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DEVELOPING CARBON FOOTPRINT ASSESSMENT OF WIND TURBINES: APPLIED TO THE UNITED KINGDOM

RESEARCH PROJECT

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ABSTRACT

Wind energy is being developed in many countries in order to achieve their target of reducing CO_2 emissions, but wind energy is not free of them, although they are not produced during the electricity generation process, carbon footprint is embodied in the turbine's life cycle. The aim of this research is to create a methodology to calculate the carbon footprint embodied in a wind turbine during the whole life cycle in order to understand the benefits of the wind energy. The methodology developed considers all carbon dioxide emissions embodied in the whole life cycle of a wind turbine, it includes the carbon footprint due to the manufacture and the transportation of the materials to the location where the wind turbine is placed, energy consumed during the installation, operation & maintenance, decommissioning and finally, the transportation to the landfill where wind turbine is uninstalled, however it is necessary to dock the carbon footprint from the materials which have been recycled. It was determinated which power rating is more efficient in terms of CO_2 savings for turbines of the same technology (onshore or offshore) and it was shown, in case of onshore wind turbines, that the more installed capacity the wind turbine has, the more efficient it is in terms of CO_2 savings. However, in case of offshore turbines, the less the installed capacity is, the more efficient the turbine is. Moreover, it was known that most of the carbon footprint of onshore and offshore turbines is due to the manufacture of the materials, around an 80%, this is because most of the carbon footprint embodied in a wind turbine is produced before it starts working. Although, if wind turbines are recycled more than 30% of carbon footprint is saved, so it is really important to recycle them. Furthermore, it was estimated that the payback time in terms of carbon dioxide emissions for an average onshore and offshore UK turbine is around one year and two months. Finally, it was estimated that the total CO_2 emissions savings in UK due to the wind technology is more than 79,000,000 tonnes of CO_2. Moreover, it was shown that ratio carbon footprint/energy generated in UK onshore turbines is 18.9 gCO_2/kWh and 20.1 gCO_2/kWh in the offshore one, while the electricity generation mix ratio in United Kingdom is 275 gCO_2/kWh, so wind energy brings important benefits in reducing carbon footprint.

GLOSSARY OF TERMS

Life Cycle Inventory – LCI

Operation & Maintenance – O&M

United Kingdom – UK

Carbon footprint – CF

Tonnes – t

Kilogramme – kg

Gramme – g

Gigawatt-hour – GWh

Megawatt-hour – MWh

Kilowatt-hour – kWh

Carbon dioxide – CO_2

1. INTRODUCTION

In December 2015 in Paris, 195 countries made a climate agreement, first time ever, to reduce greenhouse gas emissions and keep the global temperature below 2ºC in comparison to preindustrial levels. The next step of this agreement is achieving zero CO_2 emissions as early as in 2050. The development of this agreement comes as the result of environmental damages produced by green house emissions.

It is necessary to reduce fossil fuels consumptions, since they increase greenhouse gases. They can be replaced by renewable energies such as wind power. They have different advantages: they are inexhaustible, while conventional energy sources such as coal, gas, oil or nuclear energy are not; they reduce energy dependency, since they use renewable sources, such as wind, solar, organic matter, available all around the planet, while fossil fuels need to be sold and carried from some countries to others; they are increasingly competitive, since they are reducing their cost and can compete against conventional energies. Moreover policies support them, since the European Union 20-20-20 targets are a 20% cut in emissions of greenhouse gases, a 20% increase in the share of renewables in the energy mix and a 20% cut in energy consumption by 2020.

There are two types of wind technologies: offshore and onshore. Offshore wind installations have different advantages over onshore ones *(Instituto para la Diversificación y Ahorro de Energía (IDAE), 2006)* there are no obstacles on the sea that could reduce wind speed, therefore speed is higher and towers can be smaller than onshore wind towers; it is windier at sea, so bigger turbines can be manufactured in order to produce more energy; marine areas are larger, so there are more spaces where wind turbines can be placed, then offshore wind farms can be bigger than onshore ones; they eliminate the visual impact, since they are placed far away from population centres, therefore sound restrictions are not as rigorous as onshore ones, then blade tip speed can be increased, so weight can be reduced which means that production costs are lower.

On the other hand, offshore wind turbines represent some problems: there are no electrical infrastructures to connect these offshore installations with consumption centres; this technology is really expensive because of foundation and electricity grid costs; it is difficult to assemble and maintain these installations on the sea and costs and assembling difficulties are proportional to undersea depth and distance from the shore.

Next step in offshore wind energy is placing turbines in deeper water to benefit from better wind conditions, however, as mentioned before, the deeper and more distanced from the shore, the more difficult and expensive it is. Furthermore, the carbon embodied is bigger as well *(Kaldellis & Apostolou, 2017)*, since towers are taller because they need to be moored on the sea bottom, a lot of ballast is required to make the foundations, the generator and its blades are bigger too, cables to transport electricity are longer to reach the shore. To sum up, the more material needed, the more carbon emissions during their manufacture. Moreover, the fuel consumption for trucks and ships to carry out the materials to the place where they are sited, is high. And then, their maintenance must be done by a helicopter which increases even more the carbon embodied *(Weinzettel et al., 2009)*, this is why offshore carbon footprint is bigger than onshore one.

As said beforehand, offshore wind turbines are placed far away from population centres, so they do not have visual impact or the need for noise restrictions. But they continue having environmental consequences, such as noise, toxic effects and electromagnetic fields from cables, that are socially accepted only because they are located in marine ecosystems. Moreover, it can affect birds as well, since they can collide with facilities and they must change their migratory movements *(Kaldellis et al., 2016)*.

1.1. Current and up to date

Pollution in the world is increasing so renewable energies are being developed to reduce CO_2 emissions. Wind energy can produce a big amount of energy, but there is a carbon footprint embodied in their life cycle.

Berndt *(Berndt, 2015)* shows that there is an important amount of CO_2 emissions associated with concrete foundations. A substantial reduction can be achieved if fly ash or blast furnace slag is used. Moreover, the more compressive strength, the less environmentally friendly the foundation is.

Offshore wind turbines are being developed, and they will replace onshore ones because they can be placed where wind speed is higher, since the more distanced from the shore, the better wind conditions. But the main problem is they are really expensive and have an important carbon footprint embodied, although reducing this carbon footprint is possible.

New techniques are being studied to reduce carbon footprint such as increasing wind turbines reliability and more efficient maintenance, building vessels to make installation and maintenance easier or using floating platforms to be placed in deeper water *(Kaldellis et al., 2016)*.

Importing and exporting wind energy can be a good way to reduce CO_2 emissions. It *(Cleary et al., 2016)* shows that the more wind energy, the less gas and coal fired generation, so important reductions can be achieved.

1.2. Electricity generation in the United Kingdom

It is shown that renewable energies are in second place in electricity generation after gas in 2016 in the United Kingdom and they will increase their percentage year on year *(Department for Bussines, Energy and Industrial Strategy, 2017)*.

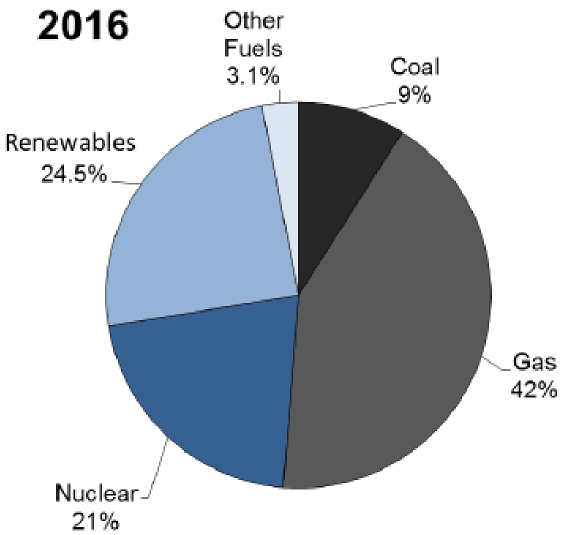

Figure 1.1. Electricity generation distribution (Department for Bussines, Energy and Industrial Strategy, 2017)

The total electricity production in 2016 was 336,438 GWh, so renewable energies generated 83,225 GWh. Wind energy is the most used to produce electricty among all renewable energies.

It produced around 45% of green energy in the United Kingdom in 2016, that makes 37,368 GWh. It corresponds to 11.1% of the total electricity generation in the UK.

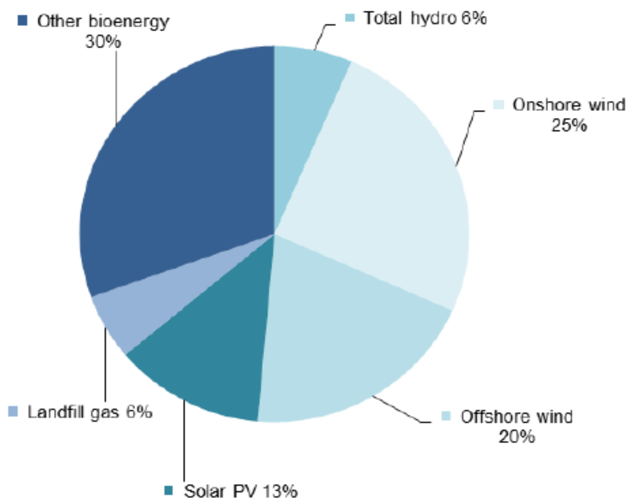

Figure 1.2. Renewable electricity generation *(Department for Bussines, Energy and Industrial Strategy, 2017)*

1.3. Offshore and onshore wind turbines in the United Kingdom

The next table shows the number of operational wind turbines at end of December 2016 in the UK, the installed capacity and the electricity power generated *(Department for Bussines, Energy and Industrial Strategy, 2017)*.

Table 1.1. Onshore and Offshore Wind characteristic

Type of technology	Number of turbines	Installed capacity (MW)	Power generated (GWh)
Onshore Wind	13,100	10,923	20,962
Offshore Wind	1,465	5,293	16,406

The differences between onshore and offshore technology are shown in the following table:

Table 1.2. Onshore and Offshore wind turbines characteristics

Type of technology	Installed capacity per turbine (MW)	Power generated per turbine (GWh)
Onshore Wind	0.83	1.60
Offshore Wind	3.61	11.20

As it is shown, offshore installed capacity per turbine is four times the onshore one. Moreover, power generated per offshore turbine is ten times the onshore turbine one.

In the next table, it is shown how many hours per year, turbines are working with full power and the percentage of time that it happens.

Table 1.3. Onshore and Offshore wind turbines working time

Type of technology	Total working time (h)	Percentage of time (%)
Onshore Wind	1,919	21.85%
Offshore Wind	3,100	35.29%

Therefore, offshore wind turbines are working with full power more time than onshore ones, so they are more energetically efficient and have more power but their main problem is the cost and the amount of carbon embodied in them, which is more than in onshore turbines.

This figure shows all wind farms installed in United Kingdom and their installed capacities.

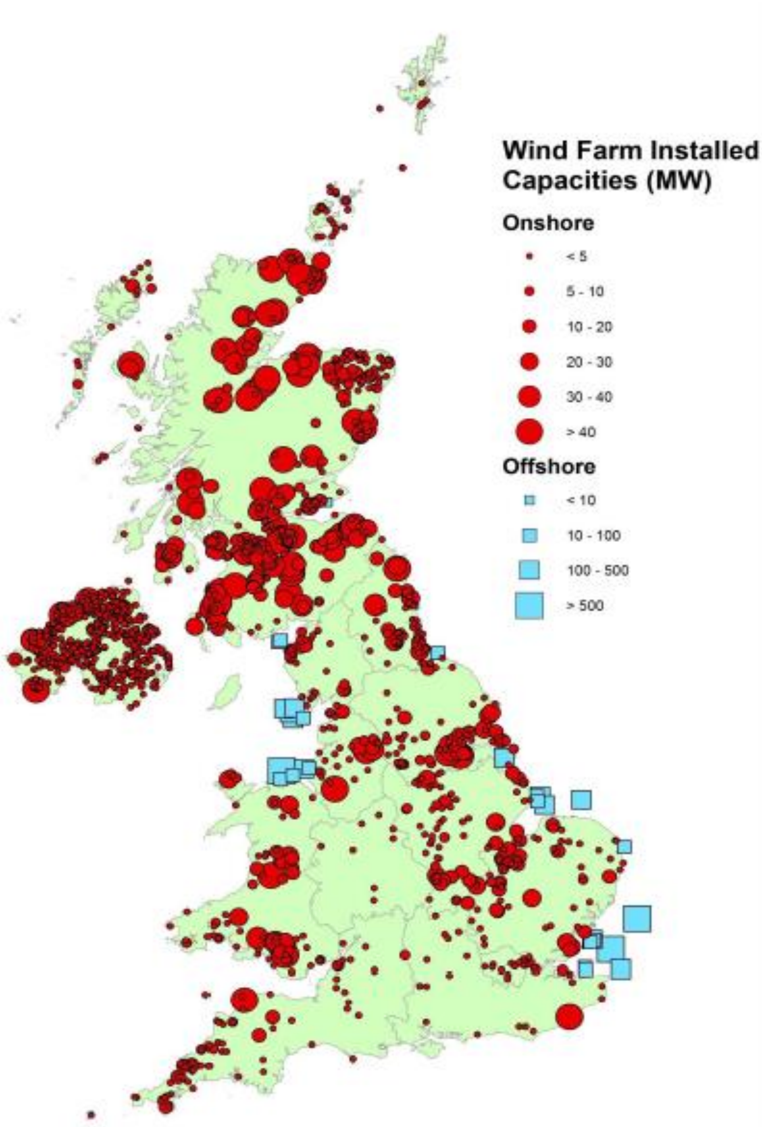

Figure 1.3. Wind farms in United Kingdom (Department for Bussines, Energy and Industrial Strategy, 2017)

2. BACKGROUND AND LITERATURE REVIEW

Wind power started in the 1960s when people began to worry about climate change. During the Oil Crisis in the 1970s alternative power sources where developed, such as wind energy, but the total installed capacity was little, around 1500 MW. Wind turbines were not highly developed until the 2000s when Europe made an important investment *(Ahlfors, 2017)*, when governments started to be worried about environmental pollution. Nowadays, the evolution is still linear, getting bigger each year.

