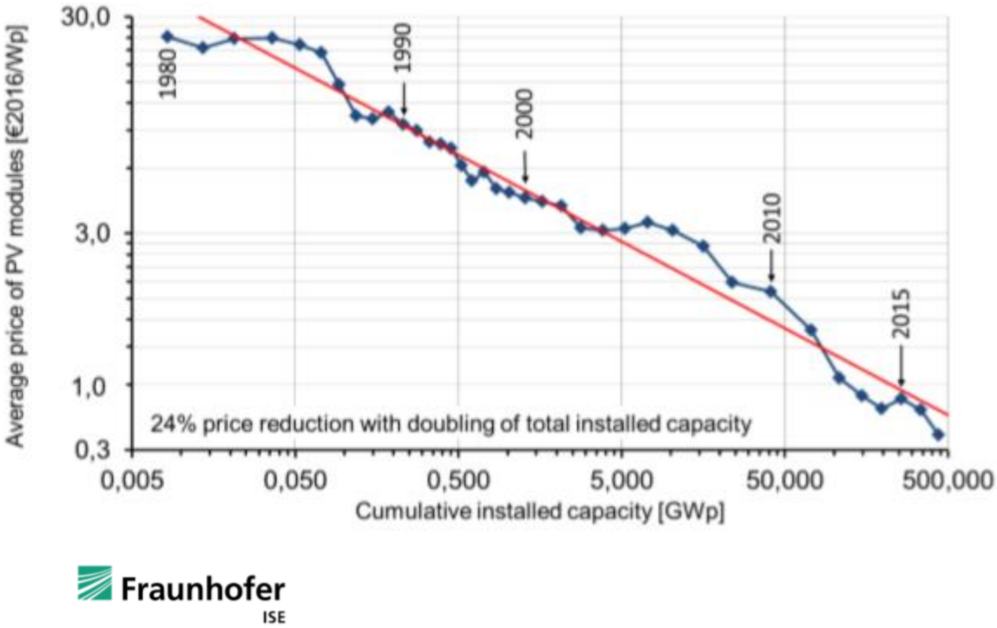


Figure 10: Historical price development of PV modules

3.3 Technical Aspects

3.3.1 Wind Power

Wind power is the first renewable energy in Germany. Only onshore and offshore wind turbines supply around 20% of yearly energy of the country. Between 2022 and 2019 the installed wind capacity increased by 41.3 GW backed by the German government energy transition plan. Furthermore, wind turbines are a mature technology that offers low price energy and avoids burning any fuel during their lifespan.

The basic operation of a wind farm is simple. In the first instance the rotor transforms the aerodynamical force exerted by the wind on the turbine blades into a rotational movement. Then the gear box function is to increase rotational speed extracted from the rotor. Meanwhile, the generator is used to transform kinetic energy into an electric current. The voltage of the electric flow should finally be increased in order to be delivered to the electrical grid for its transmission and distribution to the consumer.

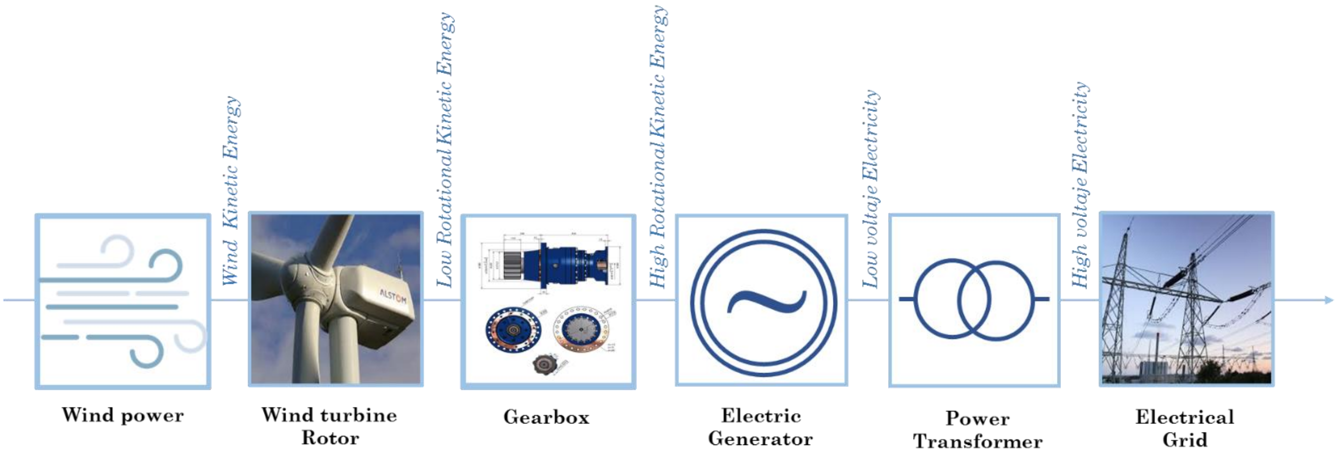


Figure 11: Wind Power Plant operation

The following are the most relevant elements of a wind power plant :

Tower: The tower has a significant weight in the wind turbine mass and volume. It is mainly made out of steel plates. It consists of the tower section with some additional elements like platforms, ladders and fixtures for cables. The tower section design may change according to site wind conditions.

Nacelle: Nacelle is a very complex array of components, in which gear box and electrical generator stand out. Nacelle foundation, nacelle cover, main shaft, yaw system, brake and flanges are some of the secondary relevant elements . Steel is the material used in the nacelle's frame, casing and machinery. The gear box is based on iron and steel. Meanwhile, the generator is made of steel (~60%), copper (~30%) and cast iron [8] Other components consist mainly of steel and fibreglass.

Rotor: When speaking about the rotor we refer to the set of blades, hub and spinner, that is, the mobile part of the wind turbine. In one side, blades are primarily made from carbon fibre and

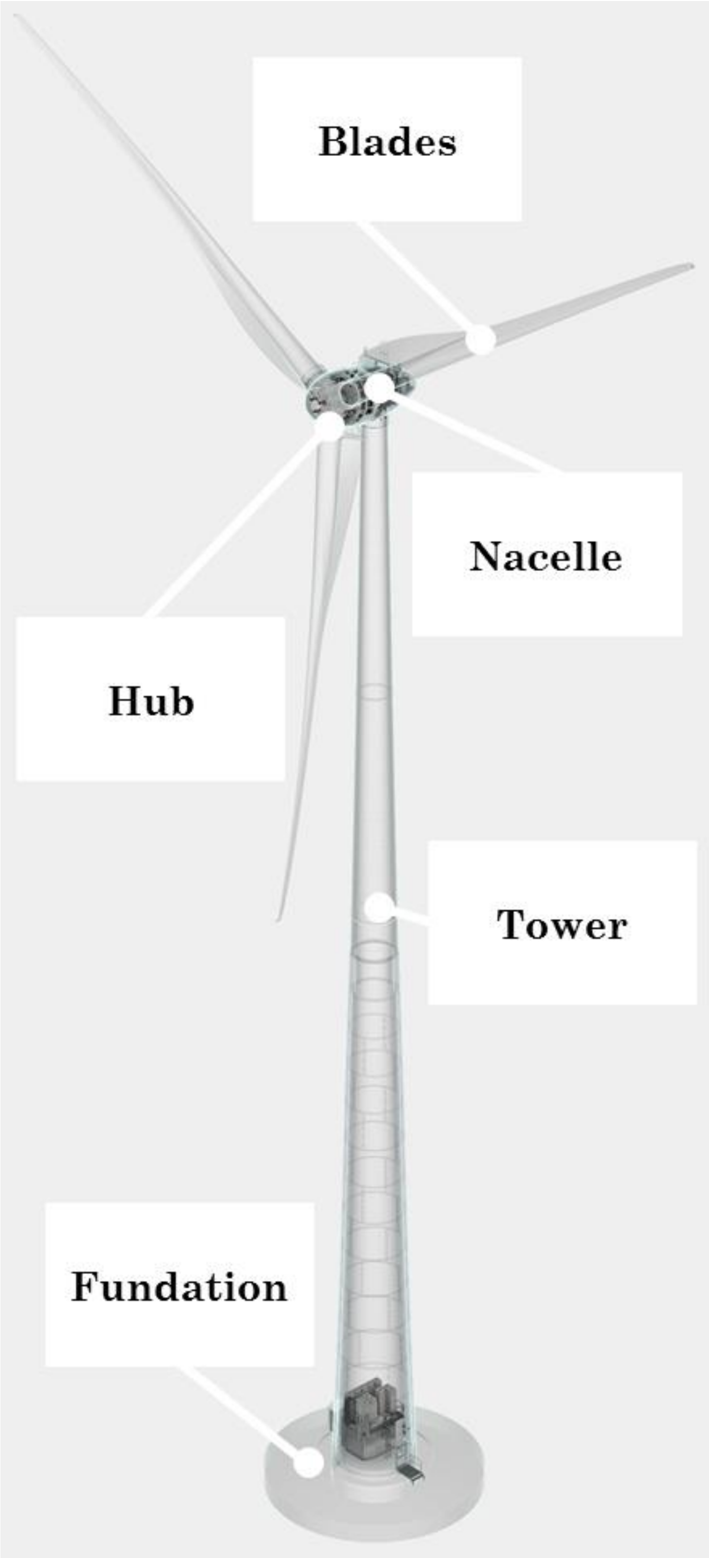


Figure 12 Wind Turbine Enercon E-70/2 MW

woven glass fibres infused with epoxy resin and glued with polyurethane. In the other side blade hubs consists of cast iron and internals.

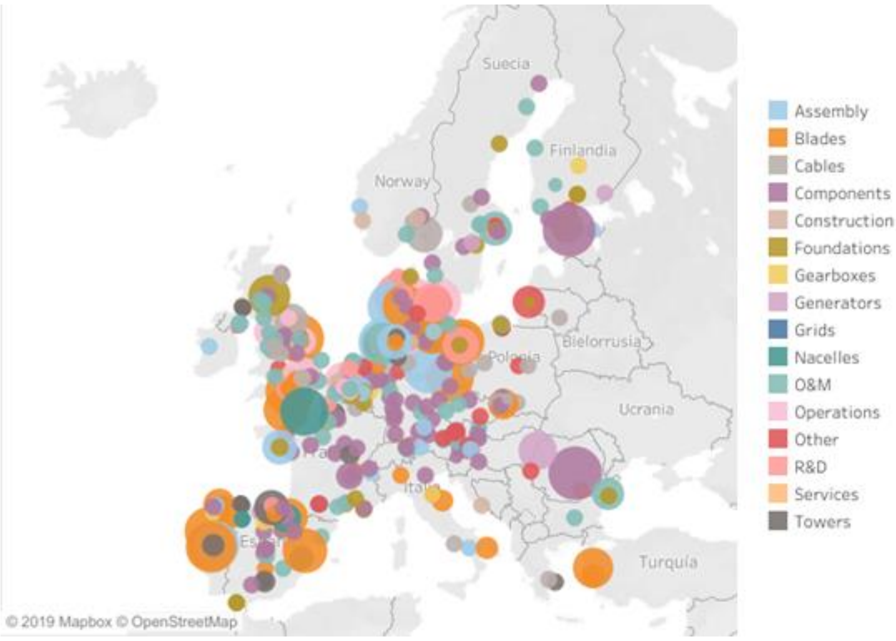
Foundation: Due to the dimensions of this structures, the wind turbines need foundations to support the loads of the tower and the turbine by distributing the forces into the ground. As the studied case is an onshore plant, the foundations consist of concrete and steel. The foundation can change depending on groundwater level, terrain, wind loading or design of the wind turbine.

Cabling : The cabling takes into account the inside cabling of each wind turbine unit as well as the site cabling, connecting turbines between them, connecting the turbines to the transformer station and finally the transformer to the grid. The composition of cabling is basically aluminium, copper, steel and polymers. The amount and type of cabling depends, among others, of voltage used distribution of plant in the site and distance from the plant to the grid.

Transformer station: Transformer station is the part of the system used to transform the electric current coming out of the wind turbines from medium voltage level to high voltage level to be able to deliver it to the grid. The electricity was previously transformed from direct low voltage current to alternating medium voltage current in the converters placed at the bottom of the wind turbine's tower. Transformer mainly consists of steel, copper, aluminium and resin.

Electronics: Control units for signal and power and other electronic devices are used all along the plant.

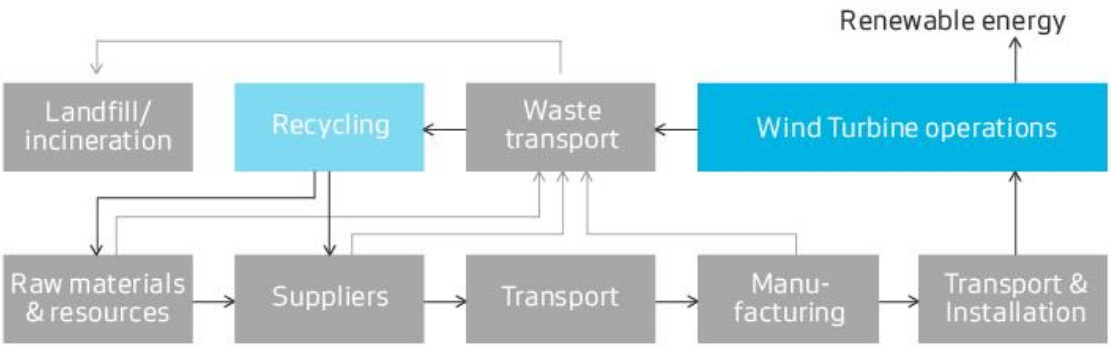
It is worth mentioning for this analysis that, the wind industry is very present in Europe and in Germany specifically. That will mean that the production of components and their assembling is ordinarily carried on relatively near the installation site. Nonetheless, the value chain for wind turbines components is widely spread around the world.



[9]

Figure 13: Regional Map Wind Industry in Europe

The model for the study is an on-shore, grid-connected wind power plant. The turbines that conform the wind field use horizontal axis and 3 blade technology as it is the most prevalent worldwide.



[10]

Figure 14: Wind Power Plant Life Cycle Schema by Vestas

Wind power LCA analysis was made based on the following Unit Product in *Ecoinvent 3.5* :

electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | APOS, S – DE UUID [d4063658-9d16-32a3-98cd-ac078876ac4a]

The dataset in Ecoinvent v3.5 is using collected data for Germany in 2012. It approximates the results using average 2MW turbine . Typical lifespan considered is 20 years.

The analysed process includes

- Extraction of all raw materials for the construction of the wind turbine and their treatment.
- Energy needed for erection and dismantling of the wind turbine.
- Decommissioning of the wind turbine and the treatment of the resulting materials in the end of the lifetime.
- transformation of the electricity produced in order to deliver into the grid

and doesn't include

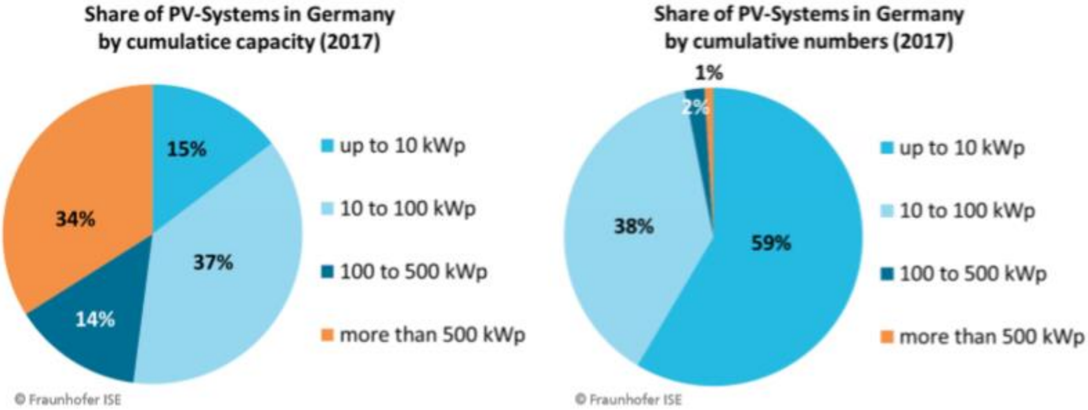
- Energy for the assembling of the materials .
- Transportation of materials to the construction site.

3.3.2 Photovoltaics

Solar photovoltaics is a technology which has not still reached the maturity. Nevertheless, 1,7million PV systems are installed in Germany accounting for about 8% of the total power generation produced in Germany in 2018.

Speaking about PV module production, in 2017 China & Taiwan hold the lead with a share of 70%, followed by Rest of Asia-Pacific & Central Asia with 14.8%. Europe contributed with a share of 3.1% (compared to 4% in 2016); USA/CAN contributed 3.7%. [11]

According to the Figure 15, published by Fraunhofer Institute, 59% of PV-systems in Germany have a capacity up to 10 kWp. That means that almost 2/3 of the PV-systems are small equipment installed in private houses or businesses . For this reason, small scale private systems have been chosen to be studied, as the most representative case, rather than solar PV farms. This is explained because many times what is sought with this technology is the decentralisation of the energy production. We are aware that comparisons between large scale power plants and small PV facilities should be carefully done.

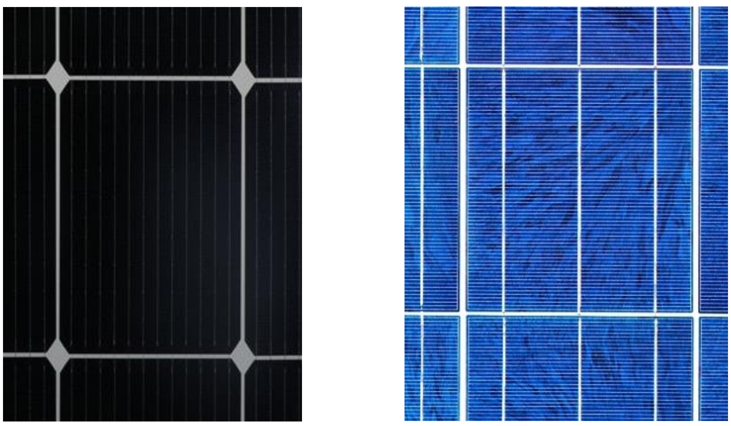


[11]

Figure 15: Share of Photovoltaic technologies in Germany

Other aspects concerning PV systems should be mentioned to stablish a panorama of current commercial PV technology. Silicon based wafers represented 95% of the total production in 2017. Multi-crystalline solar cells accounted for about 62% of total commercial production. The efficiencies of commercial distributed modules of this technology are in the range of 17%, while in a laboratory a record of 22.3% efficiency has been achieved for multi-crystalline silicon wafer-based technology. [11]

The solar panels take the energy of photons from sun irradiation and transform it in a low voltage electric current. The inverter transforms low voltage DC power into an AC power to make the charge possible for household devices. When the solar system generates more electricity than needed the excess is poured into the grid. At periods with lack of power, like for example at night, electricity is imported from the grid to the building's network.



Monocrystalline Si cell

Polycrystalline Si

Figure 16: Difference between Monocrystalline and Polycrystalline silicon cells.

Photovoltaic panel: The solar panel is manufactured following a layer structure as is shown in Figure 17. The central components are the polycrystalline silicon wafers. Tempering flat glass (~10 kg/m² PV) , aluminium alloy (~3 kg/m² PV), ethylenvinyl acetate (EVA)(~1 kg/m² PV), polyvinylfluoride (Tedlar) and copper are the other remarkable components of the PV panel.

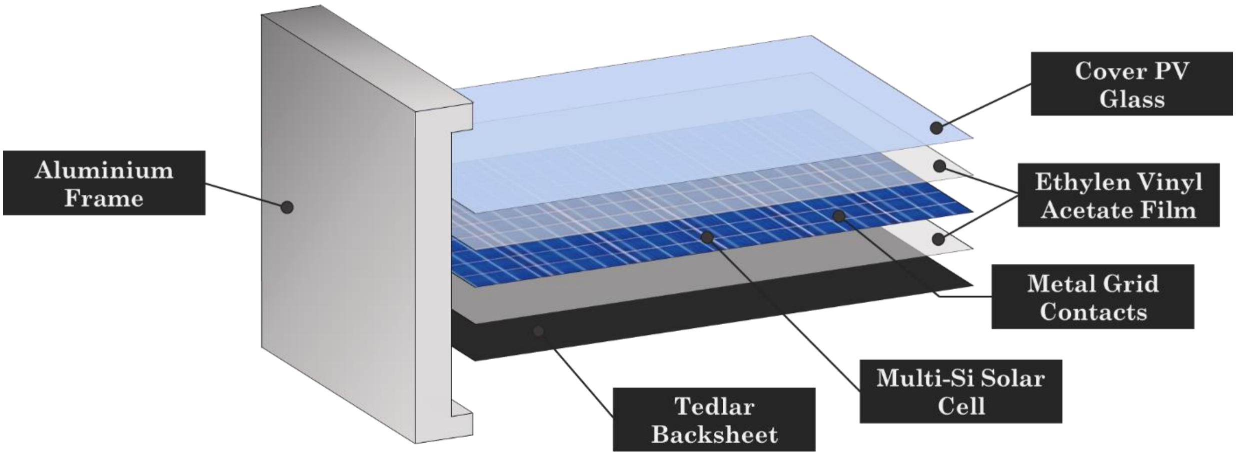


Figure 17: Schema of Typical Solar Panel Layers

Inverter: In this case a 2,5 kW inverter is used for the model. It's around 18,5 kg weight and it has a 93,5 % efficiency. An inverter of this characteristics will be primarily composed of approximately 17 kg/unit of steel, 10 kg/u of copper and 2,5 kg/unit of aluminium.

Mounting system: Is the structures needed to attach the solar modules to the building's roof. It will mainly need ~6 kg /m² PV of aluminium and ~3 kg /m² PV of steel.

Electric installation: It refers to all the parts between the panel and the grid like

- lightning protection
- cabling in the PV panel area
- fuse box
- cabling from the PV panels to inverter
- cabling from the inverter to the electric meter

It's mainly made of copper (~15 kg/u) and polyethylene (~12 kg/u).

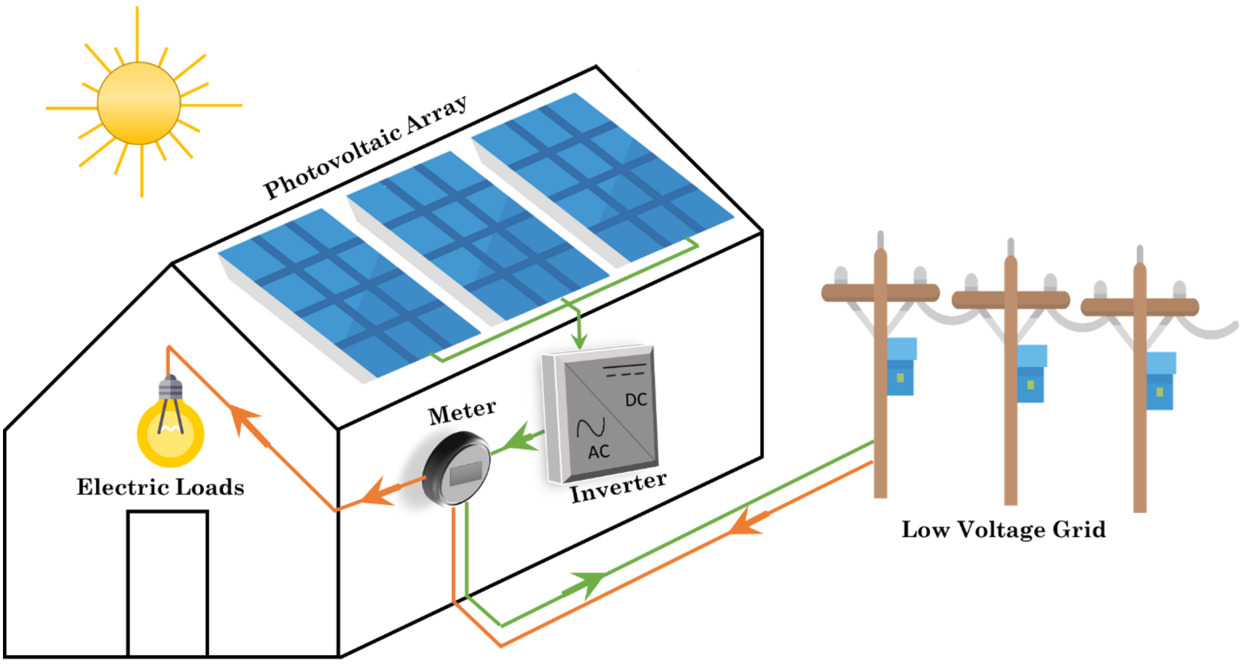


Figure 18: Basic scheme of on-grid solar PV power system

Solar Photovoltaic LCA analysis was made based on the following Unit Product in *Ecoinvent 3.5* :

electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | electricity, low voltage | APOS, U

UUID [baf7b18e-fb9a-346d-8ab0-5ffd92d91a76]

It models a typical grid-connected, low voltage solar system. The model uses a basic building integrated, multi-Si module of 3kWp of power. The module is installed on a slanted roof. The considered lifespan of the system is of 30 years. Data used to build the model were picked for Germany in 2012. a model with more up-to-date data is not available.