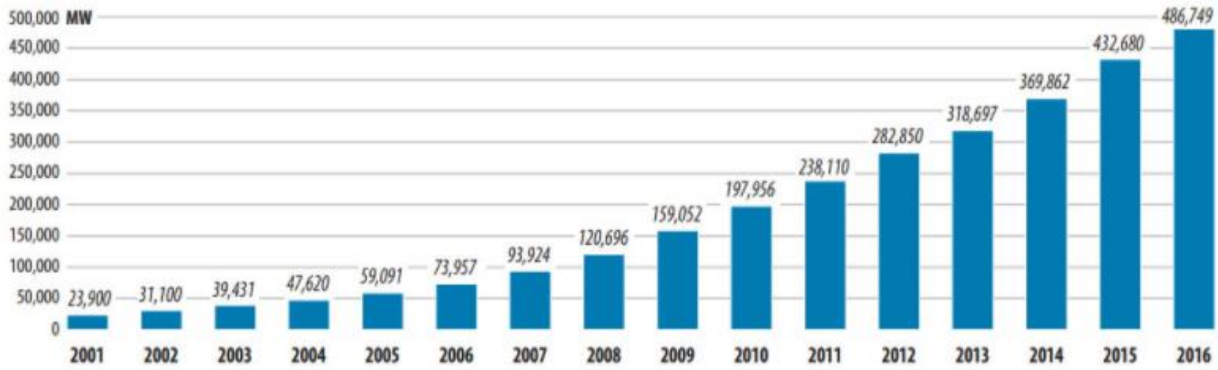

Figure 2.1. Wind energy capacity installed in the world (Asociación Empresaria Eólica (AEE), 2018)

Offshore installed capacity is considerably less than the onshore one. This is because it is a recent technique, from the 2000s, and it is still very expensive. However, it is shown that evolution is exponential, so every year offshore installed capacity increases considerably. In the future, this will be the most used technique, since energetic efficiency is bigger than in onshore turbines as wind conditions are better at sea, but firstly, cost reductions have to be achieved.

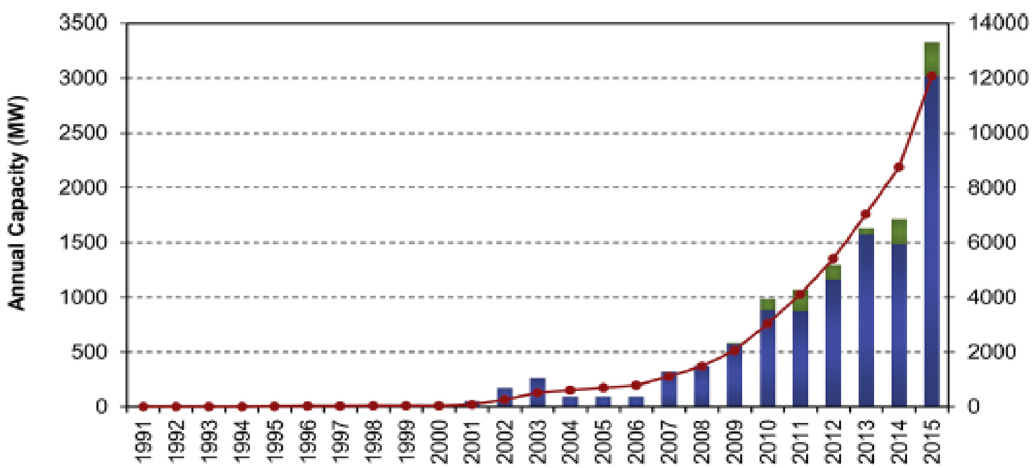

Figure 2.2. Offshore wind energy installed capacity (Kaldellis & Apostolou, 2017)

Although there are not CO_2 emissions while wind turbines are generating electricity, there is an important carbon footprint embodied in the cycle life that was already explained.

There are different methods to calculate the amount of carbon footprint embodied in a wind turbine, all of them are different, so it is necessary to develop a methodology that allows to calculate with accuracy the total amount of carbon dioxide embodied in a wind turbine during the whole life cycle. Methods already developed are:

- Ordinary Least Squares (OLS) analysis.
- Environmentally extended input-output (EEIO) analysis.
- Electricity production efficiency from greenhouse gas emissions.
- Life Cycled Embodied (ELC) energy analysis.

2.1. Ordinary Least Squares (OLS) analysis

Wheatley *(Wheatley, 2013)* has shown how many CO_2 tonnes per MWh are saved in the Irish power system due to wind energy. The equation to calculate it is:

$$\Delta CO_2 = \alpha \Delta D_t + \beta \Delta W_t + \gamma I_t + \eta_t \qquad \textit{Equation 1}$$

Where:

-CO_2 is the total emissions.

-D_r is the system demand (not including wind demand).

-W_t is total wind generation.

-I_t is electricity imports.

-η_t is the error due to the approximate mathematical method that is being used.

-α represents the grid average intensity.

-β the wind power savings (tCO_2/MWh).

Generation data are compiled half hourly during four days by Single Electricity Market Operator (SEMO), and it includes domestic generation and electricity transferred to Northern Ireland. However, it was not possible to collect data from all wind farms, so a statistical model is used.

Applying the OLS method (*Equation 1*) results are: grid average intensity (α) is 0.52 tCO_2/MWh and wind power savings (β) are -0.28 tCO_2/MWh, which means that if there had not been wind in 2011, CO_2 emissions would have been 12.9 Mt versus 11.8 Mt observed. It is a 9% of CO_2 reduction.

2.1.1 Critical appraisal

This method calculates the carbon dioxide savings in a power system due to wind energy, but carbon footprint embodied in a wind turbine is not considered, so it is impossible to know if there is a cannibalization effect *(Usubiaga et al., 2017)* which means that CO_2 emissions during the manufacturing of turbines are higher than savings during the generation life in a power system, so it does not bring net environmental benefits. Furthermore, imported energy would not have to be considered because emissions are produced in another country. However, *Environmentally extended input-output (EEIO) analysis* considers carbon dioxide embodied in a wind turbine, so it is a more reliable method.

Generation data are really accurate because they have been compiled from SEMO. However, some data from wind turbines have been estimated because they were not available, so the method is not going to produce exact results. Furthermore, this method considers stationary variables when they are not. Moreover, an approximate mathematical method is being used, so it is not going to get precise results.

2.2. Environmentally extended input-output (EEIO) analysis

Usubiaga *(Usubiaga et al., 2017)* shows the amount of CO_2 saved due to onshore and offshore wind turbines, including carbon footprint embodied in them into the European energy system. It compares a fictitious scenario where onshore and offshore wind technologies have never existed with the actual scenario where they do, so differences of CO_2 emissions between both scenarios can be appreciated. These differences are carbon dioxide savings due to wind energy.

To determine cumulative CO_2 emissions in both scenarios the next equation is used:

$$m = B(I - A)^{-1}(x_E + y_I) \qquad \textit{Equation 2}$$

Where:

-m is the CO_2 footprint.

-B is the amount of pollutants or natural resources emitted or consumed to produce moneraty unit output of each industry.

-I is the identity matrix.

-A shows inflows or outflows of commodity I of process j *(Suh & Huppes, 2005)*.

-y_I is the investments on energy infrastructure.

-x_E is the domestic electricity production and it is calculated:

$$x_E = z_E - z_{OWN_E} + y_E \qquad \textit{Equation 3}$$

Where:

-z_E is the intermediate demand of electricity produced.

-z_{OWN_E} is the auto consumption by the electricity sector when producing electricity.

-y_E is the final demand of electricity produced.

These results show the difference between cumulative CO_2 wind energy emissions and dioxide carbon emissions in a scenario where this technology has never been developed in Europe, so other technologies would be working instead of wind energy.

Life Cycle Inventory is chosen from 2000-2007 Eurostat, and data from 1990-1999 and 2008-2013 are estimated because they could not be found. However, the energy produced and the capacity of the plants are chosen from 1990-2013 Eurostat databases because they were available.

To determine the generation mix in the scenario where wind energy does not exist, it is considered that the shortfall in electricity generation (there are no wind turbines) is filled by the same percentages of the other technologies. However installed capacity is calculated with another algorithm in order to reduce the power plants installed.

Figure 2.3 shows the differences between CO_2 emissions due to onshore wind turbines and CO_2 emissions of technologies that would be working instead of onshore wind energy. There is not a cannibalization effect since onshore wind technology does not emit too much CO_2 in its manufacturing process.

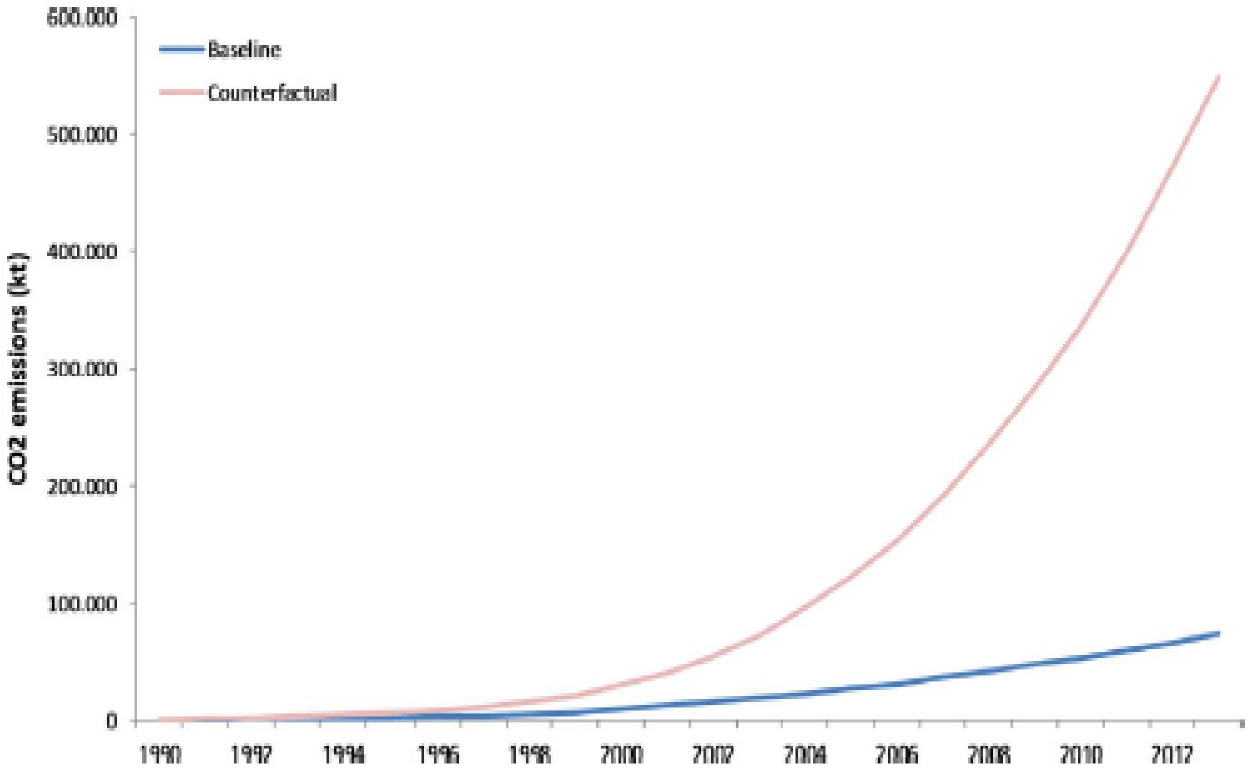

Figure 2.3. Cumulative CO_2 emissions of onshore wind turbines compared to a non-onshore scenario (Usubiaga et al., 2017)

Figure 2.4 shows the differences between CO_2 emissions due to offshore wind turbines and CO_2 emissions of technologies that would be working instead of offshore wind energy. Although offshore technology is recent, from the beginning of the 21st century, it did not have positive environmental effects until 2004, this is because installing and manufacturing offshore turbines emit a lot of CO_2, but it is compensated because they almost do not contaminate when electricity is generated.

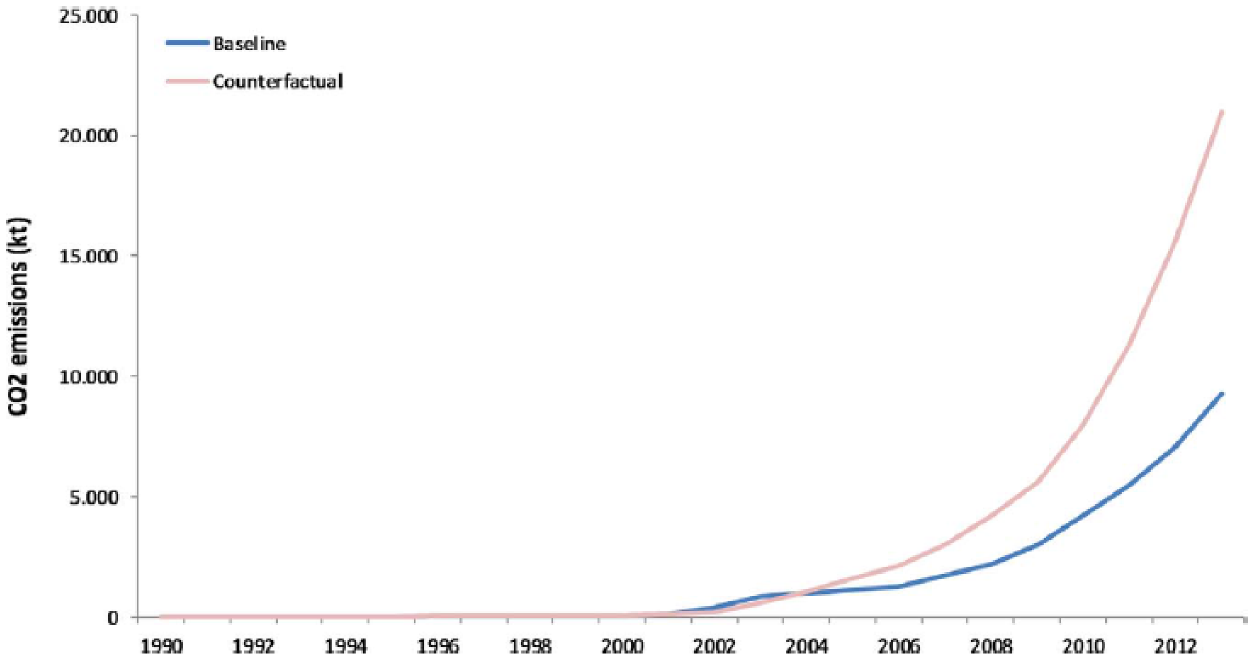

Figure 2.4. Cumulative CO_2 emissions of offshore wind turbines compared to a non-offshore scenario (Usubiaga et al., 2017)

2.2.1 Critical appraisal

This method calculates the CO_2 footprint as emissions during the electricity productions and during the manufacturing process, so it includes all the life cycle of the installations, which is the correct way to know if there is a cannibalization effect in renewable energies. Furthermore, this method uses electricity generation instead of demand to know the footprint, so it is accurate because there are energy losses during the electricity transportation and auto consumption, therefore electricity production is always higher than demand. Moreover, the carbon footprint of energy infrastructure generators is considered as well, therefore this method is really accurate.

However, it is a method a bit complicated to carry out because of the matrix calculations, while *Electricity production efficiency from greenhouse gas emissions* method is simpler and it considers all CO_2 emissions in the life cycle as well.

Some of the Life Cycle Inventory data (1990-1999 and 2008-2013) are estimated, so they are not accurate. Installed Capacity should have been calculated like the generation mix, instead of trying to reduce the power plant installed, since it does not reflect the reality, due to the fact that countries usually have more installed capacity than they really need to meet the demand.

Non-Onshore and non-offshore scenarios should be analyzed together as well. Moreover, this analysis cannot compare onshore and offshore technology, since it is obvious that offshore carbon footprint is higher than the onshore. It would be necessary to compare $kgCO_2$ per MWh than just kg, so onshore and offshore wind technologies can be assessed and compared to each other. Because if $kgCO_2$ are only considered, onshore turbines would be more environmentally-friendly, however they generate less electricity than the offshore ones and this lack of energy should be produced by a non environmentally friendly technology, so it makes the ratio (tonnes of CO_2/MWh) decrease. Therefore, energy produced is a crucial factor in carbon footprint as well, to compare onshore and offshore technologies.

2.3. Electricity production efficiency from greenhouse gas emissions

Tomporowski *(Tomporowski et al., 2017)* shows the benefits of an offshore wind turbine, such as emission reductions and the increase of energy produced. These benefits are calculated:

$$E(t) = \frac{\mu \cdot t}{m_W + m \cdot t + m_Z} \quad \textit{Equation 4}$$

Where:

-E(t) is integrated efficiency index for t years of use.

-μ is the average annual energy output at the stage of use.

-m_W is CO_2 emission at the manufacturing stage.

-m is average annual CO_2 emissions at the stage of use.

-m_Z is CO_2 emission at the post use management stage (storage or recycling).

Efficiency is calculated using average data from a 2 MW wind turbine, such as energy output and emissions at the stage of use.

Figure 2.5 shows that if wind turbines are recycled, CO_2 emissions reduce considerably, so efficiency would be higher, it would be a cleaner energy and the carbon payback period would be less. Furthermore, the more years the turbine works, the more efficient it will be, because contamination during energy generation is almost zero.

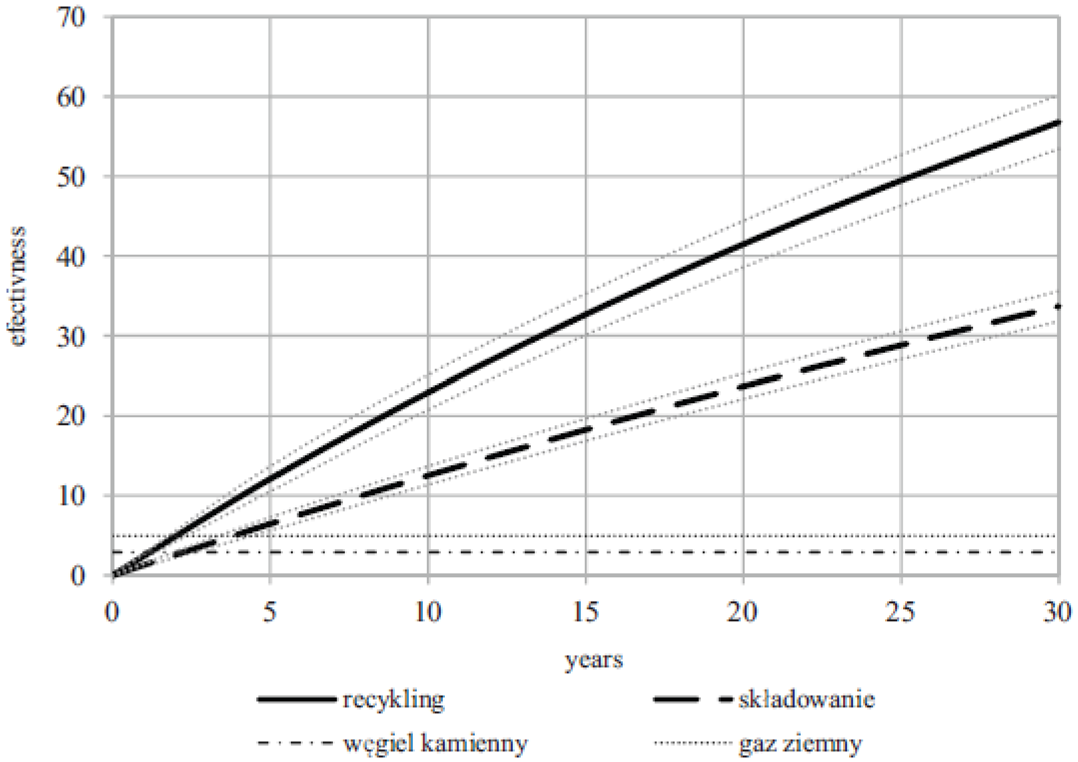

Figure 2.5. Differences between integrated efficiency index if a wind turbine is recycled and if it is not (Tomporowski et al., 2017)

2.3.1 Critical appraisal

The main problem is that the mean is considered in energy output and CO_2 emissions, as both can be different from one year to another. Moreover, E units are MWh/kgCO_2, and other units would be more appropriate to determine how efficient this technology is in comparison to the generation mix energetic of the country, like kgCO_2/MWh, so CO_2 payback period could be calculated. *Life Cycled Embodied (ELC) energy analysis* uses this ratio (kgCO_2/MWh).

It is an innovative idea to consider the CO_2 emissions (m_Z) positive if the waste is not recycled, and negative if it is.

It would also be worth it to observe if this offshore turbine was compared with an onshore one to determine which one is more efficient. It could be used to compare efficiency between onshore and offshore wind turbines in a whole country as well.

2.4. Life Cycled Embodied (ELC) energy analysis

Kaldellis *(Kaldellis & Apostolou, 2017)* shows carbon footprint in onshore and offshore wind technology and they are compared. Carbon footprint is calculated:

$$ELC = \frac{E_C + E_{O\&M} + E_D}{R} \qquad \textit{Equation 5}$$

Where:

-E_C is CO_2 emissions in construction.

-$E_{O\&M}$ is CO_2 emissions in operation and maintenance.

-E_D is CO_2 emissions in decommission that can be CO_2 saved if wind turbines are recycled.

-R is energy generated throughout a turbine's lifetime.

Table 2.1 demonstrates that offshore wind turbines have more power than onshore ones, however the CO_2 footprint is higher because they require more material and it has to be transported a longer distance. Although offshore technology produces more energy, carbon intensity is still higher than the onshore one.

Table 2.1. Carbon footprint of offshore and onshore wind technology

Literature Sources	Onshore		Offshore	
	Power Rating (MW)	Carbon Intensity (g/KWh)	Power Rating (MW)	Carbon Intensity (g/KWh)
(Ardente et al., 2008)	0.66	14,8	-	-
(Oebels & Pacca, 2013)	1.5	7.1	-	-
(Yang & Chen, 2013)	1.5	7.2	-	-
(Pehnt, Oeser & Swider, 2008)	-	-	5	22.0
(Tremeac & Meunier, 2009)	4.5	16	-	-
(Wagner et al., 2011)	-	-	5	32.0
(Weinzettel et al., 2009)	-	-	5	11.5
(Garrett & Ronde, 2013)	2	7.7	-	-
(Reimers, Özdirik & Kaltschmitt, 2014)	-	-	5	16.8
(Bonou, Laurent & Olsen, 2016)	2.3-3.2	7	4-6	11
(Crawford, 2009)	3-0.65	-	-	-
(Dones et al., 2007)	0.8	-	2	-
(Martínez et al., 2009)	2	-	-	-
(Schleisner, 2000)	0.5	9.7	0.5	16.5
(Dolan, 2007)	-	-	1.8	24
Average	**1.9**	**9.9**	**3.8**	**19.1**

2.4.1 Critical appraisal

It is thought that this is the most simple and accurate method to determine the carbon footprint embodied in a wind turbine.

Carbon intensity units are g/KWh, therefore onshore and offshore wind technologies can be compared to carbon emissions in electricity generation mix. However, this unit depends on the electricity generated so much, so if a turbine is more environmentally friendly, but it is placed in a bad location where it is not windy, this ratio would not reflect that the turbine is cleaner in terms of CO_2 than another one in a better location.

So, maybe another ratio should be used to compare wind turbines of the same technology, such as carbon footprint/power rating or installed capacity.

Moreover, these results are not valid because there are big differences between turbines of the same technology. This is because they are placed in countries with different wind conditions such as Italy, Brazil or China, so there it is, the same problem mentioned above. Moreover, each researcher uses a different methodology in order to calculate the total carbon footprint of a wind turbine which increases the differences.

2.5. Aims and objectives

The aim of this research is to create a methodology that allows to calculate the carbon footprint embodied in a wind turbine, considering all carbon emissions embodied during the whole life cycle in order to understand the benefits of the wind energy in terms of carbon dioxide savings.

The objectives of this research proposal are:

- To collect data about the amount of material, energy and fuels needed to manufacture, install and maintain a wind turbine.
- To calculate the total amount of carbon embodied in a wind turbine and determine what (material, operation & maintenance, energy, transport, disposal) produces more CO_2 emissions.
- To analyze these results and establish a relationship between the amount of carbon embodied in a wind turbine as a function of the installed capacity in onshore and offshore wind technology.
- To determine what installed capacity in each technology (onshore or offshore) is more efficient in term of CO_2 savings.
- To collect data about the amount of energy produced by offshore and onshore wind turbines in the United Kingdom and the electricity generation mix and its carbon dioxide emissions.
- To estimate the carbon footprint embodied in the United Kingdom due to the wind energy.

- To determine the payback time in terms of carbon dioxide emissions in the United Kingdom.
- To estimate the cumilative carbon footprint savings in the United Kigdom due to the wind technology.

3. RESEARCH METHODOLOGY

The aim of the research is to determine a methodology to calculate the carbon footprint embodied in a wind turbine and apply this methodology to the United Kingdom wind energy in order to compare offshore and onshore wind turbines and to know the benefits that wind energy brings in terms of CO_2 savings. These are the steps that must be taken.

3.1. Data acquisition

The first step in making the research is compiling data from different papers which include all materials needed to manufacture an onshore or offshore electricity wind generator, the amount of diesel burnt by vehicles and the amount of material savings due to recycling.

Data from electricity mix generation, onshore and offshore installed capacity and energy produced need to be found in order to estimate the carbon emissions in the United Kingdom due to offshore and onshore wind turbines.

A database of the amount of CO_2 emissions embodied in a wind turbine per material unit needs to be found to estimate the total carbon footprint in a wind generator.

3.2. Carbon footprint methodology

Although there are no CO_2 emissions while the turbine is generating electricity, there is a carbon footprint embodied in the following phases, these phases need to be considered in order to calculate the whole carbon dioxide emissions embodied in a wind turbine *(Ardente et al., 2008)*:

- Manufacturing of wind turbines: they are made of different material such as steel, iron, glass reinforced plastic, cooper, aluminum, etcetera. Therefore, when these materials are being produced, there are carbon dioxide emissions due to the manufacturing process.
- Energy: the carbon footprint due to the energy consumption during the installation and the decommissioning of wind turbines, since excavators, compactors and other contruction machines are used.

- Transport: materials need to be carried from the place where they are manufactured to where the generator is going to be placed. Trucks, planes and ships carry these materials using diesel, so there is an important carbon dioxide emission due to the engine combustion. Moreover, there is another transport phase when the turbines are uninstalled, and these materials need to be carried to the landfill. In this research, it is assumed that all transport distances are equal in order to get more homogeneous results.
- Operations and maintenance cycles: during the operation period there is a need to replace around 15% of the generator's components and the personnel is transported by diesel cars.
- Decommissioning phase: 90% of metals and 20% of blades materials can be recycled, so it can help to reduce carbon footprint in a wind turbine.

Now, it will be explained which method will be used to consider the carbon footprint embodied in a wind turbine during all these phases explained above.

Ordinary Least Squares (OLS) analysis will not be used because this method calculates the carbon dioxide savings in a power system due to the wind energy, but carbon footprint embodied in a wind turbine is not considered, so it is impossible to know if there is a cannibalization effect *(Usubiaga et al., 2017)*.

Environmentally extended input-output (EEIO) analysis is really accurate since it calculates the CO_2 footprint as emissions during the electricity productions and during the manufacturing process, so it includes the whole life cycle of the installations, which is the correct way to know if there is a cannibalization effect in renewable energies. Furthermore, this method uses electricity generation instead of demand to know the footprint, so it is accurate because there are energy losses during the electricity transportation and auto consumption, therefore electricity production is always higher than demand. However it will not be used because it is a bit complicated to apply because of the matrix calculations.

Moreover, the results are kg of CO_2 embodied in a wind turbine, so this analysis cannot compare onshore and offshore technologies, since it is obvious that offshore carbon footprint is higher than onshore. It would be necessary to compare kg of CO_2 per MWh than just kg, so onshore and offshore wind technologies can be assessed and compared to each other. Because if kg of CO_2 are only considered, onshore turbines would be more environmentally-friendly, however they generate less electricity than offshore ones and this lack of energy should be produced by a not environmentally friendly technology, so it makes the ratio (tonnes of CO_2/MWh) decrease. Therefore, energy produced is a crucial factor in carbon footprint as well.

Electricity production efficiency from greenhouse gas emissions considers all carbon dioxide emissions as well, and it is a much simpler method, the only problem is that the results are expressed like a efficiency percentage so it is difficult to know the amount of emissions and how efficient this technology is in comparison to the generation mix energetic of the country which is usually expressed like kgCO_2/MWh. So it will not be the method used.