4 Analysis and Results

From this section on, the research will seek to go deeper into the Life Cycle of two specific technologies, PV and wind power. It will be attempted to find the main sources of the atmospheric GHG emissions along the life cycle and search for possible alternatives.

To begin with, the results in the following table where calculated in OpenLCA. They correspond to power produced in Germany. It gives an idea of the range of values of GWP comparing different existing energy technologies.

	GWP100, OpenLCA DE *(kg CO2_eq/kWh)*
Lignite	**1,223**
Hard coal	**1,050**
Oil	**0,873**
Natural gas, combined cycle	**0,419**
Photovoltaic, utility	**0,097**
Photovoltaic, roof installed	**0,094**
Wind, onshore power plant, 1-3 MW	**0,018**
Wind, offshore power plant, 1-3 MW	**0,016**
Nuclear Power, PWR	**0,011**
Hydropower, run-of-river	**0,004**

Table 1: GWP OpenLCA results

In addition, the values of the same indicator where consulted in three more sources to verify the reliability of the results in OpenLCA.

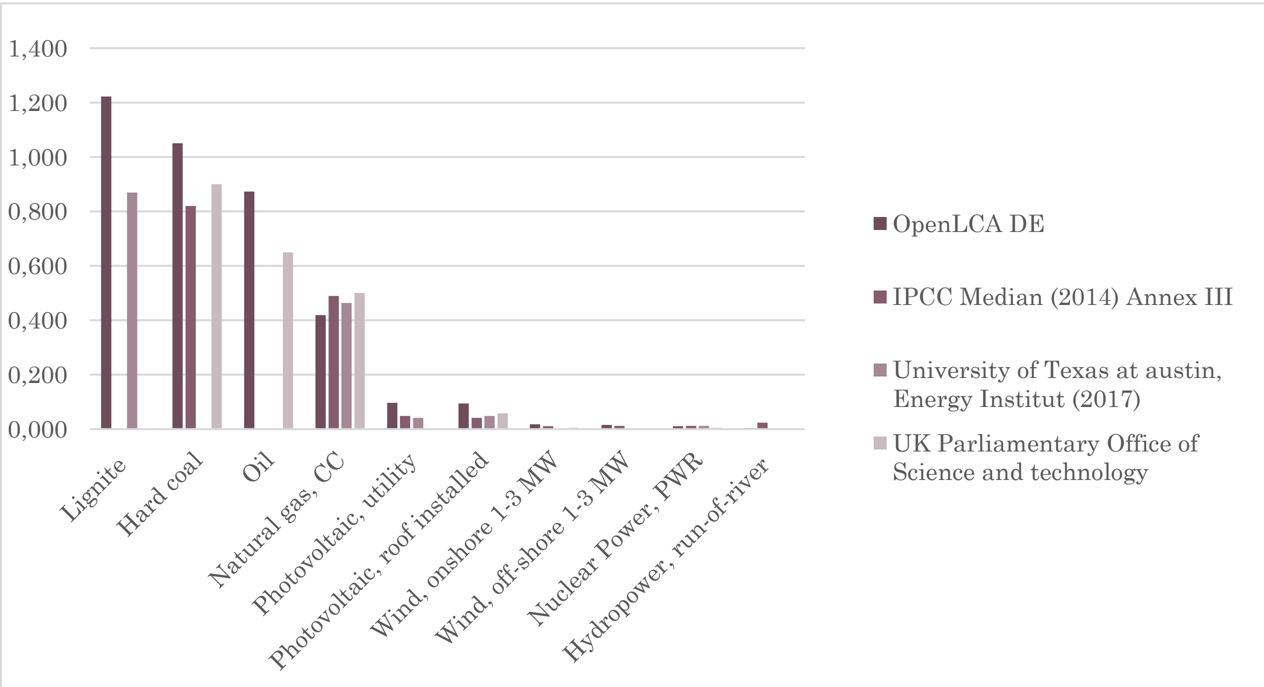


Figure 19: GWP100 Lifecycle emissions (kg CO2_eq/kWh).

The values found for CO2_eq Intensity vary from one source to another but they are within the same range. Consequently, the results approached by OpenLCA can be taken as valid.

The values obtained are not surprising. The sum of emissions during the lifetime of fossil fuels technologies can be around 100 times bigger than the emissions over the lifetime of a renewable energy technology or the nuclear. That is happening since the firsts, fossil fuel technologies, have emissions all along their useful life because they need to do the combustion of the fuel to obtain the energy. Meanwhile, the seconds, renewable and nuclear, have emissions around 0 kgCO2 during their useful life. The only emissions during this phase of their life can be related to maintenance or running of the plant in the case of nuclear.

Next, a deeper analysis on Wind and Photovoltaic will be done. The research will focus on the most pollutant processes included inside their life cycle.

4.1 Wind Power Atmospheric Impact

The major ecological impacts, regarding atmospheric emissions, for a wind power plant are on its building and decommissioning phase.

During the service life of the power plant there are few processes that can contribute to issue GHGs. Transport of workers to the area or maintenance activities as lubricant oil or substitution of pieces of the wind turbine can be mentioned between them. However, the impact of O&M processes is negligible.

The distribution of the ecological impact can be distinguished in the results and it's clearly showed in the following chart.

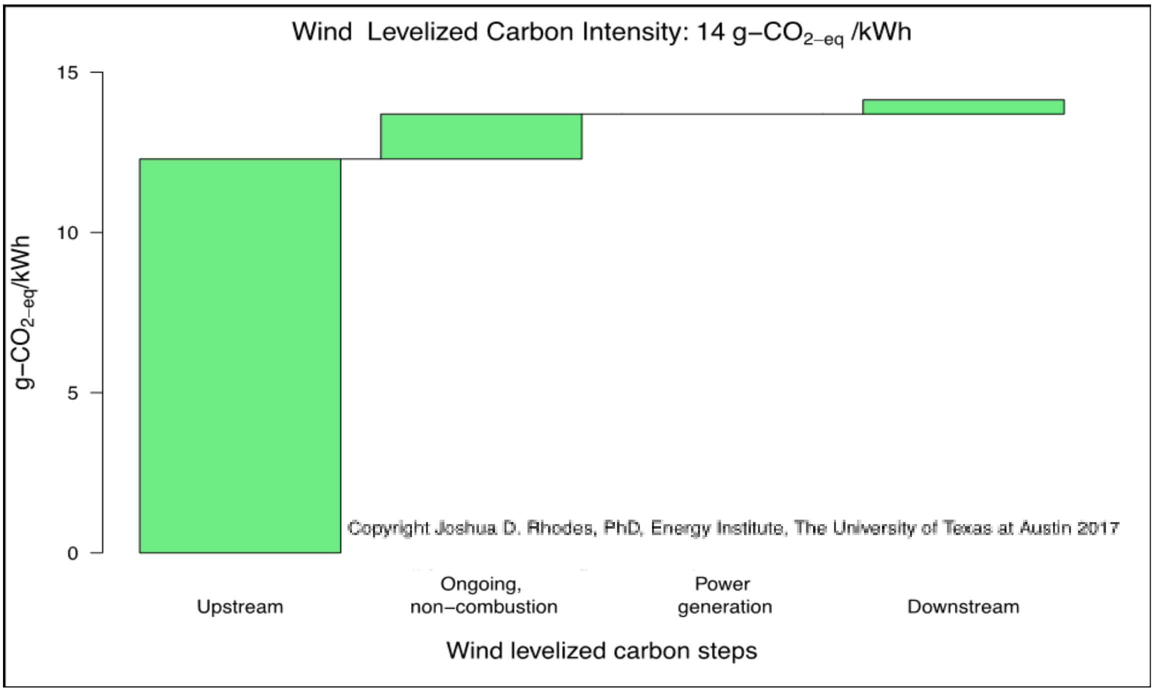


Figure 20: Wind levelized carbon Intensity distribution over Life Cycle

Among the production of wind turbines, four fields stand out for their significant impact.

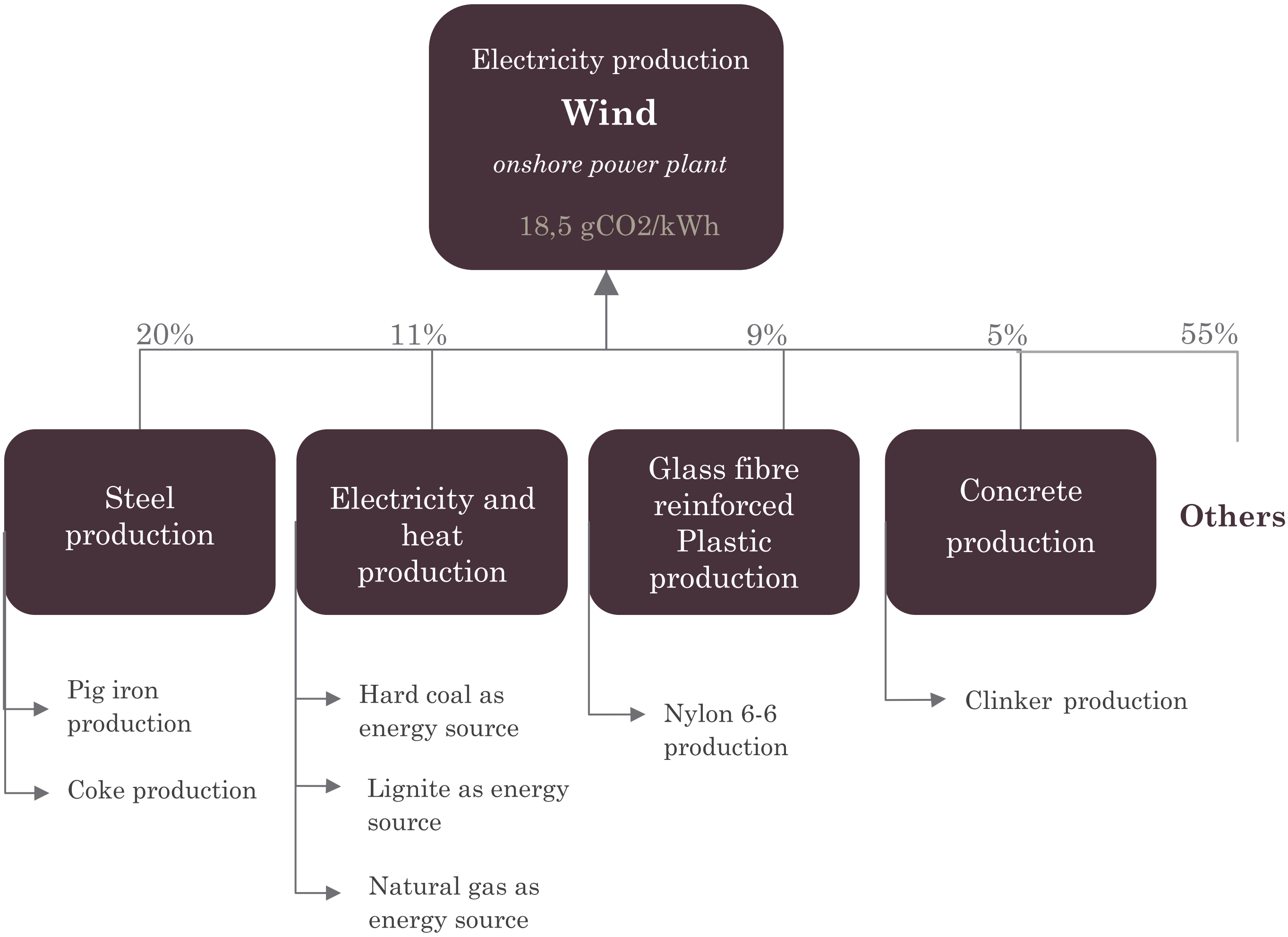


Figure 21: Most pollutant processes in Wind Power Life Cycle

Process	Location	g CO2 eq/kWh	%
pig iron production | pig iron | APOS, U	GLO	**1,977**	10,70
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | APOS, U	RoW	**1,090**	5,90
clinker production | clinker | APOS, U	RoW	**0,832**	4,50
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | APOS, U	RoW	**0,781**	4,22
sinter production, iron | sinter, iron | APOS, U	GLO	**0,618**	3,35

Table 2: OpenLCA results. 5 most pollutant processes in Wind Power Life Cycle

To consult the rest of the processes in the OpenLCA results go to *Appendix 2 – Results Wind Power in OpenLCA.*

OpenLCA Results include an analysis of around 4500 processes from which 99% represent less than 1% of the total GHG emissions. The length of this work does not permit the individual analysis of each one of the processes. That's why the processes with a very low impact have been grouped in the section "Others".