Life Cycled Embodied (ELC) energy analysis is the method chosen to this research since it considers all carbon footprint embodied in a wind turbine. Results are given like kg of CO_2/MWh, so onshore and offshore turbines can be compared to each other and it is a simple method.

Carbon footprint will be expressed in different units in order to make some comparison easier. Then result units will be kg of CO_2, kg of CO_2/installed capacity and kg of CO_2/energy produced.

3.3. Analysis of the results

Once the total amount of the carbon footprint embodied in different wind turbines is calculated, there are different analysis that can be done.

A representation of tonnes of CO_2 embodied in a wind turbine as a function of the installed capacity of the turbine will be carried out, since like all materials data will be compiling from papers with different turbines technology and different installed capacity. There will be different representations for onshore and offshore wind technologies. Due to these representations, an equation might be developed to calculate the amount of CO_2 emissions in a wind turbine as a function of its installed capacity.

A new graphic can be developed as well if tonnes of CO_2/installed capacity are represented in as a function of the installed capacity, then it will be possible to know what size of turbine of the same technology (onshore or offshore) is more efficient in terms of reducing carbon dioxide emissions. This ratio is better than tonnes of CO_2/energy produced because it does not depend on the electricity generated, so if a turbine is more environmentally friendly, but it is placed in a bad location where it is not windy, this ratio would reflect that the turbine is cleaner than other one in a better location, while tonnes of CO_2/energy produced ratio would not, because if energy produced is little, then it makes this ratio (tonnes of CO_2/energy produced) increases.

So, a bar chart can represent what operations (wind turbine manufacture, operation & maintenance, foundation/substructure, electrical connections, installation, disposal) emit more carbon dioxide in onshore and offshore wind turbines. Therefore, companies will be able to focus on reducing the carbon footprint in those operations.

Once the relationship between the carbon footprint and installed capacity in offshore and onshore wind technologies is achieved, it will be possible to estimate the total amount of carbon footprint (kg) embodied in wind turbines in the United Kingdom through the average offshore and onshore installed capacity in the United Kingdom and the total amount of wind turbines.

Once the total amount of CO_2 embodied in onshore and offshore turbines is calculated it will be possible to determine which technology is more efficient in terms of CO_2 savings. The ratio amount of CO_2/energy produced will be used since offshore carbon footprint is bigger, but it is compensated because offshore turbines produces much more energy than onshore ones. This ratio can be calculated from the total amount of carbon dioxide, the number of years that a wind turbine works, the annual energy produced by this technology in the United Kingdom and the total number of wind turbines. The technology (onshore or offshore) with the minor ratio will be more environmentally friendly.

When average carbon footprint per onshore and offshore wind turbine in the United Kingdom is estimated, then CO_2 savings can be calculated in comparison to the generation mix energetic emissions in the UK, therefore the payback time in terms of carbon dioxide emissions can be calculated for onshore and offshore turbines.

Moreover, it is necessary to compare actual electricity generation mix to one scenario where wind energy never has been developed in the United Kingdom. Thus, all CO_2 savings due to the onshore and offshore wind turbines throughout the history can be calculated as some researchers have done *(Usubiaga et al., 2017)*.

The main problem of this research is that carbon footprint in the United Kingdom will be estimated, so the results will not be extremely accurate because material data are not going to be compiled from every wind turbine in the United Kingdom, but it will be estimated based on different wind turbine sizes around the world, therefore results will be similar to the reality but they will not be exact.

4. *DATA PRESENTATION AND ANALYSIS*

It will be explain how to calculate the carbon footprint embodied in a wind turbine considering all phases in order to create a methodology which can be followed to estimate accurately the carbon dioxide emissions embodied in a wind turbine.

Moreover, it will be explained how to calculate the carbon footprint factor (carbon footprint/energy produced) in the United Kingdom over the years in a scenerario where wind energy was never developed.

4.1. Turbine Models

Different wind turbines with different installed capacity have been analyzed in order to get more accurate results. Moreover, it can be analyzed what installed capacity is more efficient in terms of CO_2 savings and how the carbon emissions change due to the installed capacity.

The next table shows the different researchers investigations that were used to get information about the wind turbines around the world.

Table 4.1. Wind turbines chosen for the research

Onshore		**Offshore**	
Author	Installed capacity (MW)	Author	Installed capacity (MW)
(Schleisner, 2000)	0.5	*(Schleisner, 2000)*	0.5
(Ardente et al., 2008)	0.66	*(Dolan, 2007)*	1.8
(Dones et al., 2007)	0.8	*(Dones et al., 2007)*	2
(Crawford, 2009)	0.85-3	*(Bonou, Laurent & Olsen, 2016)*	5
(Oebels & Pacca, 2013)	1.5	*(Reimers, Özdirik & Kaltschmitt, 2014)*	5
(Yang & Chen, 2013)	1.5	*(Weinzettel et al., 2009)*	5
(Martínez et al., 2009)	2		
(Bonou, Laurent & Olsen, 2016)	2.75		

4.2. Life Cycle Assessment

The total carbon footprint embodied in a wind turbine is due to different stages such as raw material extraction and manufacture, wind farm construction, wind farm operation and wind farm decommissioning. Transportation of all materials and people has to be included as well. The life cycle assessment of different turbines are shown in *Appendices* section.

4.2.1 Data acquisition

Different resources have been used to calculate the total carbon footprint in different turbines as of the total amount of materials needed, the transportation of all these materials and people, the energy used while the manufacture and operation and the turbine decommissioning, like papers showed in *Table 4.1*. The same Life Cycle Inventory (LCI) Database was used in all wind turbines analysis to get more homogenous information in order to be able to compare each other instead of using the LCI Database corresponding to each paper. This LCI Database is "Inventory of Carbon & Energy (ICE) Version 1.6a made by Prof. Geoff Hammond & Craig Jones" *(Hammond & Jones, 2008)*.

This database shows the carbon embodied of different building materials. Although the ideal condition would be considering the carbon footprint since the extraction of raw materials until the end of the life cycle (including manufacturing, transport, energy to manufacture the equipment, heating & lighting of factory, maintenance, disposal… etc), known as "Cradle-to-Grave", this database uses "Cradle-to-Gate", which includes all CO_2 emissions until the product leaves the factory gate.

Most of the data included in the LCI Database are from the United Kingdom. Although in some case it was no possible to get the UK data, so foreign data was included.

4.2.2 Materials

Wind turbines are made of different materials. The mass of these materials were got from researches showed in *Table 4.1*. To calculate the carbon emissions embodied in the material of a wind turbine since they were extracted like raw materials until the product leaves the factory gate, including manufacturing, transport, energy to manufacture the equipment, the maintenance and heating & lighting of factory ("Cradle-to-Gate"), a database was used *(Hammond & Jones, 2008)*.

These materials are used to manufacture all parts in a wind turbine *(Office of Energy Efficiency & Renewable Energy, 2018)*:

- Anemometer: measures the wind speed and transmits data to the controller.
- Blades: when the wind blows over them, they lift and rotate and make the rotor spin as well. Three blades are the most efficient combination.
- Controller: starts up the machine at wind speeds from 20 kilometers per hour and disconnect the machine at about 90 kilometers per hour to avoid damages in the turbine due to the high winds.
- Gear box: connects the low-speed shaft (blades) to the high-speed shaft (drives the generator) and increases the rotational speed from 30 rpm to about 1500 rpm, which is the rotational speed required by most generators to produce electricity.
- Generator: produced 50-cycle AC electricity.
- Nacelle: sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake.
- Pitch: turns blades out of the wind to control the rotor speed, and to keep the rotor from turning in winds that are too high or to low to produce electricity.
- Rotor: blades and hub together form the rotor.
- Tower: made from turbular steel, concrete or steel lattice. Supports the structure of the turbine. Because wind speed increases with height, taller towers enable turbines to caputre more energy and generate more electricity.
- Wind vane: measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.
- Yaw drive: orients upwind turbines to keep them facing the wind when the direction changes.
- Yaw motor: powers the yaw drive.

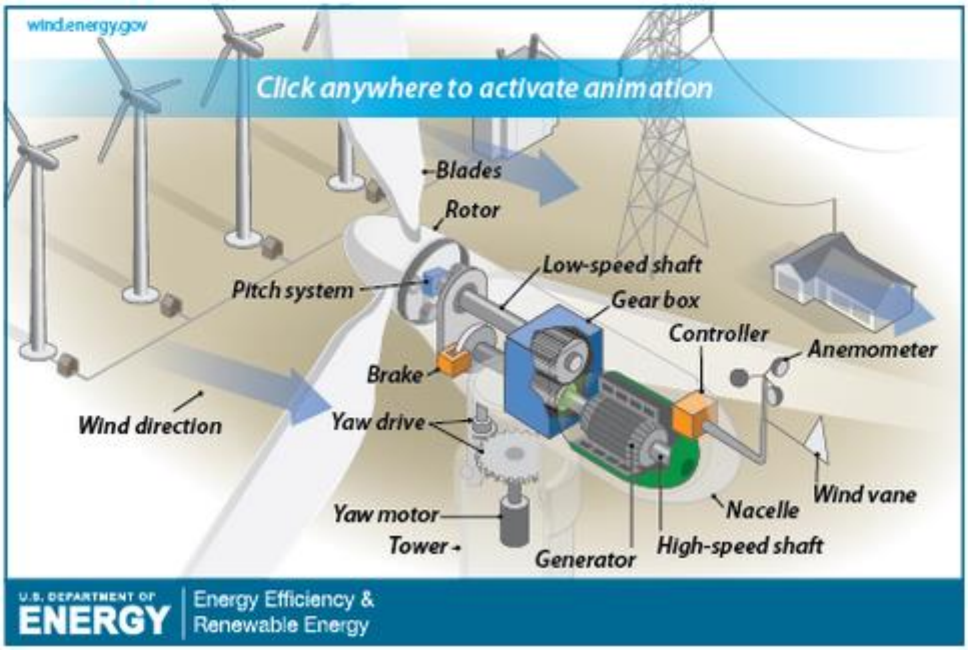

Figure 4.1. Parts of a wind turbine *(Office of Energy Efficiency & Renewable Energy, 2018)*

But materials are needed to some building works such as *(Ardente et al., 2008)*:

- Lay-bay: wind turbines are placed on flattened surfaces made of compacted crushed stone and limestone. But this data was not included in the analysis due to the lack of information.
- Paths and road connections: lay-bays are connected to each other with paths constituted by a compacted terrain based on a crushed stone ground. But this data was not included in the analysis due to the lack of information.
- Foundations: all wind generators are installed into a steel reinforced concrete foundation and the first section of the tower is dipped on the foundation.
- Electric cables: the turbines are connected to transformers and to the electrical grid with various cable typologies.
- Cables trenches: Internal walls are reinforced with concrete and filled with sand and crushed stone. On the upper side trenches are covered wih PVC tiles.
- Transformer room.

4.2.3 Transport

This research considers carbon emissions embodied in transport of all materials from the factory where they were manufactured to the location where wind turbines were installed. Moreover, transport during the decommissioning phase from the turbine place to the landfill is also included.

Below it will be shown how this transport footprint was calculated for onshore and offshore wind turbines. In order to get similar results in all transport carbon footprint, the same distance was considered for all onshore turbines, and another distance was considered for all offshore turbines. So the only factor that changes the CO_2 emissions during the transportation phase is the amount of materials carried and not the distance. Below it is shown how this distance was calculated.

Onshore wind turbines

The following table *(Oebels & Pacca, 2013)* was used in order to calculate the distance all turbine materials were carried. It shows transportation data for 14 onshore wind turbines.

Table 4.2. Component transport to operation site

Component	Vehicle	CO_2 emissions	CO_2 emission factor	Distance
		t CO_2	gCO_2/tkm	km
Steel tower	truck	11.68	37	140
Concrete tower	truck	147.56	37	370
Rotor	truck	24.02	37	3000
Blades	truck	1.99	37	200
Transformer	truck	0.29	37	140
Nacelle	truck	3.3	37	140

The transport factor [t·km] was used because it depends on weight and distance, and it is an accurate way to calculate the carbon footprint of the tranpostation phase. The transport factor of all components from a wind turbine will be calculated like:

$$Transport\ factor\ (t \cdot km) = \frac{CO_2\ emissions\ (t) \cdot 10^6}{CO_2\ emissions\ factor\ (gCO_2/tkm)} \cdot \frac{1}{14\ turbines} \quad \textit{Equation 6}$$

The total weight of all wind turbines carried was calculated as well:

$$Total\ weight\ (t) = \frac{CO_2\ emissions\ (t)\cdot 10^6}{CO_2\ emissions\ factor\ (gCO_2/tkm)} \cdot \frac{1}{Distance\ (km)} \quad \textit{Equation 7}$$

Table 4.3. Transport factor for an onshore turbine

Component	Vehicle	CO_2 emissions	CO_2 emission factor	Transport factor	Total weight
		t CO_2	gCO_2/tkm	tkm	t
Steel tower	truck	11.68	37	315560	2254
Concrete tower	truck	147.56	37	3988230	10779
Rotor	truck	24.02	37	649200	216.4
Blades	truck	1.99	37	53800	269
Transformer	truck	0.29	37	7840	56
Nacelle	truck	3.3	37	89180	637
Total transport factor	5103810 tkm				14211.4
Total transport factor per turbine	364558 tkm				1015.1

Next, the avarage transport distance of all components was calculated:

$$Distance\ (km) = \frac{Total\ transport\ factor\ (t\cdot km)}{Total\ weight\ (t)} = \frac{5103810}{14211.4} \approx 359\ km \quad \textit{Equation 8}$$

Therefore, it was assumed that all materials of onshore wind turbines have been carried 359 km by truck. Then, this distance was multiplied by the total amount of the materials of each wind turbine, so the total transport factor per turbine was obtained.

The transport factor of every wind turbine was multiplied by another factor named emissions factors, which shows the grammes of CO_2 emissions embodied per kilometre and tonne, consequently the total CO_2 emissions due to the transport phase was obtained. This factor considers the component transportation to the operation site and the empty return paths. The value of this factor is 50 grammes of CO_2/tkm for trucks *(Fernández, 2018)*.

<u>Offshore wind turbines</u>

The following table *(Weinzettel et al., 2009)* shows the total transport factor and the total amount of materials carried without gravel and sand because it is not considered in other papers for manufacturing a 5 MW offshore turbine. This research includes more types of transport than onshore one, since turbines are placed on the sea, such as truck transport, barge transport, train transport and helicopter transport. It is known that helicopter transport is used for 700 h and one helicopter that can lift around 1000 kg to help during the maintenance and installation phase usually consumes around 200 kg per hour *(Tasmanian helicopters, 2018)*, so the total amount of diesel is 140000 kg.