In the schema above it can be seen that steel production for wind turbine accounts for around 20% of the emissions. According to the calculations in DTU International Energy Report 2014 [12], about 172 t steel and cast iron are included in a 2 MW wind turbine, which is 70-80% of the wind turbine total mass. If we assume that the tower is almost 100% made of steel, then we have that the 83% of the mass of steel is in the tower structure. An approach of the distribution of steel in the wind turbine has been made below.

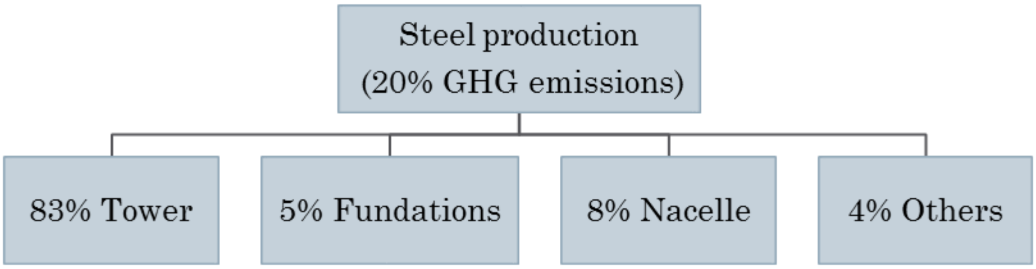


Figure 22: Distribution of steel in the wind turbine

OpenLCA analysis has been used to estimate which is the impact of recycling the steel. In the studied model only the recycling of reinforced steel is included. The unit process checked is:

treatment of waste reinforcement steel, recycling | waste reinforcement steel | APOS, U - RoW UUID [5770b1f4-9562-347f-b479-20d3f2f0eda6]

The result shows that the emissions caused by recycling process is : 57,92 g CO2_eq/kg steel

In the process of recycling, all steel scraps can be mixed to produce at the end different grades of steel depending on the demand. Therefore, it can be assumed that the resulting value obtained for reinforcing steel can be used for all the steel components of the turbine.

A comparison has been made between the primary production of reinforced steel and its production through recycling.
The unit process used for the calculation is:

reinforcing steel production | reinforcing steel | APOS, U - RER
UUID [85bfa8b0-c37d-3010-9e6c-f524b4833882]

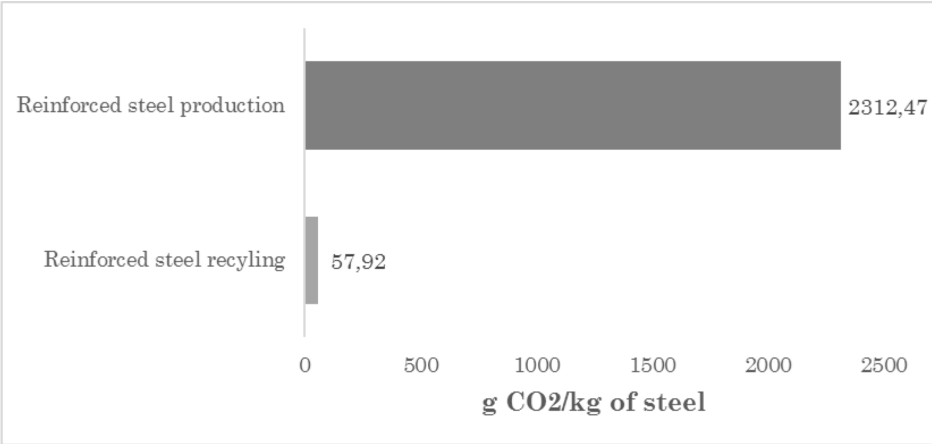


Figure 23: Comparison of Emission in Primary and Secondary Steel production from OpenLCA results.

The impact of electricity used in the production of the wind turbine components is 11% over the total GHGs emitted along the Life Cycle of a wind turbine. Share of fossil fuels (hard coal, oil, natural gas) in electricity production worldwide is 60% and around 40% in European Union. As it was mentioned before, many components are assembled in Germany and Europe, but also the minor components for their manufacture come from all around the world. As the low carbon energies penetrate in the market this percentage will drop by itself. If this scenario happens, this impact can drop from 11% (2 g CO2_eq/kWh) to the half, 5% (1 g CO2_eq/kWh).

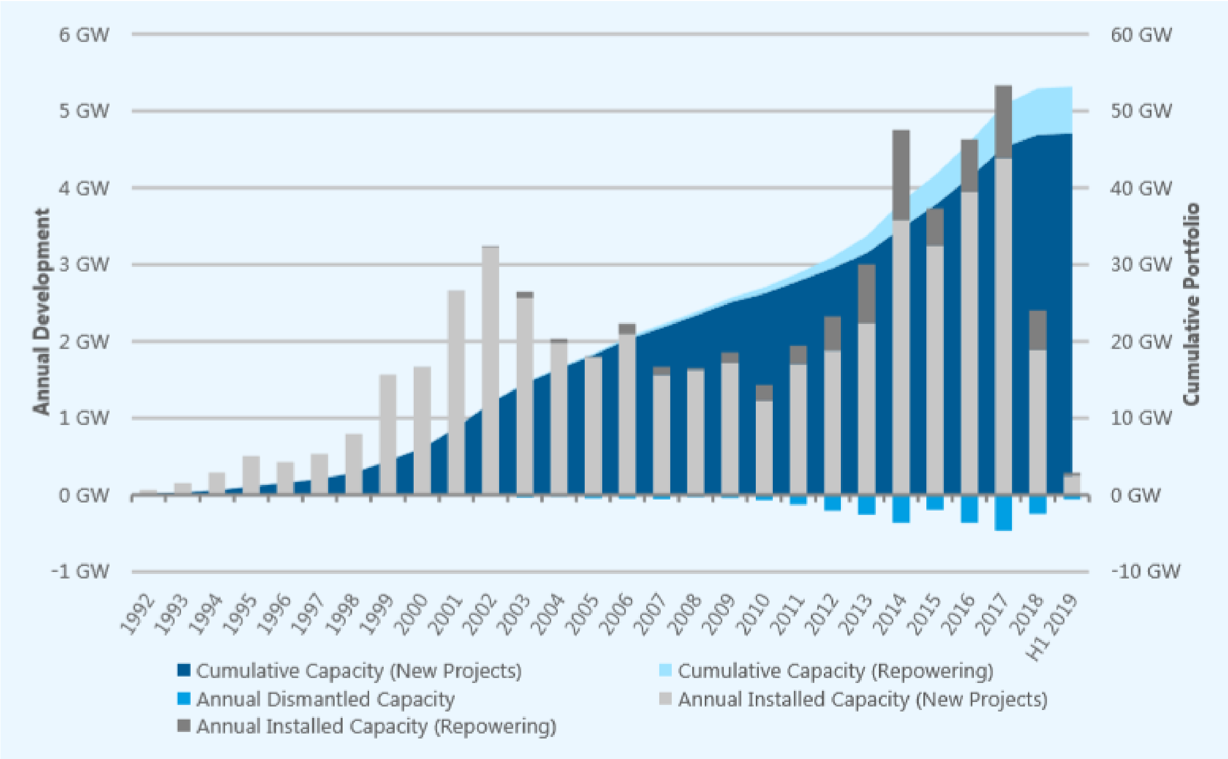
Glass fibre reinforced plastic is the third field with the highest impact (9%). When we have a look at the processes in the results, we see they correspond more specifically to Nylon 6-6 glass-filled manufacture. This composite material is the component of the blades. One of the biggest challenges the wind industry is currently facing is the recycling of this composite as the materials are very attached and they are difficult to separate.

The last factor that has been highlighted is the manufacturing process of concrete needed for the foundation of wind turbines. Clinker is the main component of concrete and it can be seen that it is the third most atmospheric pollutant process in the analysis. ***¡Error! No se encuentra el origen de la referencia.***.

4.1.1 Solutions for future Wind Power

The reduction of GHG emissions in wind power life cycle goes through the optimization of manufacture and end of life, since the emissions during the service life are almost zero.

Around 1999 and 2002 wind power had its breakthrough in the market. Around 9 GW of new wind power plants were installed. Back then the design lifespan was stablished in about 20 years. This results in a multitude of wind turbines whose generation licenses are currently expiring.



DEUTSCHE WINDGUARD

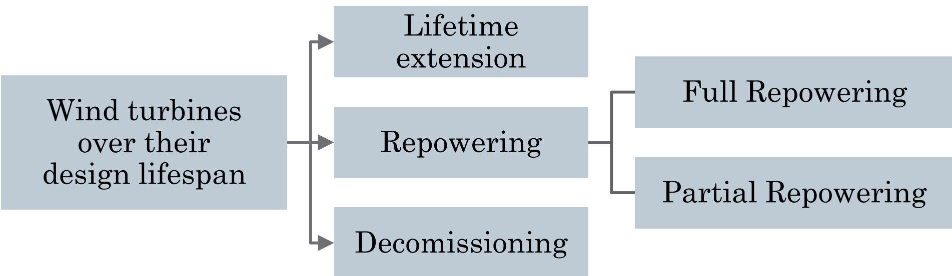
Figure 24: Annual Development Onshore Wind Energy in Germany.

The question now is the design of new generation wind turbines and how to deal with out-of-date turbines to make them more environmentally sustainable.

In one side, there is a good management of the end-of-life.

It has to be mentioned that most of the times the considerations about dismantling a wind plant is made according to the end of commercial agreements, as the Power Purchase Agreement, and regarding the economical yield of the plant. These commercial agreements are usually set for periods shorter than the useful life of the turbines, 12 to 15 years.

The options to be decided on are the following:



- When the project is being cost-effective and the conditions of the wind turbines are good it can be considered to extend their lifetime. Proofs of structural stability, especially for load-transferring structures are needed in these cases. This option can be technically feasible as it has been observed in many cases that the actual service life is longer than the designed lifetime (20 years). The extension of the useful life of a wind turbine means

the cumulative energy output at the end-of-life increases and thus the impact of the manufacture and extraction of raw materials is more amortized, in ecological terms.
The extension of useful life of the model 2 MW wind turbine from 20 to 25 years means extending 1/4th part of the turbine design life. Then:

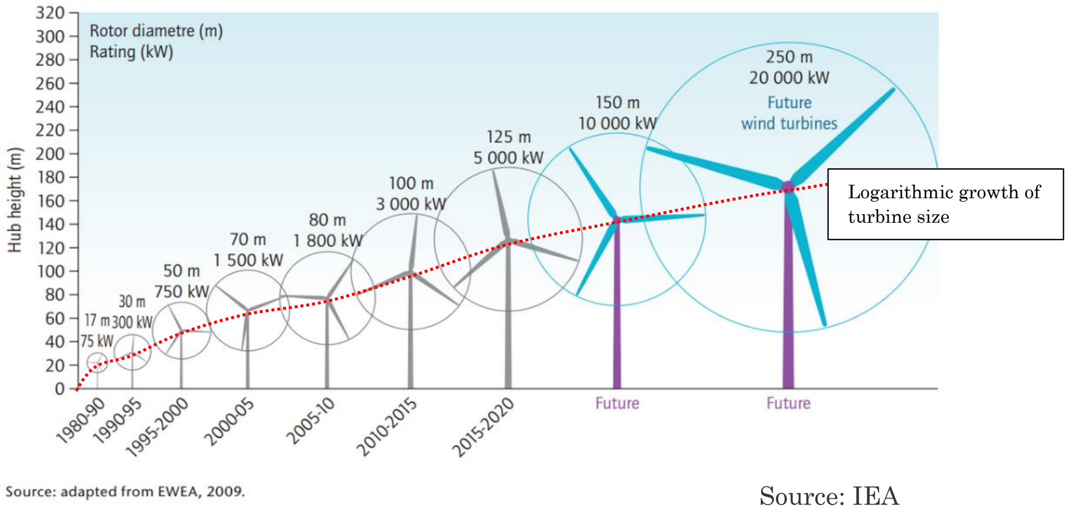
Added energy generated along the whole service life (kWh) * 1,25 = Added energy generated included the extended life period

But the energy production in the last years is reduced because the equipment is becoming less efficient. Finally, that can mean a reduction in its carbon intensity of around 18%, making a rough calculation.