Table 4.4. Transport factor for an offshore wind turbine

Means of transport	Transport factor	Total weight
	tkm	t
Truck transport	876000	1851
Transport barge	3600000	1851
Train transport	581000	1851
Transport helicopter	140000 kg of diesel	-

Next, the average transport distance per means of transport was calculated:

$$Distance\ (km) = \frac{Total\ transport\ factor\ (t{\cdot}km)}{Total\ weight\ (t)} \qquad \textit{Equation 9}$$

The table shows the average distance per means of transport:

Table 4.5. Average distance per means of transport for an offshore wind turbine

Means of transport	Transport factor	Total weight	Distance
	tkm	t	km
Truck transport	876000	1851	473
Transport barge	3600000	1851	1945
Train transport	581000	1851	314
Transport helicopter	140000 kg of diesel	-	-

Therefore, it was assumed all materials of offshore wind turbines have been carried 473 km by truck, 1945 km by barge and 315 km by train. Then, these distances were multiplied by the total amount of materials of each offshore wind turbine, so the total transport factors per turbine was obtained. However, for helicopter transport, the amount of diesel needed for each offshore turbine was calculated from the turbine installed capacity:

$$Diesel\ (kg) = 140000\ kg \cdot \frac{X\ MW}{5\ MW} \qquad \textit{Equation 10}$$

The following table shows the emissions factors that the transport factor should be multiplied by in order to obtain the total CO_2 emissions per means of transport.

Table 4.6. Emission factors per means of transport

Means of transport	Emissions factor	Reference
	g CO_2/tkm	
Truck transport	50	*(Fernández, 2018)*
Transport barge	7	*(Delcampe, 2009)*
Train transport	18	*(Delcampe, 2009)*
Transport helicopter	2.8 Kg CO_2 / kg diesel	*(Oficina Catalana del Canvi Climàtic, 2011)*

Then CO_2 emissions per means of transport were added to each other in order to obtain the total carbon footprint of an offshore wind turbine during the transport phase.

4.2.4 Energy

This research considers the carbon footprint due to the energy consumption during the installation and the decommissioning of wind turbines, since excavators, compactors and other contruction machines were used. The main problem was that some researches do not include the energy consumption, so one research was taken as a reference for onshore turbines, and another one for offshore turbines, then the CO_2 emissions were estimated in the other papers during this phase. Below it is shown how it was calculated:

<u>Onshore wind turbines</u>

The following table *(Yang & Chen, 2013)* shows the energy consumption during the construction and dismantling for a wind farm with 33 1.5 MW wind turbines. Then the energy per turbine was calculated:

Table 4.7. Energy consumption per an onshore wind turbine

Energy	Units	Units
	33 turbines	1 turbine
Water	10000000 kg	303030 kg
Diesel	536000 L	16242 L
Gasoline	167000 L	5061 L
Electricity	1650000 kWh	50000 kWh

These energy data were estimated for other onshore wind turbines from the installed capacitiy:

$$Water\ (kg) = 303030\ kg \cdot \frac{X\ MW}{1.5\ MW} \quad \textit{Equation 11}$$

$$Diesel\ (L) = 16242\ L \cdot \frac{X\ MW}{1.5\ MW} \quad \textit{Equation 12}$$

$$Gasoline\ (L) = 5061\ L \cdot \frac{X\ MW}{1.5\ MW} \quad \textit{Equation 13}$$

$$Electricity\ (kWh) = 50000\ kWh \cdot \frac{X\ MW}{1.5\ MW} \quad \textit{Equation 14}$$

When the amount of energy was already estimated, then it was multiplied by the emission factors showed in the next table in order to obtain the CO_2 emissions.

Table 4.8. Emission factors per type of energy

Energy	Emission factor	Reference
Water	0 $kgCO_2/kg$	*(Hammond & Jones, 2008)*
Diesel	2.61 $kgCO_2/L$	*(Oficina Catalana del Canvi Climàtic, 2011)*
Gasoline	2.38 $kgCO_2/L$	*(Oficina Catalana del Canvi Climàtic, 2011)*
Electricity	0.275 $KgCO_2$ / kWh	*(Loughran, 2018)*

Then CO_2 emissions per type of energy were added to each other in order to obtain the total carbon footprint of an onshore wind turbine during the construction and decommissioning phase.

<u>Offshore wind turbines</u>

Unlike onshore wind turbines, energy used in the operation phase is also included such as electricity, oil and diesel. The following table *(Weinzettel et al., 2009)* shows the energy consumption during the whole life cycle of a 5MW offshore wind turbine, including installation, operation, maintenance and decommissioning.

Table 4.9. Energy consumption per an offshore wind turbine

Energy	Units
	1 turbine
Electricity	177000 kWh
Oil	22600 L
Diesel	922 MJ
Electricity from oil	470 kWh

These energy data were estimated for other offshore wind turbines from the installed capacitiy:

$$Electricity\ (kWh) = 177000\ kWh \cdot \frac{X\ MW}{5\ MW} \qquad \text{Equation 15}$$

$$Oil\ (L) = 22600\ L \cdot \frac{X\ MW}{5\ MW} \qquad \text{Equation 16}$$

$$Diesel\ (MJ) = 922\ MJ \cdot \frac{X\ MW}{5\ MW} \qquad \text{Equation 17}$$

$$Electricity\ from\ oil\ (kWh) = 470\ kWh \cdot \frac{X\ MW}{5\ MW} \qquad \text{Equation 18}$$

When the amount of energy was already estimated, then it is multiplied by the emission factors showed in the next table in order to obtain the CO_2 emissions.

Table 4.10. Emission factors per type of energy

Energy	Emission factor	Reference
Electricity	0.275 $KgCO_2/kWh$	*(Loughran, 2018)*
Oil	2.96 $kgCO_2/L$	*(Carbon Independent, 2018)*
Diesel	0.0736 $kgCO_2/MJ$	*(ENPOS, 2018)*
Electricity from oil	0.6 $KgCO_2$ / kWh	*(University of Reading, 2016)*

Then CO_2 emissions per type of energy were added to each other in order to obtain the total carbon footprint of an offshore wind turbine during the whole life cycle due to the energy consumption.

4.2.5 Operation & Maintenance

The useful life of onshore and offshore turbines is supposed to be 20 years long. During this time, it is necessary to do maintenance and control cycles. Moreover, the personnel who work is transported by diesel cars which produce CO_2 emissions as well. Therefore, there is energy consumption *(Yang & Chen, 2013)* such as electricity, water and gasoline.

Additionally, it *(Ardente et al., 2008)* has been estimated that the 15% of generator's components are assumed to be substituted by new ones. Below, it is shown how it was calculated the carbon footprint during the operation & maintenance (O&M) phase for onshore and offshore wind turbines.

Onshore wind turbines

The following table *(Yang & Chen, 2013)* shows the total energy consupmtion during the operation & maintenance phase.

Table 4.11. Energy consumption per an onshore wind turbine during the operation & maintenance

Energy	Units	Units
	33 turbines	1 turbine
Electricity	3320000 kWh	100606 kWh
Water	438000 kg/year	265460 kg
Gasoline	5800 kg/year	3516 kg

These energy data were estimated for other onshore wind turbines from the installed capacitiy:

$$Electricity\ (kWh) = 100606\ kWh \cdot \frac{X\ MW}{1.5\ MW}$$ *Equation 19*

$$Water\ (kg) = 265460\ kg \cdot \frac{X\ MW}{1.5\ MW}$$ *Equation 20*

$$Gasoline\ (kg) = 3516\ kg \cdot \frac{X\ MW}{1.5\ MW}$$ *Equation 21*

When the amount of energy was already estimated, then it was multiplied by the emission factors showed in the next table in order to obtain the CO_2 emissions.

Table 4.12. Emission factors per type of energy

Energy	Emission factor	Reference
Electricity	0.275 $kgCO_2/kWh$	*(Loughran, 2018)*
Water	0 $kgCO_2/kg$	*(Hammond & Jones, 2008)*
Gasoline	3.18 $kgCO_2/kg$	*(Oficina Catalana del Canvi Climàtic, 2011)*

It is known that 15% *(Ardente et al., 2008)* of generator's components are supposed to be substituted by new ones during the whole life cycle. To consider this fact in the carbon footprint, the total amount of CO_2 emissions from the wind generator materials were multiplied by 0.15 in order to obtain the extra CO_2 emissions due to the extra amount of materials.

The main problem is that a lot of papers show the materials list, but it is not known how many of these materials belong to the wind generator. So, the percentage of carbon dioxide due to the wind generator materials was calculated from the total emissions of the materials *(Ardente et al., 2008)*, then this percentage was assumed for all onshore turbines. Next, it is shown how this percentage was calculated.

The carbon footprint of all materials is calculated in the paper *(Ardente et al., 2008)*, like it was explained in *Materials* section. Then it is calculated the percentage of carbon footprint due to generator materials of the total materials carbon dioxide emissions like it is shown in the following table.

Table 4.13. Percentage of carbon footprint due to the wind generator materials

	Name	Amount	Unit	kg CO2/unit	Total Kg CO2	
	Material					
Wind generator materials	Steel	66434	kg	2.75	182694	60%
	Cast iron	6001	kg	1.91	11462	
	Glass reinforced plastics	4950	kg	8.10	40095	
	Copper	924	kg	3.83	3539	
	Paints	389	kg	3.56	1385	
	Lubricant oils	111	kg	9.95	1106	
	Aluminium	85	kg	11.50	978	
	PVC	65	kg	2.41	157	
	Bronze	5	kg	4.10	21	
Building works	Aggregate quarrying	1973455	kg	0.01	9867	40%
	Local soils and stones	939409	kg	0.06	52607	
	Steel	11139	kg	2.75	30632	
	Polypropylene	10	kg	5.03	53	
	HDPE	1035	kg	1.60	1656	
	Polybutadiene	467	kg	4.02	1879	
	Aluminium	754	kg	11.50	8666	
	Copper	263	kg	3.83	1007	
	PVC	1721	kg	2.41	4148	
	Sand	254753	kg	0.01	1274	
	Concrete	372480	kg	0.13	48422	
	Total				401646	100%

So it is assumed that 60% of the total carbon footprint of the materials is due to the wind generators materials. So the next equation was used in order to calculate the carbon emissions due to the replacement of the 15% of wind generator's components.

$$CO_{2\,replacement}\ emissions\ (kg) = 0.15 \cdot 0.6 \cdot CO_{2\,total\ materials} \qquad \textit{Equation 22}$$

Then, this carbon emissions due to the replacement of wind generator's component was added to the carbon footprint of the energy, so the total CO_2 emissions due to the operation & maintenance phase were obtained for an onshore wind turbine.

<u>Offshore wind turbines</u>

In contrast to onshore wind turbines, energy consumption is not considerer during the operation & maintenance phase, since it was included in *Energy* section. It is known that 15% *(Ardente et al., 2008)* of generator's components are supposed to be substituted by new ones during the whole life cycle, so it will be calculated like it was explained above.

It is calculated the carbon footprint of all materials in the paper *(Dones et al., 2007)*, like it was explained in *Materials* section. Then it is calculated the percentage of carbon footprint due to generator's materials of the total materials carbon dioxide emissions like it is shown in the following table.

Table 4.14. Percentage of carbon footprint due to the wind generator materials

	Name	Amount	Unit	kg CO2/unit	Total Kg CO2	
	Material					
Building works	Reinforced steel	80000	kg	2.75	220000	19%
	Concrete	120000	kg	0.13	15600	
Wind generator materials	Steel	113210	kg	2.75	311328	81%
	Epoxy resine	547	kg	5.7	3118	
	Glass fibre reinforced plastics	40938	kg	8.1	331598	
	Chromium steel	60643	kg	2.75	166768	
	Cast iron	33866	kg	1.91	64684	
	Steel, low alloyed	15050	kg	2.75	41388	
	Rubber	100	kg	3.18	318	
	Aluminium	845	kg	11.5	9718	
	Copper	986	kg	3.83	3776	
	Lubricant	150	kg	9.95	1493	
	Copper	3900	kg	3.83	14937	
	Lead	7575	kg	2.61	19771	
	Steel, low alloyed	8766	kg	2.75	24107	
	PVC	3500	kg	2.41	8435	
	Total				1237037	100%

So it is assumed that 81% of the total carbon footprint of the materials is due to the wind generators materials. So the next equation was used in order to calculate the carbon emissions due to the replacement of the 15% of wind generator's components.

$$CO_{2\,replacement}\ emissions\ (kg) = 0.15 \cdot 0.81 \cdot CO_{2\,total\ materials}$$ *Equation 23*

So the total CO_2 emissions due to the operation & maintenance phase were obtained for an offshore wind turbine due to the replacement of the wind generator's component.

4.2.6 Decommissioning phase

The plant's decommissioning is a life cycle phase not completely predictable. It was *(Ardente et al., 2008)* supposed that 90% of wind generator metals would be recycled. It is necessary to uninstall the wind turbine, and components, which are not recycled, they are disposed to a landfill, but this energy consumption is included in *Transport* and *Energy* phases. Below it is explained how the CO_2 emissions for onshore and offshore turbines during the decommissioning phase was calculated.

<u>Onshore wind turbines</u>

It *(Ardente et al., 2008)* is supposed that 90% of wind generator metals are recycled. To consider this fact in the carbon footprint, the total amount of CO_2 emissions from the wind generator metals were multiplied by 0.9 in order to obtain the CO_2 emissions savings due to the recycling.

The main problem is that a lot of papers show the materials list, but it is not known how many of metals belong to the wind generator. So, the percentage of carbon dioxide due to the wind generator's metals was calculated from the total emissions of the metals *(Ardente et al., 2008)*, then this percentage was assumed for all onshore turbines. Next, it is shown how this percentage was calculated.