- As the wind power plant ages, the efficiency of the equipment is reduced and the maintenance and operating costs grow. The term repowering is used to define the update of an aging wind power fleet. This way, a more efficient use is made of the existing locations and the average capacity factor of the power station grows. Repowering results to be economically advantageous in many cases.
  New turbines models are more efficient, with longer hub heights and bigger rotor diameters to capture higher wind speeds and wider areas. The average power rating, for onshore projects, installed in Germany in 2018 was 3,2 MW according to Wind Europe 2018 report [13].

  There are two options in case of repowering.

  The first one is the partial repowering. It consists of replacement of some components of the turbines while others are conserved. Commonly the blades and the nacelle are substituted for a new design ones which are more efficient. The new installed blades have slightly larger diameters. The tower, foundations and electrical system are conserved. A review of conditions and update needs to be done to ensure they can sustain the load of new components and the new electrical outputs.



Source: IEA

Figure 25: Evolution wind turbine size.

The second option is the full repowering. In this case the whole fleet of turbines and towers is replaced. Previous towers are not compatible if new larger rotor designs want to be installed, and the old foundations, designed to support structures of 70-90 m high, are not able to support the load of new structures which can reach the 130-140 m. Other infrastructures as electric network and roads are also updated. The growing trend of the turbine's size forces to set less turbines in the same location, as they require more space. However, the total installed power capacity of the project is finally increased.

A full repowering means the reduction of tonnes of material used per kWh of wind energy produced. More specifically the quantity of steel.

Typical cases of repowering nowadays :

Turbines in Dismantled Project

Rated power: 0,9 – 1,5 MW

Hub Heights: 50 – 80 m

Rotor diameters: 50 – 100 m

Repowering →

Turbines in Repowering Project

Rated power: 3 – 4 MW

Hub Heights: 110 – 140 m

Rotor Diameters: 115 – 130 m

A calculation has been made comparing two Vestas machines, a previous design with an up-coming model. *Appendix 5* – Material Use in Turbines. Vestas

Assuming

- Logarithmic development growth of wind technology. The size of future models will grow slower as turbines cannot grow infinitely.
  As the evolution of machines slows down, the next repowering will be worthwhile in a longer period of time. Now the repowering is being made in about 15 year from the beginning of service life. We can forecast that the

  next repowering will take place in around 20 years.
- Yearly Average Wind Speed: 8 m/s
- Percentage of steel in the tower : 83%
- 2 units of an old model 2 MW turbine are substituted for 1 new model 3,45 MW turbine.

	Previous model (2 MW)	**Repowering model (4,2 MW)**	**Variation**
Tonnes steel/ unit	171,3	410,7	
Tonnes of steel	342,6	410,7	
AEP (GWh)	8	17	
Estimated service life	15	20	
Energy generated over service life (GWh)	240	340	↑ 100 GWh
Steel rate (t/ GWh)	1,4	1,2	↓ 0,2 t steel/GWh

Table 3: Repowering approach

It can be seen that the use of the steel for energy production is more efficient so the carbon intensity of steel decreases.

According to World Steel Association, in the new generation turbines, the upgrade of steel from the current used quality in the tower , S355, to S500 could save up to 30% of material. That would mean a reduction of 1,1 g CO2_eq avoided per every kWh generated.

- In some cases, the complete decommission of the whole wind project is made. The dismantled components must be disposed or sold in second-hand markets to be recommissioned, usually in Eastern Europe or South American countries.
  In the case of complete dismantling and in the case of a full repowering, recycling should be regarded as a way to reduce the impact of wind power. Collaboration between wind and chemical industry is under way to increase the circularity. Latest data for recycling of wind turbine components is shown in *Appendix 4* – Recycling rates and disposal routes for wind turbines

  The benefits of using steel as a construction material is that it is 100% recyclable. Steel can be infinitely recyclable without any consequences for its properties. Moreover, steel has a high intrinsic value and in the case of the towers and foundation of wind turbines is very easy to recover and collect. In another side, the recycling of steel is a process which was already consolidated from other industries as automotive or construction. Guarantee the recycling of the steel components coming out of dismantled turbines and purchasing recycled steel in the manufacturing is a good solution to reduce the impact as it prevents the higher emissions of production of primary material.

  At the time of dismantling the rotor of the turbine the disposal of the blades still presents a challenge. The composite material is burdensome to separate completely and hence the big proportion of blades that end in landfills. *Appendix 4* – Recycling rates and disposal routes for wind turbines components

  The incineration of the blades is not an option because it is expensive and highly pollutant. Rethinking the design of the blades structure would facilitate the recycling task. Meanwhile, an alternative solution that is arising is, in one hand, combustion of the organic fraction of the composite in the cement manufacture in order to replace the coal as a fuel. In the other side, the glass fibres have turn out to be suitable to be used in cement production. The fibreglass can be recovered through thermic and chemical treatments. Siliceous ash used in cement manufacture can be partially substituted by the ashes left by glass. The concrete produced could be used in the building of new wind turbines foundations. In the experiences of Lägerdorf cement plant in Germany, they found that up to 50% of the clinker used for concrete could be replaced by this fibreglass ashes. This reduction of material used in concrete for foundations would mean:

Impact of Concrete in total GHG emissions: 5%	→	– Reduction of concrete material in a 50 % + Impact of glass fibre recovery (10%)	→	Approached reduction of emissions over the total impact : ~2%

A precise calculation would be needed to determine if the balance in CO2 emissions of carrying out the recycling processes, is really positive or negative on the contrary.

The reutilization of blades in non-industrial applications, as for example street furniture or integrated in building construction would be positive as well.

- Another approach to the GHG emissions in the wind turbines is to focus on the design of new generation turbine's structure. The steel production is currently having a big impact and about 83% of the steel is in the tower. Therefore, the logical thing to do is to seek the optimization of the amount of material used in the tower structure. Currently 90% of the turbines are using tapered tubular towers. One idea would be to reinvent lattice towers to adapt them to the needs of new designs instead of continuing using tubular towers. A lattice tower could save from 20 to 30% of material compared to a traditional tower structure [17] and maintaining the same strength. In terms of emissions, this would translate into a reduction of the 5%.

Impact of Steel in total GHG emissions: 20% → [– Reduction of steel material in a 25 %] → Approached reduction of emissions over the total wind power impact : ~5%

4.2 Photovoltaics Atmospheric Impact

The emissions of photovoltaic life cycle are concentrated in the building and decommissioning phase, as it is usual in renewable energies. The chart provided by University of Texas Energy Institute illustrates this.

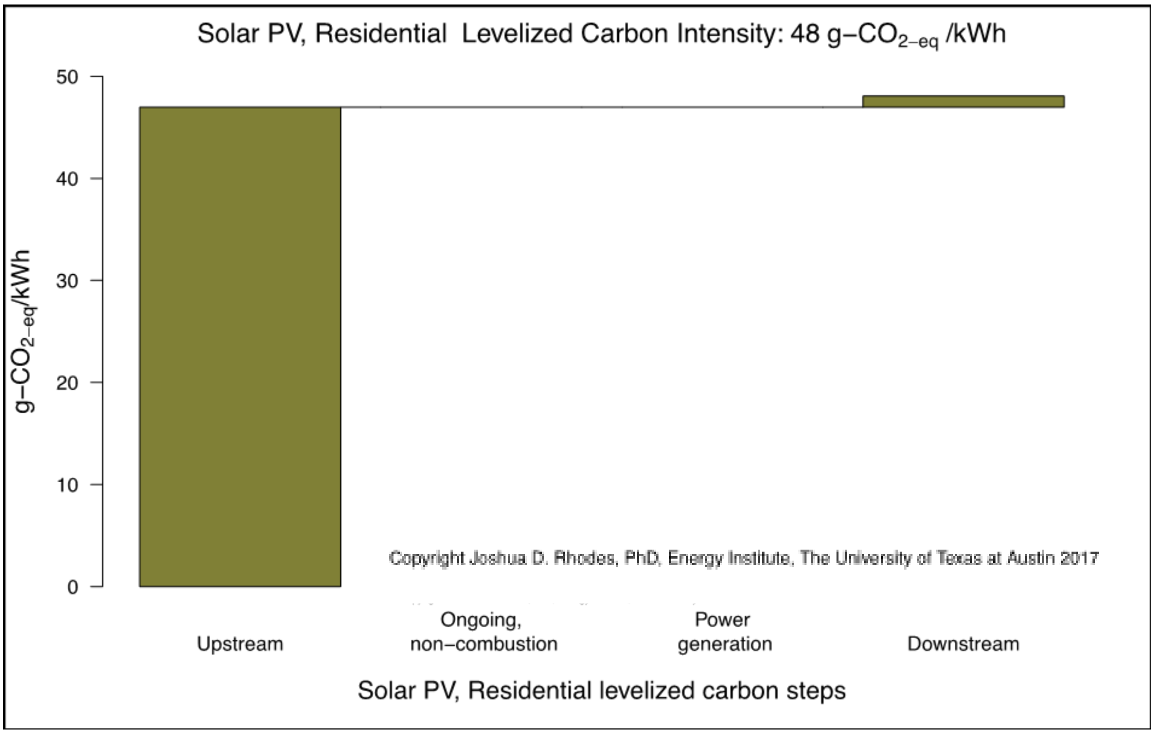


Figure 26: Residential PV levelized carbon Intensity distribution over Life Cycle

Among the production of PV panels, four fields stand out for their significant impact:

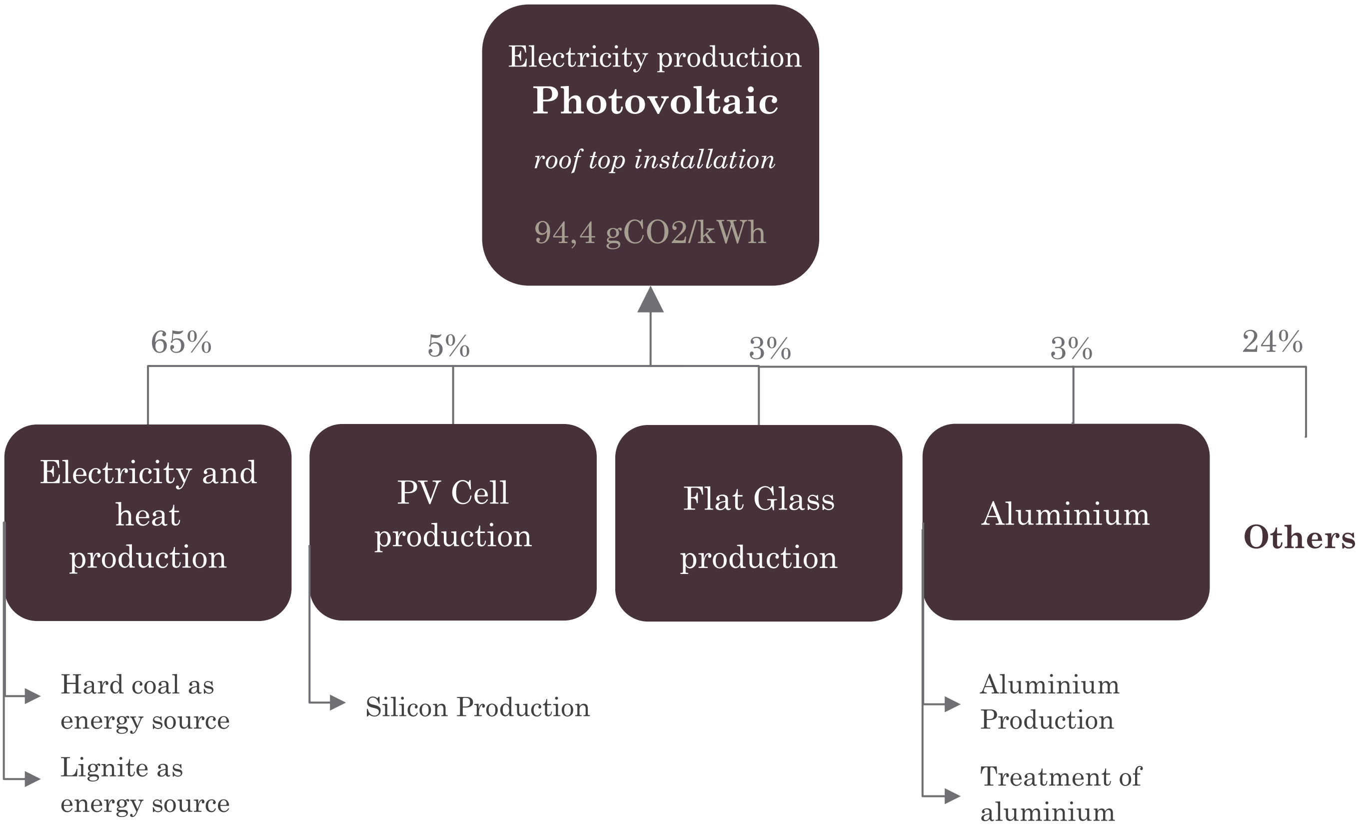


Figure 27: Most pollutant processes in Photovoltaic Power Life Cycle

The following Table shows the six processes that have the biggest impact within the life cycle of a PV roof installation.

	Location	gCO2_eq / kWh	%
hard coal mine operation and hard coal preparation | hard coal | APOS, U	CN	**3,607**	3,82
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | APOS, U	RoW	**2,574**	2,73
electricity production, lignite | electricity, high voltage | APOS, U	DE	**2,215**	2,35
flat glass production, uncoated | flat glass, uncoated | APOS, U	RoW	**2,209**	2,34
electricity production, hard coal | electricity, high voltage | APOS, U	CN-NM	**2,072**	2,19
silicon production, metallurgical grade | silicon, metallurgical grade | APOS, U	RoW	**1,842**	1,95

Table 4: OpenLCA results. 6 most pollutant processes in Photovoltaic Power Life Cycle

To consult the rest of the processes in the OpenLCA results go to *Appendix 3 – Results Photovoltaic in OpenLCA.*

It needs to be mentioned that the Ecoinvent in providing data of 2012. Due to the speed at which PV technology is evolving the results obtained do not correspond exactly with the current situation for PV installations. More updated data is still not available.

It is clearly shown in the schema above that the greatest impact of the PV model studied comes the electricity used in the manufacture of the panels.

From the results obtained for PV roof installation in OpenLCA analysis it has been calculated that:

- Electricity consumption represents 55% over the total GWP impact.
- 27 % of the atmospheric impact is taking place in China.

China lately policies have pledge on renewables and is subsidizing the production of solar panels. This way China manufacturers are being able to sell the panels at half of the price of producing them. This has put the German manufacturers out of the market against their Chinese competitors. The biggest labour costs and tougher environmental regulation in Germany solar industry don't help to equalise the competence. For this reason, currently about 80% of the panels installed in Germany come from Asia. [14]
Despite China's race for renewables, their energy mix is still highly attached to fossil fuels. The consumption of high carbon power to produce the solar panels in China is the cause of their high environmental impact.

In the other side, photovoltaic installed capacity increases very quick while there is still not developed technology to manage the solar modules disposal. Between the processes in Ecoinvent there is not any process for panels treatment for recycling. Besides, many of the waste components disposal consists in incineration, sometimes without energy recovery, which has GHG emissions.

4.2.1 Solutions for future Photovoltaic Power

- PV cell production, more precisely silicon production is an industrial process with a high impact level. Furthermore, many hazardous waste is delivered from this manufacturing. The reduction of amount of silicon used in the PV cell production will reduce the impact.

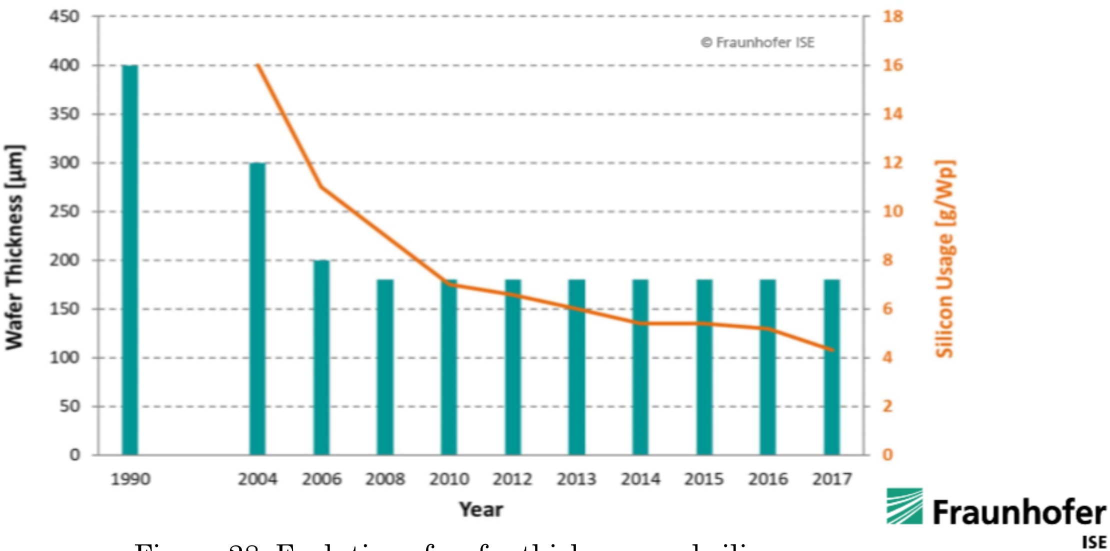


Figure 28: Evolution of wafer thickness and silicon use

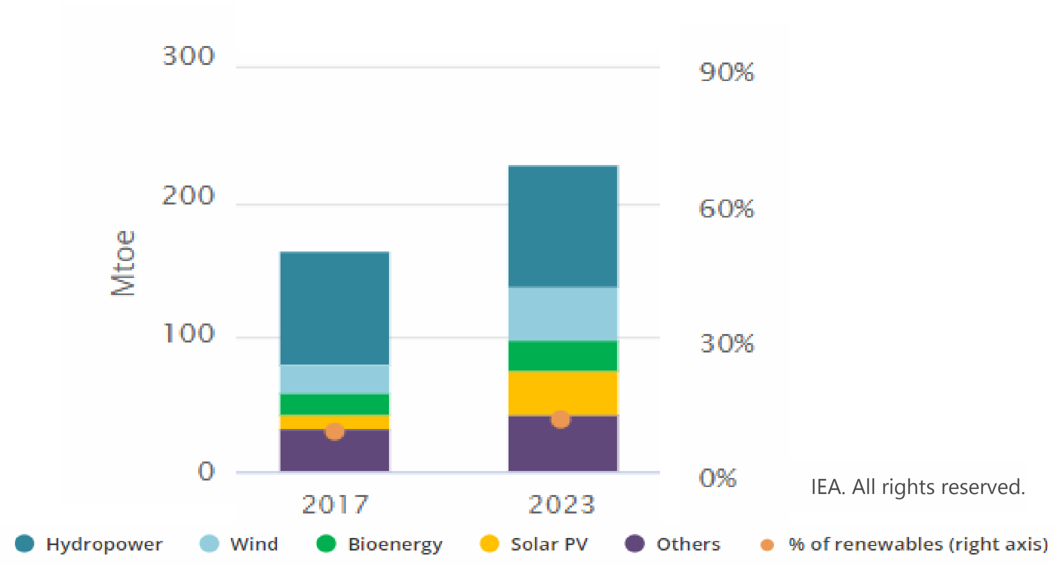
The silicon usage per kWp has decreased at a logarithmic rate since the manufacture of first wafers until 4 grams/kWh in 2017, but the progress is reaching its limits. A 20% reduction of silicon use in wafers could reduce about 1 g of CO_2_eq/kWh regarding the 5% impact shown in the results in OpenLCA. Now, thin film technology is taking the market but its manufacturing is also questionable in terms of environmental impact and emissions.

- Addressing the issue of PV modules production, one option would be to boost the transfer of large-scale manufacturers to central Europe.
  The transportation impact from the production site to the installation site will be reduced, power used for panel production will have less impact as generally, the percentage of non-fossil fuel technologies is higher in the energy mix of European countries.
  Until now the efforts of the German government have failed. In the case that the measures taken by German government will succeed in the task of refloating the PV industry, other environmental factors are not beneficial.

  For example, silicon has to be imported from China or Russia. The volume of raw material that will have to be transported would be bigger than the volume of transporting the manufactured panels, increasing the emissions for transportation. Building new large production facilities will have impact in CO_2 emissions. On top, production phase CO_2 emissions will be moved to Germany.

  This option does not look feasible neither positive for total GHG emissions balance.

- Due to the reasons given above, the other option left is wait for China to increase renewables share in their power mix . This one seems the more realistic scenario.
  IEA presents this forecast for the Chinese power generation scenario.



The share of renewables in total final energy consumption in the European Union is calculated using the methodology outlined in IBRD, World Bank and IEA (2015), Global Tracking Framework (GTF) 2015. The exact calculation and inclusion of specific energy flows may differ from that outlined in EU Directive 2009/28/EC.

Figure 29: Renewable energy consumption in major markets, 2017 and 2023, China. Mtoe and %

According to this forecast, China is slowly going towards a more low carbon emission electricity mix. Some more years will be needed to define the tendency. In any case, in the current solar industry situation, the reduction of PV panels production impact is not in Germany's hands.

- Decommissioning and disposal process for PV modules are decisive in the sustainability of the technology. Until now the panels ended up in landfills but the amount of PV waste coming has set out the need of an effective and safe treatment process. At end-of-life, well implemented procedures should be more strictly regulated by state policies for a more efficient collection of waste modules. Effort should be putted in studying how components of solar panels can be reused to avoid the extraction of new raw material to reduce the GHG emissions of the production process. For example, the aluminium frame and the glass cover of the panel can be easily separated and recycled.

  Many private PV modules holders are not decommissioning their installations because, despite the drop on the efficiency of the equipment, the maintenance costs are low, they still get enough free electricity for self-consuming and they are receiving money from feed-in tariffs for their surplus energy feed into the grid. That is making the facilities to extend their lifespan, which is beneficial for the reduction of carbon intensity.

  The process of recycling solar modules is a brand-new issue in the chemical industry. The process is still not well-developed.

  A further study should be made to calculate if when accounting the GHG emissions of recycling the modules PV is still environmentally friendly.

5 Conclusions and Outlook

5.1 Summary

Along the study it has been seen that, despite the positive contribution of wind onshore power and small photovoltaic generating facilities to reduce the carbon emissions of German energy industry, this technologies can still go further in their aim to produce the electricity demanded by society with lower carbon emissions.

The aspect with highest impact in wind onshore power is the production of steel.

The alternatives presented to reduce the atmospheric impact of a Wind turbine are:

- Try to adapt commercial agreements to be able to extend as long as possible the service life of wind projects without compromising their economic security.
- When repowering, balance the avoided GHG emissions of generating higher amounts of power with wind technology with the added emissions of manufacturing brand new components for a new project.
- Increase the recycling rates of steel from the tower and foundations, composite material for the blades and concrete from foundations and the use of this recycled materials in the manufacture of next generation turbines.
- Come back to the lattice towers concept.

The aspect with highest impact in small photovoltaic installations is the electricity consumption for the manufacturing process.

The alternatives presented to reduce the atmospheric impact of PV are:

- Reduction of silicon material use in PV wafers.
- The increase of renewable share in China or the use of low carbon electricity for the manufacturing process.
- Development of safe and efficient recycling processes for the solar modules.

The two main ideas that arise are the reduction of material used for components of energy facilities, particularly steel in wind and silicon in PV, and the need of improving the recyclability of the components.

It has been seen that, the use of fossil fuels in the production of components for the renewable wind and photovoltaic energy facilities is not dispensable.

Also, the idea is noticed that, the increase of renewables share itself, causes the reduction of CO_2 emissions to the atmosphere produced by manufacture of components for renewable installations.

5.2 Conclusion

GHG emissions to the atmosphere is relevant but it isn't the only factor that needs to matter in the decision of choosing an energy technology. Resource depletion, toxicity for human health and other impacts caused by the building, operation and decommissioning of the technology should count in the decision making along with the GWP.

The exchange of knowledge and collaboration between industries (energy industry, chemical industry, metallurgical industry) for the development of the new models for wind and photovoltaics is of vital importance for the sustainability of the product. The design phase needs to develop facing the decommissioning and recycling phases.

Policies and energy development should not be led by the Green trend. They should be well planned trough wise and conscious measures which are based in a broad view of the energetic scene. This will be crucial for the society development, influencing the environmental safety, the economy and the energetic independence of the county.

If Germany wants to relay mainly in wind and solar in the future, the transition must be accompanied by a development in the design and all the other processes in the life cycle of the product.