Table 4.15. Percentage of carbon footprint due to the onshore wind generator metals

	Name	Amount	Unit	kg CO2/unit	Total Kg CO2	
	Material					
Wind generator materials	Steel	66434	kg	2.75	182694	83%
	Cast iron	6001	kg	1.91	11462	
	Copper	924	kg	3.83	3539	
	Aluminium	85	kg	11.50	978	
	Bronze	5	kg	4.10	21	
Building works	Steel	11139	kg	2.75	30632	17%
	Aluminium	754	kg	11.50	8666	
	Copper	263	kg	3.83	1007	
	Total				238997	100%

So it is assumed that 83% of the total carbon footprint of the metals is due to the wind generators metals. However, when a material is recycled, different manufacture processes are needed to make the new material from the recycled one, so there is not a 100% of CO_2 emissions savings. It *(Hammond & Jones, 2008)* is showed that primary steel carbon dioxide emissions are 2.75 kg CO_2/kg, and secondary steel emissions are 0.43 kg CO_2/kg. Therefore, it is shown that there is a big percentage of emissions savings, but it is not a 100%. Based on this information, the CO_2 emission savings percentage was estimated.

$$\%CO_2 savings = \frac{2.75-0.43}{2.75} \cdot 100 = 84\% \approx 80\% \qquad \textit{Equation 24}$$

So, it was assumed that when a metal is recycled there is a 80% of CO_2 emissions savings. So the next equation was used in order to calculate the carbon emissions savings due to the recycling of the 90% of wind generator metals.

$$CO_{2\,emission}\ savings\ (kg) = 0.8 \cdot 0.83 \cdot 0.9 \cdot CO_{2\,total\ metals} \qquad \textit{Equation 25}$$

This is how CO_2 emission savings were calculated, considering that 90% of wind generator metals are recycled, 83% of the metals to manufacture an onshore wind turbine are from the generator and there is a 80% of CO_2 emission savings when metals are recycled.

Offshore wind turbines

It is assumed that 90% of wind generator metals are recycled as well. The main problem is that a lot of papers show the materials list, but it is not known how many of metals belong to the wind generator. So, the percentage of carbon dioxide due to the wind generator metals was calculated from the total emissions of the metals *(Dones et al., 2007)*, then this percentage was assumed for all offshore turbines. Next, it is shown how this percentage was calculated.

Table 4.16.Percentage of carbon footprint due to the offshore wind generator metals

	Name	Amount	Unit	kg CO2/unit	Total Kg CO2	
	Material					
Building works	Reinforced steel	80000	kg	2.75	220000	28%
	Steel, low alloyed	8766	kg	2.75	24107	
Wind generator materials	Steel	113210	kg	2.75	311328	72%
	Chromium steel	60643	kg	2.75	166768	
	Cast iron	33866	kg	1.91	64684	
	Steel, low alloyed	15050	kg	2.75	41388	
	Aluminium	845	kg	11.5	9718	
	Copper	986	kg	3.83	3776	
	Copper	3900	kg	3.83	14937	
	Total				856705	100%

So it is assumed that 72% of the total carbon footprint of the metals is due to the wind generators metals and when a metal is recycled there is a 80% of CO_2 emissions savings as it was explained above. So the next equation was used in order to calculate the carbon emissions savings due to the recycling of the 90% of wind generator metals.

$$CO_{2\,emission}\ savings\ (kg) = 0.8 \cdot 0.72 \cdot 0.9 \cdot CO_{2\,total\,metals} \qquad \textit{Equation 26}$$

This is how CO_2 emission savings were calculated, considering that 90% of wind generator metals are recycled, 72% of the metals to manufacture an offshore wind turbine are from the generator and there is a 80% of CO_2 emission savings when metals are recycled.

4.2.7 Total carbon footprint

To calculate the total carbon footprint of a wind turbine, the carbon embodied in all phases has been added to each others.

$$Carbon\ footprint_{no\ recycled}\ (kg) = CO_{2\ materials} + CO_{2\ transport} + CO_{2\ energy} + CO_{2\ O\&M}$$ *Equation 27*

Moreover, if the wind turbine is recycled, it is necessary to consider the CO_2 savings in the decommissioning phase.

$$Carbon\ footprint_{recycled}\ (kg) = Carbon\ footprint_{no\ recycled} - CO_{2\ decommissioning}$$ *Equation 28*

This is how the total carbon footprint, if wind turbine is recycled or if it is not, was calculated for onshore and offshore wind turbines.

4.3. Carbon footprint factor in UK if no wind energy

Total carbon footprint saving in UK due to the wind energy section shows a comparison between the actual electricity generation mix to one scenario where wind energy never has been developed in the United Kingdom.

For that, the ratio grammes of CO_2/kWh (Energy produced) if wind technology had not been developed in the UK has to be estimated year by year. Data related to electricity generation has been collected from DUKES *(Department for Bussines, Energy and Industrial Strategy (1), 2000-2017)*. It will be shown how to calculate the ratio just for the year 2016 and the results for the other years will be in Appendices in *Carbon footprint per kilowatt without considering wind energy* section, since all ratios have been calculated the same way.

It is necessary to know the carbon footprint embodied in each technology. They are shown in the following table.

Table 4.17. Carbon footprint of the different types of energy in UK

Type of energy	Carbon footprint (g CO2/KWh)	Reference
Fuels	600	*(University of Reading, 2016)*
Coal	800	*(University of Reading, 2016)*
Gas	400	*(Committee on Climate Change, 2013)*
Nuclear	20	*(Committee on Climate Change, 2013)*
Solar	55	*(Committee on Climate Change, 2013)*
Landfill gas	170	*(Committee on Climate Change, 2013)*
Bioenergy	240	*(Committee on Climate Change, 2013)*
Hydro	8	*(University of Reading, 2016)*

Now, the total carbon footprint per technology has been calculated from the total amount of energy produced in 2016 without considering wind energy.

Table 4.18. Carbon footprint per kilowatt in UK without wind energy in 2016

2016	Total energy = 3,36439 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	3.10%	10429578000	600	6.25775E+12
Coal	9.00%	30279420000	800	6.05588E+12
Gas	42.00%	1.41304E+11	400	6.35868E+13
Nuclear	21.00%	70651980000	20	2.11956E+12
Solar	3.19%	10715550300	55	5.89355E+11
Landfill gas	1.47%	4945638600	170	8.40759E+11
Bioenergy	7.35%	24728193000	240	5.93477E+12
Hydro	1.47%	4945638600	8	39565108800
Wind energy	11.03%	-	-	-
			Total	8.54244E+13
			gCO2/kWh	286.6591589

Therefore, the carbon footprint due to the electricity generation mix without considering wind energy is 286.66 grammes of CO_2/kWh in United Kingdom in 2016.

The following table shows the ratio (grammes of CO_2/kWh) year on year.

Table 4.19. Ratio (grammes of CO_2) year on year without considering wind energy

Years	2016	2015	2014	2013	2012	2011	2010	2009	2008
Ratio (g CO_2/kWh)	321.54	381.62	432.98	419.78	479.22	441.18	445.26	435.91	476.82
Years	2007	2006	2005	2004	2003	2002	2001	2000	-
Ratio (g CO_2/kWh)	479.35	483.04	460.28	460.44	457.38	445.14	451.79	453.13	-

5. RESULTS

5.1. Total carbon footprint

The total carbon footprint embodied in the whole life cycle of a wind turbine was calculated applying the *Life Cycle Assessment* explained above. Results are shown like the total amount of carbon dioxide emissions due to the wind turbines (t CO_2). However, a lot of papers (indicated in *Background and literature review*) do not show their results with these units, since they indicate the results like CO_2 savings due to the use of this technology, a ratio (kgCO_2/kWh) to compare wind energy to other types of energy, or a percentage (%) to show the effectiveness of this technology.

Therefore, a lot of terms are shown to demonstrate that this technology is more environmentally-friendly than other types of technologies, but the total amount of CO_2 emissions is not known. This is why this research uses tonnes of CO_2 to show the results. The following table shows the total carbon footprint of different onshore and offshore wind turbines without considering the recycling at the end of the life cycle.

Table 5.1. Total carbon footprint of onshore and offshore wind turbines

	Onshore		Offshore	
Name	Capacity (MW)	t CO2	Capacity (MW)	t CO2
(Schleisner, 2000)	0.5	298.6	0.5	426.1
(Ardente et al., 2008)	0.66	503.4	-	-
(Dones et al., 2007)	0.8	636.1	2	1633.3
(Crawford, 2009) (1) *(Crawford, 2009) (2)*	0.85 3	521.8 1436.5	-	-
(Oebels & Pacca, 2013)	1.5	938.4	-	-
(Yang & Chen, 2013)	1.5	1029.6	-	-
(Dolan, 2007)	-	-	1.8	2218.5
(Martínez et al., 2009)	2	1090.5	-	-
(Bonou, Laurent & Olsen, 2016)	2.75	1155.6	5	6274.5
(Reimers, Özdirik & Kaltschmitt, 2014)	-	-	5	5859.0
(Weinzettel et al., 2009)	-	-	5	7289.1

The following figure shows the total amount of carbon dioxide emissions per turbine. Big difference are shown between onshore and offshore technology. Installed capacity of offshore wind turbines is bigger than in onshore ones, this is because there are no obstacles on the sea what reduce wind speed, therefore speed is higher, so bigger turbines can be manufactured in order to produce more energy. On the other hand, when onshore and offshore turbines have the same installed capacitiy, the carbon footprint in offshore ones is higher, since towers are taller because they need to be moored on the sea bottom, a lot of ballast is required to make the foundations, the generator and its blades are bigger too, cables to transport electricity are longer to reach the shore. To sum up, the more material needed, the more carbon emissions during their manufacture. Moreover, the fuel consumption for trucks and ships to carry out the materials to the place where they are sited, is high. And then, their maintenance must be done by a helicopter which increases even more the carbon embodied *(Weinzettel et al., 2009)*.

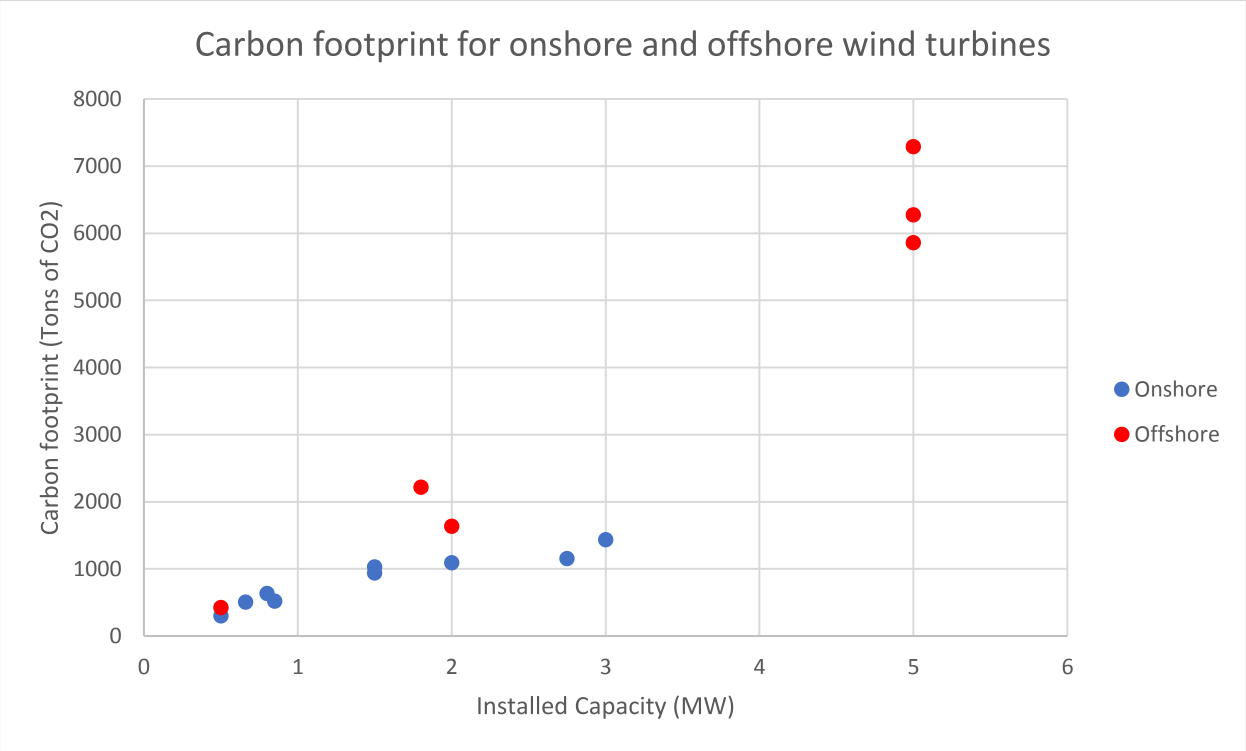

Figure 5.1. Carbon footprint for onshore and offshore wind turbines

No papers were found where total CO_2 emissions were represented as a function of the installed capacity in order to know how the carbon footprint changes with the turbine size. Moreover, a mathematical function can be obtained to estimate easily the carbon dioxide emissions from the installed capacity.

From the data calculated in *Table 5.1* a logarithmic equation has been developed to determine the carbon footprint as a function of onshore installed capacity, this can be shown in *Figure 5.2*.

When the installed capacity is low, the CO_2 emissions change on a linear way. However, the bigger the installed capacity is, the more slowly the carbon dioxide emissions increase. This is because the amount of material needed to manufacture an onshore wind turbine does not increase linearly with the installed capacity, but the bigger the installed capacity is, the less material is needed in proportion. So this evolution of the carbon footprint as a function of onshore installed capacity can be approximatated using a logarithmic equation.