Enhancement in existing non-CO2-emitting power technologies, energy storage and alternative energy solutions need a major boost. More investment in energy technological research is needed to front successfully the climatic dilemma. Otherwise, the deadlock in the energy industry situation will continue and Germany will be driven to continue using coal.

5.3 Outlook

Related to the research developed during this work the following issues arise as influent for the future energy scenario:

- How will the market react to the phase-out of feed-in tariffs for renewable energies in the next years?
- Thin film or crystalline silicon. Which technology will assure a low pollutant development for photovoltaic energy?
- Is recycling process of PV modules environmentally friendly? How could it be improved?
- How will it affect in the long-term to bet on coal-to-gas transition now?
- Hybrid Wind-Solar systems. How can they leverage each other.
- Which is the storage role in energy transition? How can storage condition a secure energy supply with a high renewables share.
  (Thermal storage, Melted salts storage, Pumped storage, Power-to-gas technology as solution for energy storage)

Appendices

Appendix 1 – German Energy Context

Germany is the European country with the highest total electricity production. In 2016 Germany generated 614 155 gigawatt-hour of electricity.

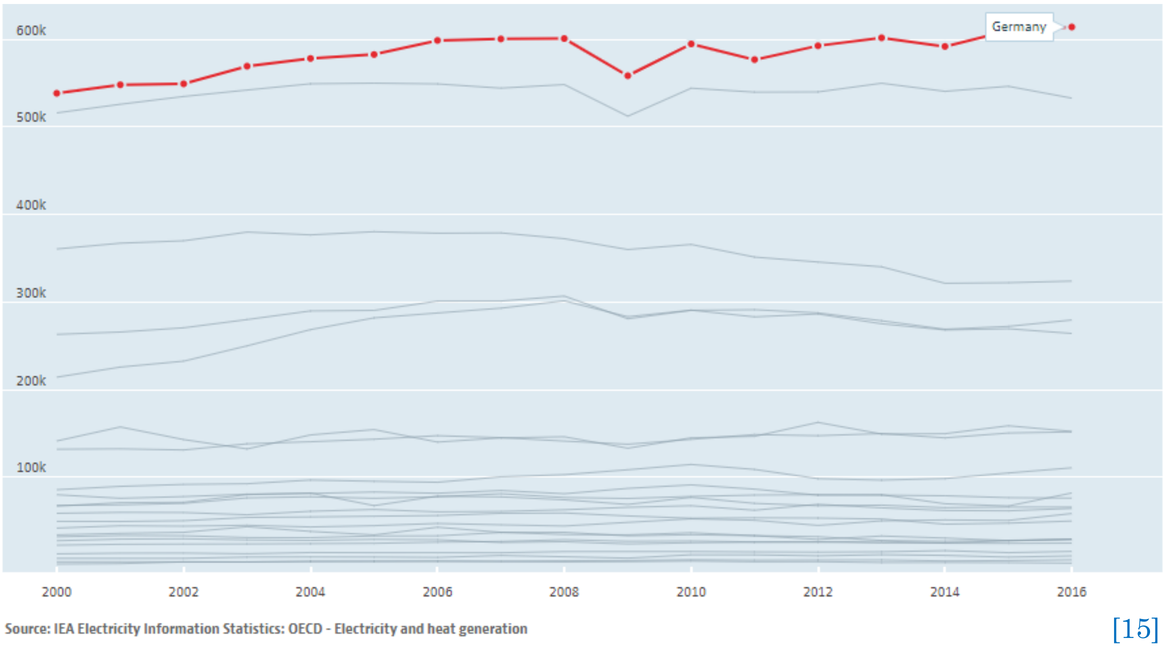
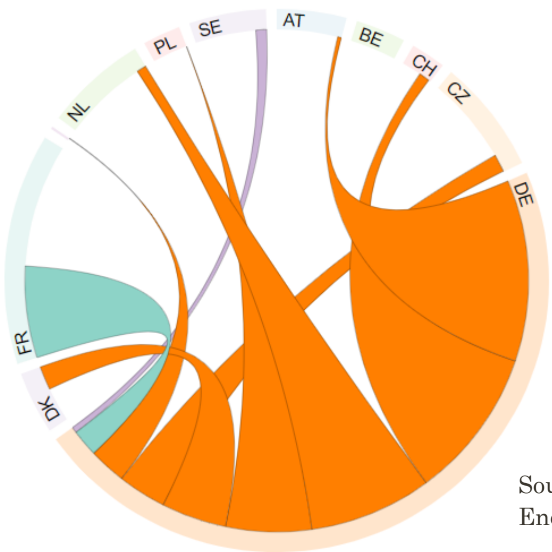


Figure 30: German Electricity generation in total GWh 2000-2017

Consequently, Germany is exporting electricity to all the surrounding countries, Denmark, France, Netherlands, Poland, Sweden, Austria, Belgium, Switzerland and Czech Republic.



Source: Fraunhofer Institute, Energy charts.

Figure 31: Electricity exchange of Germany in 2019

In the Figure 32, it can be seen how the German electric scenario has changed since the application of the Law for energy transition (EEG) (2000) until the year 2015. Wind technology experiments a huge development. As well does solar photovoltaic and biofuels, but to a lesser extent. The drop-off of the nuclear generating power can be clearly distinguished after the Fukushima accident in 2011.

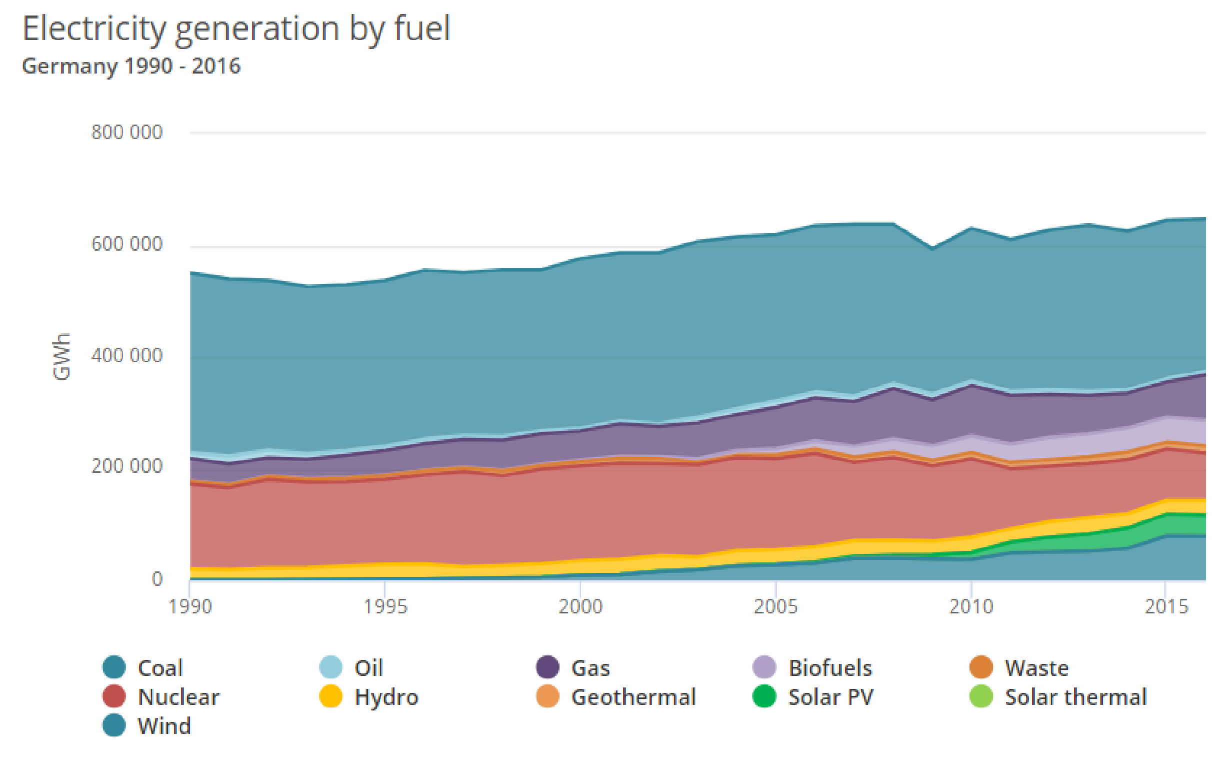


Figure 32: Energy production evolution by fuel. Germany

Inside the renewable technologies it can be noticed a clear layout of wind power in the north regions of germany overall near the sea, while photovoltaics are more frequent in the south were the the climatic conditions accompany. See Figue 33 .

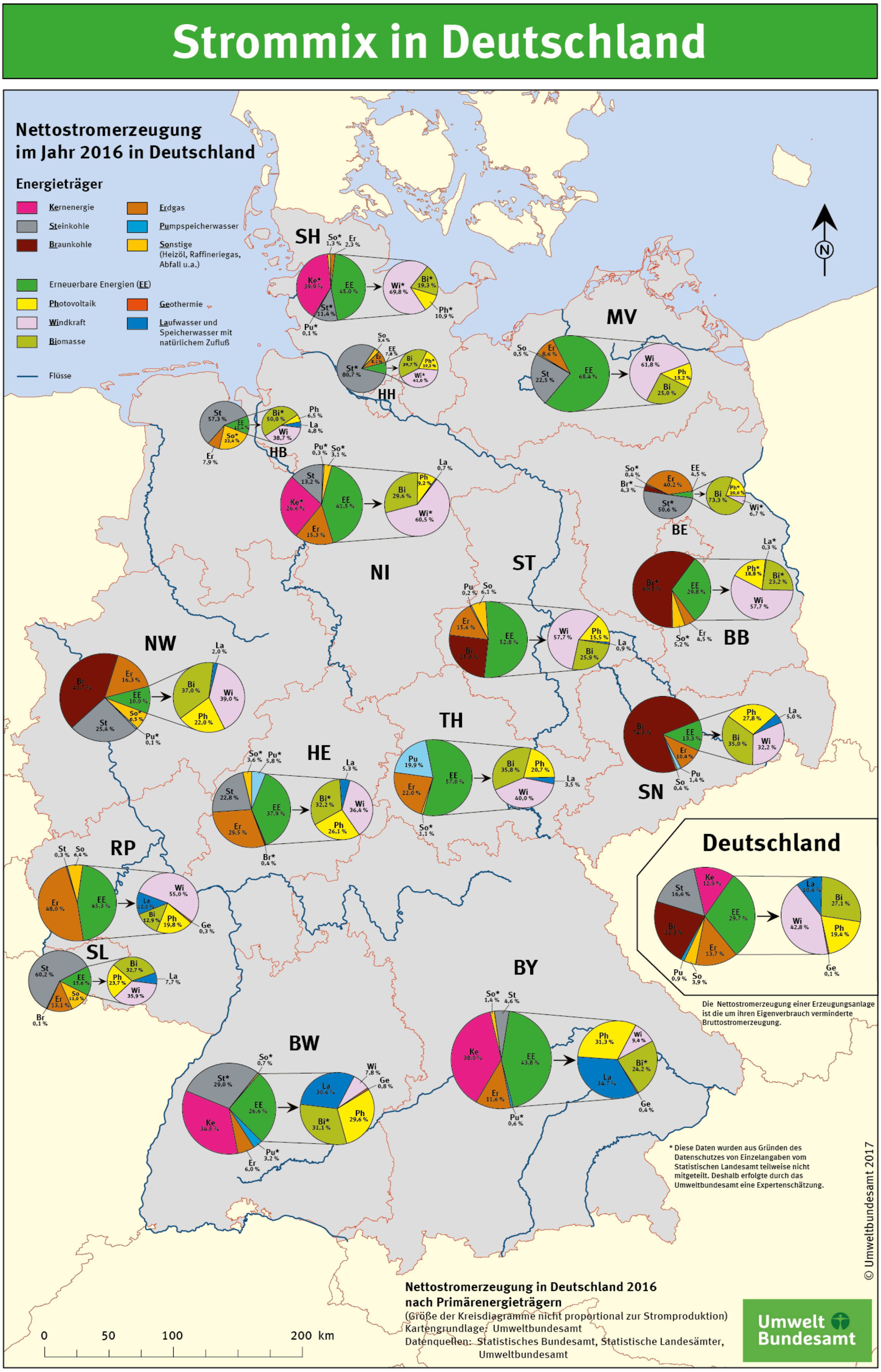


Figure 33: Power mix in Germany specified by regions (2016)