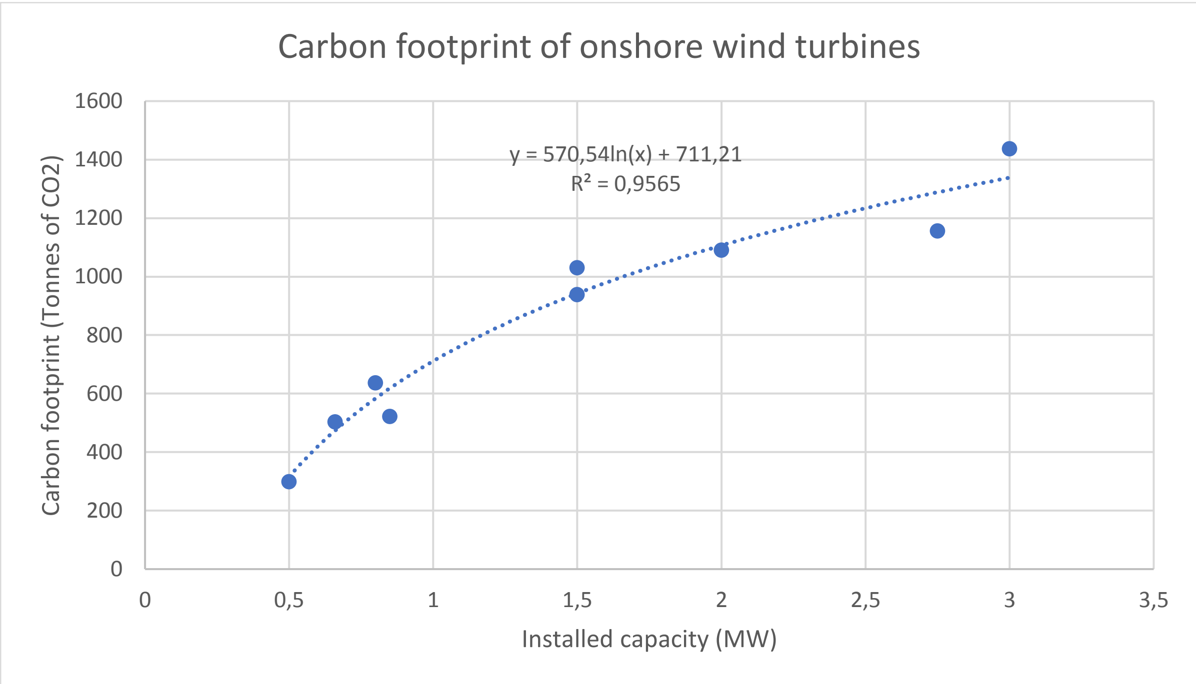

Figure 5.2. Carbon footprint evolution of onshore wind turbines

The equation, which represents the carbon footprint evolution of onshore wind turbines with a square error of 95.65%, is:

$$Carbon\ footprint\ (Tons\ of\ CO_2) = 570.54 \cdot \ln(x) + 711.21 \quad \textit{Equation 29}$$

Where x is the installed capacity expressed in megawatts (MW).

From the data calculated in *Table 5.1* a linear equation has been developed to determine the carbon footprint as a function of offshore installed capacity, this can be shown in *Figure 5.3*. The CO_2 emissions change linearly with the installed capacitiy. This is because the amount of material needed to manufacture an offshore wind turbine and the emissions due to the transport phase increase linearly with the power rating.

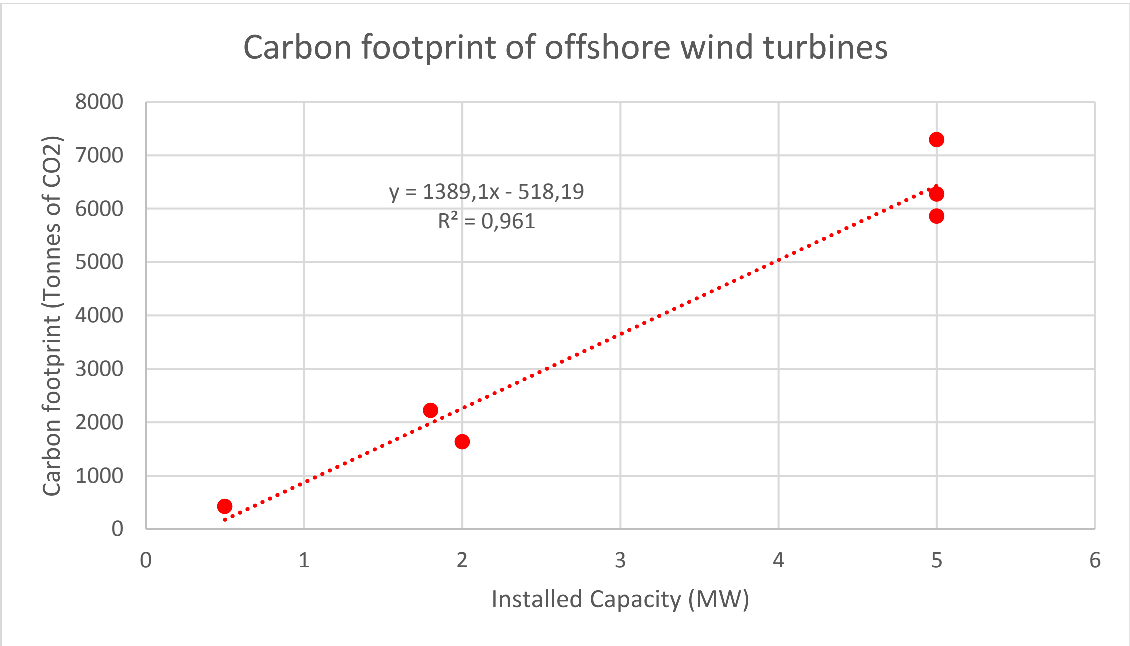

Figure 5.3. Carbon footprint evolution of offshore wind turbines

The equation, which represents the carbon footprint evolution of offshore wind turbines with a square error of 96.1%, is:

$$Carbon\ footprint\ (Tons\ of\ CO_2) = 1389.1 \cdot x - 518.19 \qquad \textit{Equation 30}$$

Where x is the installed capacity expressed in megawatts (MW).

5.2. Efficiency of wind turbines from the same technology

Other researchers have shown the differences between onshore and offshore wind technologies in order to know which one is more efficient in terms of CO_2 savings. However, no research has been carried out to compare and determine the effectiveness of the different installed capacity of turbines with the same technology (onshore or offshore) as a function of its efficiency in terms of embodied carbon.

To compare wind turbines from the same technology, the ratio of tonnes of CO_2/energy produced (kWh) cannot be used because it depends on the electricity generated so much, so if a turbine is more environmentally friendly, but it is placed in a bad location where it is not windy, this ratio would not reflect that the turbine is cleaner in terms of CO_2 savings than another one in a better location. Nevertheless, if a ratio tonnes of CO_2/installed capacity (MW) is used, turbines from the same technology can be compared without considering the energy produced. The lower this ratio is, the more efficient the turbine is in terms of carbon embodied.

The *Figure 5.4* shows the efficiency of onshore wind turbines. It is shown the more installed capacity the wind turbine has, the more efficient it is in term of CO_2 savings. However, there are not very big onshore wind turbines because there are some limitations like there are obstacles on the ground such as building, mountains… that reduce wind speed, so energy efficiency decreases as well; the bigger the wind turbine is, the more visual impact and there are sound restrictions, therefore the blade tip speed cannot be high, so weight cannot be reduced which means that production costs are higher. Thus, although onshore big turbines are more efficient in terms of CO_2 savings, it is not always possible to manufacture them because of the limitations explained above.

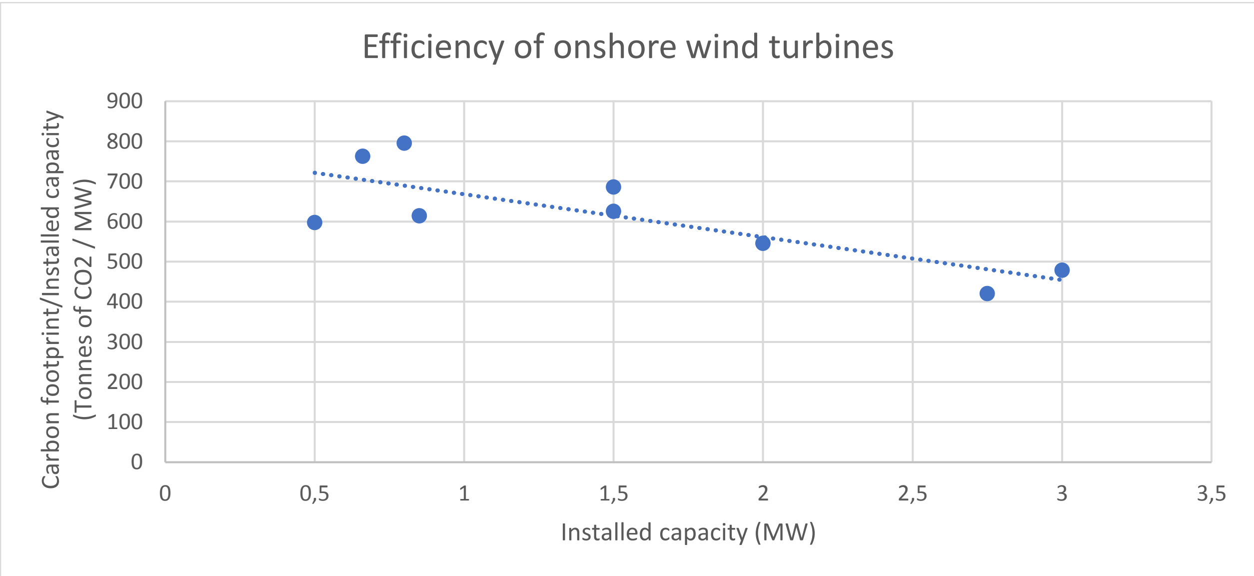

Figure 5.4. Efficiency of onshore wind turbines

The *Figure 5.5* shows the efficiency of offshore wind turbines. In contrast to onshore turbines, for offshore ones, the less the installed capacity is, the more efficient the turbine is. But there are few turbines with little installed capacity, since there are important economic restrictions like there are not electrical infrastructures to connect these offshore installations with consumption centres; towers are really tall because they need to be moored on the sea bottom; a lot of ballast is required to make the foundations; the fuel consumption for trucks and ships to carry out the materials to the place where they are sited is a lot and the maintenance must be done by a helicopter which increases the cost. Thus, although offshore small turbines are more efficient in terms of CO_2 savings, it is not possible to manufacture them because they are not economically viable.

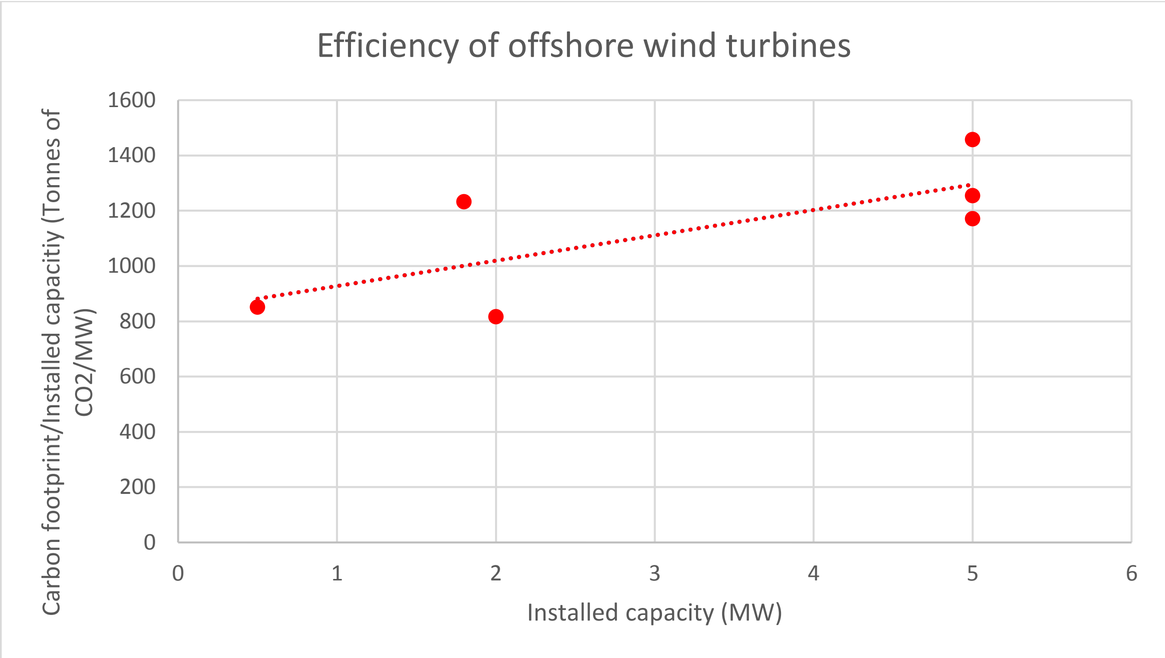

Figure 5.5. Efficiency of offshore wind turbines

Figure 5.6 shows that onshore efficiency decreases with the installed capacity, while offshore efficiency increases like it was explained above. Although, it seems than onshore efficiency is much better than the offshore one, because all onshore data are lower than offshore ones, this is not true. Because the ratio (carbon footprint/installed capacity) can only be used to compare turbines with the same technology with the same energy efficiency. Due to the fact that offshore wind technology is more efficient in terms of energy than the onshore one, as it was shown in

Table 1.3, another ratio has to be used to compare both technologies, and this ratio should include the energy generated by turbine.

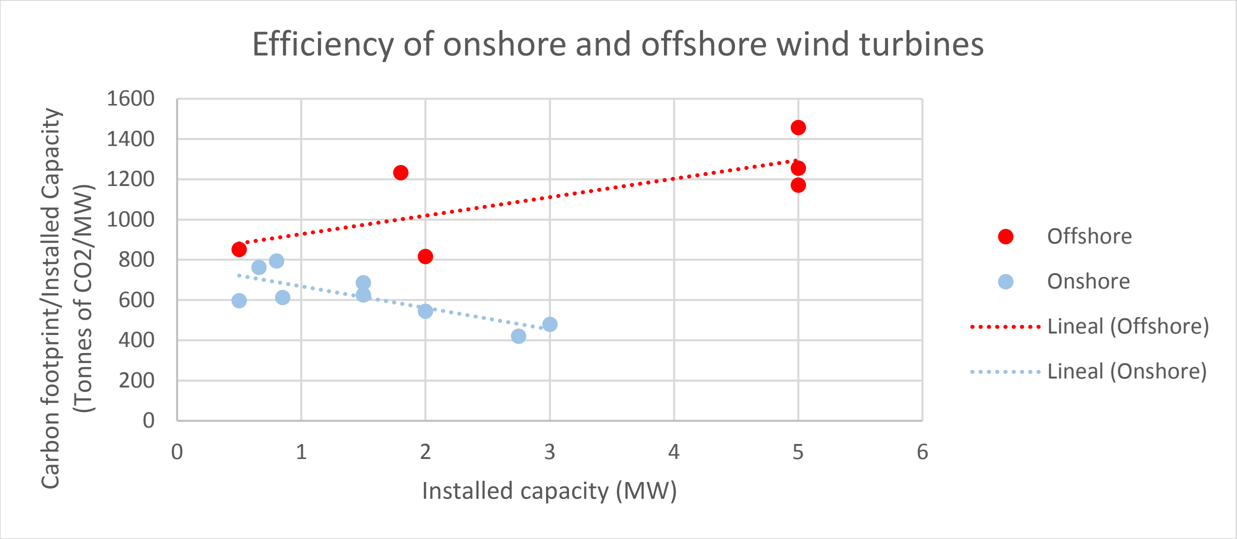

Figure 5.6. Efficiency of onshore and offshore wind turbines

5.3. Carbon footprint per life cycle phase

In order to know which phases in the life cycle of a wind turbine are less environmentally friendly and to compare the differences between both technnologies, it was calculated the carbon footprint embodied in each phase like a percentage, as it is shown in the following table.