Appendix 2 – Results Wind Power in OpenLCA

Process UUID	Process	Location	g CO2 eq/kWh	%
147a945f-cccc-32c9-afd7-1e7a81700654	pig iron production | pig iron | APOS, U	GLO	1,977	10,70
847be57f-2525-3fbc-af28-d0cb9227f7ea	nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | APOS, U	RoW	1,090	5,90
fa5f67d1-548d-3287-8835-0d6450b6fef2	clinker production | clinker | APOS, U	RoW	0,832	4,50
cd27125d-f953-3dbe-9889-4d3539cba958	heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | APOS, U	RoW	0,781	4,22
089d4fb8-8efc-342f-80f9-d524755133d3	sinter production, iron | sinter, iron | APOS, U	GLO	0,618	3,35
17df5c93-e468-3ad8-b88c-61091ec8ce70	diesel, burned in building machine | diesel, burned in building machine | APOS, U	GLO	0,614	3,32
88c8a412-e014-3550-85fa-5ecaf9b39818	nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | APOS, U	RER	0,539	2,91
a3ab30b9-0558-3adf-a072-cf7375b4e50c	hard coal mine operation and hard coal preparation | hard coal | APOS, U	CN	0,515	2,79
defa0b7b-131b-3054-9cc6-7854cfc95d8a	quicklime production, in pieces, loose | quicklime, in pieces, loose | APOS, U	RoW	0,343	1,86
f4107146-0a29-3bd1-b077-346ab7bffb7c	treatment of blast furnace gas, in power plant | blast furnace gas | APOS, U	JP	0,264	1,43
8791dd21-eefc-39af-8590-c2f23ea6854d	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, U	GLO	0,240	1,30
c5d49517-fe2a-3612-8d57-1f06483b9e94	electricity production, hard coal | electricity, high voltage | APOS, U	CN-NM	0,187	1,01
06ff0afb-b133-376f-9e74-c5c13a751bf5	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | APOS, U	Europe without CH	0,185	1,00

0bcd9978-13a5-3fef-a551-e22b3567a041	electricity production, hard coal | electricity, high voltage | APOS, U	CN-JS	0,141	0,76
6fdd9f66-6ec4-361e-8f97-430e915653ba	electricity production, hard coal | electricity, high voltage | APOS, U	CN-SD	0,140	0,76
540557ba-91e3-3bf7-b43a-46c442d2ac54	coking | coke | APOS, U	RoW	0,140	0,76
15fe3b75-d385-328a-b2af-df6da6ecb8a6	treatment of blast furnace gas, in power plant | blast furnace gas | APOS, U	KR	0,138	0,75
e51a9ced-2192-31ec-b121-218ca812fd0f	steel production, converter, low-alloyed | steel, low-alloyed | APOS, U	RoW	0,133	0,72
fa815a05-c61f-3879-a3a9-ee174ac9a431	treatment of waste polyethylene, municipal incineration | waste polyethylene | APOS, U	RoW	0,131	0,71
d8cb3108-bc0c-3afa-8d20-0a8c0b1700eb	electricity production, natural gas, conventional power plant | electricity, high voltage | APOS, U	RoW	0,124	0,67

Table 5: Results Wind. OpenLCA Analysis. Unit processes

Processes related to Steel production

Processes related to Glass Fibre reinforced Plastic production

Processes related to Concrete production

Appendix 3 – Results Photovoltaic in OpenLCA

Process UUID	Process	Location	gCO2_eq / kWh	%
a3ab30b9-0558-3adf-a072-cf7375b4e50c	hard coal mine operation and hard coal preparation | hard coal | APOS, U	CN	3,607	3,82
cd27125d-f953-3dbe-9889-4d3539cba958	heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | APOS, U	RoW	2,574	2,73
052a1124-9505-3987-ae4a-1c58abb26d45	electricity production, lignite | electricity, high voltage | APOS, U	DE	2,215	2,35
ca901374-2778-3cec-9869-cac0c4d9d854	**flat glass production**, uncoated | flat glass, uncoated | APOS, U	RoW	2,209	2,34
c5d49517-fe2a-3612-8d57-1f06483b9e94	electricity production, hard coal | electricity, high voltage | APOS, U	CN-NM	2,072	2,19
86e96f8a-beb2-3bd8-bca7-7509ea44fa29	**silicon production**, metallurgical grade | silicon, metallurgical grade | APOS, U	RoW	1,842	1,95
d8cb3108-bc0c-3afa-8d20-0a8c0b1700eb	electricity production, natural gas, conventional power plant | electricity, high voltage | APOS, U	RoW	1,636	1,73
0bcd9978-13a5-3fef-a551-e22b3567a041	electricity production, hard coal | electricity, high voltage | APOS, U	CN-JS	1,588	1,68
6fdd9f66-6ec4-361e-8f97-430e915653ba	electricity production, hard coal | electricity, high voltage | APOS, U	CN-SD	1,559	1,65
992bd34a-fdf7-3e59-8e04-32ffe20fcfb5	electricity production, hard coal | electricity, high voltage | APOS, U	CN-SX	1,204	1,28
bef3af1d-cdd0-35eb-8827-fcde24ddda61	electricity production, hard coal | electricity, high voltage | APOS, U	DE	1,189	1,26
fbaf61b3-f8ec-31f1-9bff-a6a4aa4f3744	electricity production, hard coal | electricity, high voltage | APOS, U	CN-HE	1,180	1,25
a2a9a276-e0c0-34f1-991c-08748e326903	**ethylene production**, average | ethylene, average | APOS, U	RoW	1,163	1,23

702208c9-e010-361b-be58-4b872dd9e3db	electricity production, lignite | electricity, high voltage | APOS, U	RFC		1,091	1,16
40bdb565-7e7e-3e65-9c4e-6367150f32ba	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | heat, district or industrial, natural gas | APOS, U	RU		1,079	1,14
5b2bcfdb-7370-3018-a917-8694ce2e84ac	silicon carbide production | silicon carbide | APOS, U	RoW		1,039	1,10
daf0c5a4-5efe-3d14-88b8-1b4c183a38c9	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | electricity, high voltage | APOS, U	RU		1,037	1,10
b219d2a0-2312-351a-a6fb-37abfabf769b	electricity production, hard coal, conventional | electricity, high voltage | APOS, U	ZA		1,035	1,10
f976092b-e69f-3c65-b9d0-65057527b31c	electricity production, lignite | electricity, high voltage | APOS, U	SERC		1,033	1,09
eb24c5c3-4ebe-3da3-a0ad-9922ebb7bae3	electricity production, hard coal | electricity, high voltage | APOS, U	CN-HB		1,032	1,09
66b71901-5638-3cc7-8e08-4502e95921c6	treatment of used cable | copper | APOS, U	GLO		1,000	1,06
d4660e8e-5ed7-3ad5-9193-b201e86d061b	**aluminium production**, primary, liquid, prebake | aluminium, primary, liquid | APOS, U	CN		0,998	1,06
147a945f-cccc-32c9-afd7-1e7a81700654	**pig iron production** | pig iron | APOS, U	GLO		0,980	1,04
06ff0afb-b133-376f-9e74-c5c13a751bf5	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | APOS, U	Europe without CH		0,965	1,02

Table 6: Results Photovoltaic . OpenLCA Analysis. Unit processes

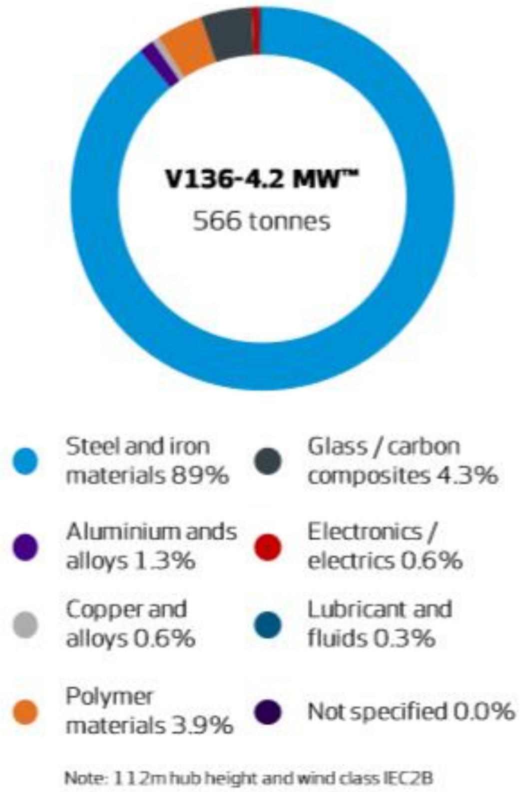
(yellow)	Processes related to Electricity production
(red)	Processes taking place in China

Appendix 4 – Recycling rates and disposal routes for wind turbines components

Material	Recycling / Disposal rate %	Disposal method
Ferrous high alloy	98	Recycling
Ferrous metal	95	Recycling
Steel		Recycling
Aluminium and aluminium alloys	95	Recycling
Copper, magnesium, nickel, zinc and their alloys	98	Recycling
Precious metals and other non-ferrous metals and alloys	98	Recycling
Plastic, rubber and other organic materials	100	Incineration with energy recovery
Electronics	50	Recycling with energy recovery
Batteries	100	Recycling
Concrete, bricks etc	64	Landfill
Sand and gravel	0	Remains in the ground after wind farm is dismantled
Blades	95	Landfill or recycling
Remaining materials		Incineration or Landfill

Modified from DTU International Energy Report 2014 [12]

Appendix 5 – Material Use in Turbines. Vestas



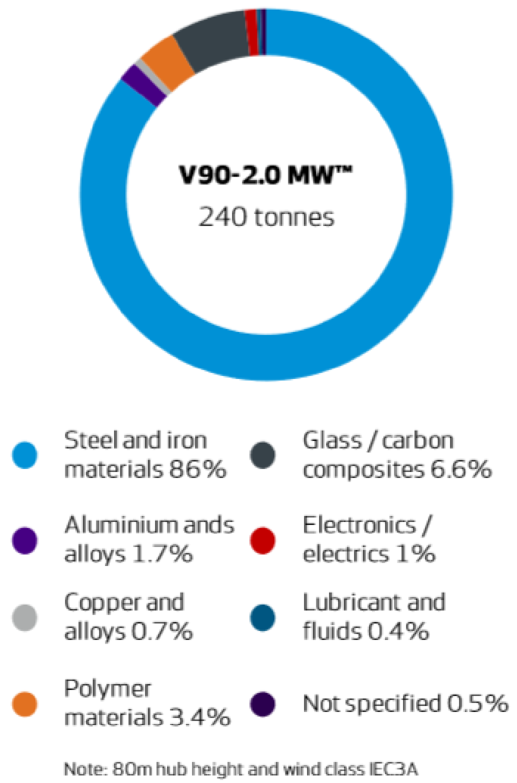


Figure 34: New generation turbine V136-4,2MW [16]

Figure 35: Previous generation turbine V90-2MW

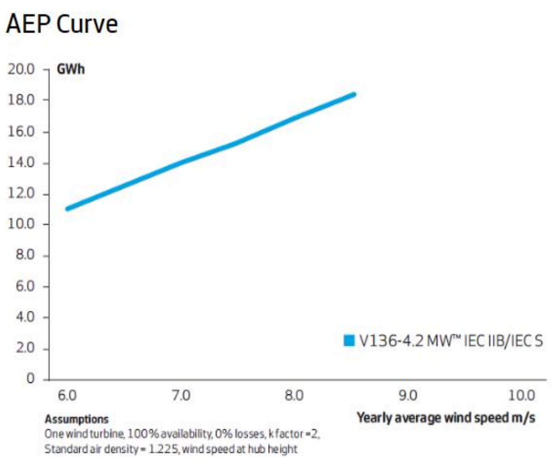


Figure 36: AEP V136 - 4,2 MW

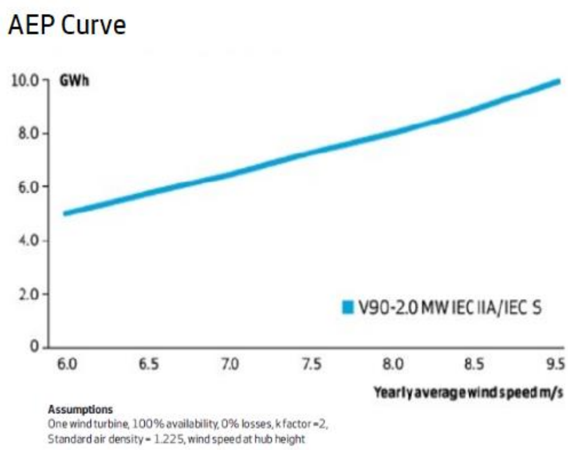


Figure 37: AEP V90 - 2 MW

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