Table 5.2. Carbon footprint of all wind turbine analysed

		Percentage (%)				
	Name	Material	Energy	O&M	Transport	Decommissioning
Onshore	*(Schleisner, 2000)*	79	8	11	2	-37
	(Ardente et al., 2008)	80	6	11	4	-28
	(Dones et al., 2007)	82	6	11	2	-36
	(Crawford, 2009) (1)	79	7	11	2	-36
	(Crawford, 2009) (2)	76	9	12	2	-33
	(Oebels & Pacca, 2013)	80	7	11	2	-35
	(Yang & Chen, 2013)	80	7	11	2	-38
	(Martínez et al., 2009)	78	8	12	2	-34
	(Bonou, Laurent & Olsen, 2016)	75	11	13	1	-33
	Onshore Average	**79**	**8**	**11**	**2**	**-34**
Offshore	*(Schleisner, 2000)*	76	3	9	12	-28
	(Dones et al., 2007)	76	3	9	12	-26
	(Dolan, 2007)	81	2	10	8	-38
	(Bonou, Laurent & Olsen, 2016)	81	2	10	7	-35
	(Reimers, Özdirik & Kaltschmitt, 2014)	80	2	10	8	-36
	(Weinzettel et al., 2009)	82	2	10	6	-33
	Offshore Average	**79**	**2**	**10**	**9**	**-33**

Figure 5.7 shows that around 80% of the carbon dioxide emissions embodied in a wind turbine (onshore and offshore) are due to the material manufacture. Furthermore, carbon footprint during the operation & maintenance is around 10% in both technologies. However, the CO_2 emissions during the transport phase is much higher in offshore technology, because distances are longer and the amount of material to transport is larger as well. Moreover, around 30% of carbon footprint can be saved if onshore and offshore wind turbines are recycled, this is why the recycle of wind turbines is so important.

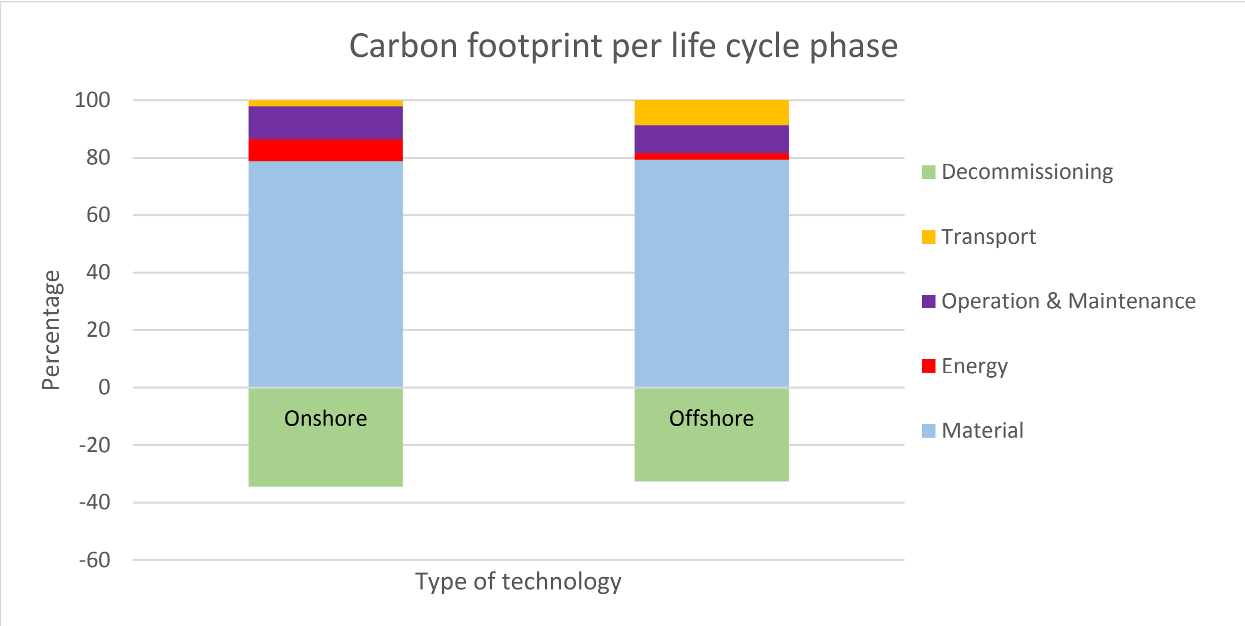

Figure 5.7. Carbon footprint per life cycle phase

Other researchers (*(Kaldellis & Apostolou, 2017)* and *(Bonou, Laurent & Olsen, 2016)*) have already estimate the percentage of carbon footprint embodied in the different phases, and their results are essentially the same, where materials carbon footprint is around the 80%, the operation & maintenance around the 10% and there are important savings if wind turbines are recycled. However, they do not included the transport phase.

5.4. Carbon footprint in the United Kingdom

Once the equations that represent the carbon footprint evolution of onshore and offshore wind turbines from the installed capacitiy have been calculated, it is really easy to estimate the carbon footprint of different wind generators, even the total carbon dioxide emissions in a whole country due to the wind energy.

The following table contains the equations to estimate the carbon footprint of onshore and offshore wind turbines in the whole life cycle (*Equation 29* and *Equation 30*) and the average installed capacity from turbines of both technologies (*Table 1.2*).

Table 5.3. Carbon footprint equations and average installed capacity in UK

Type of technology	Equation	Installed capacity per turbine (MW)
Onshore Wind	$570.54 \cdot \ln(x) + 711.21$	0.83
Offshore Wind	$1389.1 \cdot x - 518.19$	3.61

Therefore, the carbon footprint in the whole life cycle for an average onshore wind turbine is 604.9 ± 4.5 % tonnes of CO_2, while for an average offshore wind turbine is 4496.5 ± 4 % tonnes of CO_2.

Due to the fact that a database of all wind turbines with their installed capacity from the United Kingdom (UK) were not found, the total carbon footprint due to the wind energy was estimated from the carbon footprint of an average generator and the total amount of wind turbines in the UK.

The total number of onshore wind turbines in the UK is 13100, while for offshore technology is 1465. So the total carbon footprint in the whole life cycle of the turbines is 7,924,190 ± 4.5 % tonnes of CO_2 for onshore and 6,587,372.5 ± 4 % for offshore.

In order to know which technology is more efficient in terms of carbon dioxide savings it is necessary to use the ratio grammes of CO_2/kWh (carbon footprint/energy generated). This ratio is the best to compare both types of technologies because it includes carbon emissions and energy generated. Obviously, the total carbon footprint of an offshore wind turbine is going to be higher than an onshore one because of the amount of materials needed and the transport distances. However, offshore technology is more efficient like it was shown in *Table 1.3*. To calculate this ratio is only necessary to divide the total carbon footprint of each technology between the energy generated in the UK due to them in the whole life cycle.

Like it was shown in *Table 1.1*, the total amount of energy generated from onshore technology is 20962 GWh, while from offshore is 16406 GWh in 2016, but it is necessary to estimate the energy produced in the whole life cycle, so they were multiplied by 20 years of operation.

Then, the ratio for onshore turbines in UK is 18.9 ± 4.5% gCO_2/kWh and for offshore ones is 20.1 ± 4% gCO_2/kWh. Moreover, both ratios are considerably less than the electricity generation mix one, which is 275 gCO_2/kWh *(Loughran, 2018)*, so the wind energy brings a lot of benefits in term of CO_2 savings. Onshore wind turbines in the UK are more efficient in terms of CO_2 savings than offshore ones. Although, offshore technology is much more expensive than the onshore one and less environmentally friendly, the reason that some many offshore farms are being manufacture is because they are much more energetically efficient than onshore ones.

Table 5.4. Carbon footprint in UK due to wind energy

Type of technology	Carbon footprint/turbine (tonnes of CO_2)	Total carbon footprint (tonnes of CO_2)	Ratio (grammes of CO_2/kWh)
Onshore Wind	604.9 ± 27	7 924 190 ± 356 589	18.9 ± 0.9
Offshore Wind	4496.5 ± 180	6 587 373 ± 263 495	20.1 ± 0.8

The ratio (grammes of CO_2/kWh) estimated is big in comparison to the ratio from other researchers *(Kaldellis & Apostolou, 2017)* whose results are shown in *Table 2.1*. This is probably because a lot of researchers do not included all phases to calculate the carbon footprint embodied in a wind turbine like it was explained in *Life Cycle Assessment* section, where some of the carbon dioxide emissions of some phases had to be estimated because the researcher did not considered that phase. Moreover, turbines analysed *(Kaldellis & Apostolou, 2017)* are placed around the world, so the energy produced can be really different, depending on the wind conditions of each country, this would explain the big differences between the ratios as well.

5.5. Carbon footprint evolution per year in a wind turbine

The carbon footprint evolution throughout the years of a wind turbine was calculated in order to know what phases have more carbon embodied. This evolution was estimated for an average onshore and offshore wind turbine in the United Kingdom. Then, it is explained how it was calculated.

As *Table 5.4* shows the carbon footprint for a 0.83 MW onshore turbine is 604.9 tonnes of CO_2, while for a 3.61 MW offshore turbine is 4496.5 tonnes of CO_2. First of all, it is necessary to estimate the carbon footprint embodied in each life cycle phase. For that, the total amount of carbon embodied in a wind turbine was multiplied by the average percentages shown in *Table 5.2*, where these percentages show the amount of carbon embodied in each life cycle phase.

Table 5.5. Carbon embodied in an average onshore and offshore wind turbine in UK

Onshore carbon footprint = 604.9 tonnes of CO_2			Offshore carbon footprint = 4496.5 tonnes of CO_2		
Name	Material	Energy	O&M	Transport	Decommissioning
Onshore Average (%)	79	8	11	2	-34
Onshore carbon footprint (tonnes of CO_2)	**476.5**	**46.4**	**69.2**	**12.8**	**-208.4**
Offshore Average (%)	79	2	10	9	-33
Offshore carbon footprint (tonnes of CO_2)	**3567.2**	**104.9**	**434.7**	**397.2**	**-1468.9**

5.5.1 First year of operation

The next step was to determine the carbon dioxide emissions embodied per year. The moment when a turbine starts to work, there is already an important amount of carbon embodied in it due to the materials, the energy consumed during the installation and the transport of these materials.

Onshore wind turbines

For onshore wind turbines, the equation which represents the carbon footprint (CF) when turbines starts working is:

$$Initial\ CF\ (t\ CO_2) = Material + \frac{Transport}{2} + \frac{Energy}{2} \qquad \textit{Equation 31}$$

Where:

- Material: is the carbon footprint due to the manufacture of the materials.
- Transport: is the carbon footprint due to the transport of these materials. There are two transport phases, one during the installation and the other one during the decommissioning, like it was explained in the *Transport* section.
- Energy: is the carbon footprint due to the energy consumed during the installation. There are two energy phases, one during the installation and the other one during the decommissioning, like it was explained in the *Energy* section.

Offshore wind turbines

For offshore wind turbines, the equation which represents the carbon footprint (CF) when turbines starts working is:

$$Initial\ CF\ (t\ CO_2) = Material + \frac{Transport}{2} \qquad \textit{Equation 32}$$

Where:

- Material: is the carbon footprint due to the manufacture of the materials.
- Transport: is the carbon footprint due to the transport of these materials. There are two transport phases, one during the installation and the other one during the decommissioning, like it was explained in the *Transport* section. Energy was not included because for offshore turbines, the energy consumed is due to the operation and maintenance, like it was explained in the *Energy* section.

5.5.2 Years of operation

Now, it is necessary to know the carbon embodied during the operation of the wind turbine. It is assumed that all years are equal in terms of carbon dioxide emissions because it was calculated with an average.

<u>Onshore wind turbines</u>

For onshore wind turbines, the equation which represents the carbon footprint (CF) per year is:

$$CF\ per\ year\ (t\ CO_2) = \frac{O\&M}{20} \qquad \text{Equation 33}$$

Where:

- O&M: is the carbon footprint due to the operation & maintenance, which includes parts of generator which need to be changed and energy consumed in these changes and in the maintenance during the 20 years of operation like it was explained in *Operation & Maintenance* section.

<u>Offshore wind turbines</u>

However, for offshore wind turbines, the equation which represents the carbon footprint (CF) per year is:

$$CF\ per\ year\ (t\ CO_2) = \frac{O\&M}{20} + \frac{Energy}{20} \qquad \text{Equation 34}$$

Where:

- O&M: is the carbon footprint due to the operation & maintenance, which includes parts of the generator that need to be changed during the 20 years of operation like it was explained in *Operation & Maintenance* section.

- Energy: is the carbon footprint due to the energy consumed in these changes and in the maintenance during the 20 years of operation.

5.5.3 Last year of operation

Finally, it is necessary to know the carbon footprint embodied during the last operation year of a wind turbine, which includes the energy consumed during the uninstalling, the transport of the materials to the landfill, the savings of CO_2 emissions due to the recycling and the carbon footprint embodied in a normal year of operation.

Onshore wind turbines

For onshore wind turbines, the equation which represents the carbon footprint (CF) during the last year of operation is:

$$CF\ last\ year\ (t\ CO_2) = Decommissioning + \frac{Transport}{2} + \frac{Energy}{2} + \frac{O\&M}{20} \quad \textit{Equation 35}$$

Where:

- Decommissioning: is the CO_2 savings due to the recycling of the materials.

- Transport: is the carbon footprint due to the transport of the materials to the landfill. There are two transport phases, one during the installation and the other one during the decommissioning, like it was explained in the *Transport* section.

- Energy: is the carbon footprint due to the energy consumed during the unistalling. There are two energy phases, one during the installation and the other one during the decommissioning, like it was explained in the *Energy* section.

- O&M: is the carbon footprint due to the operation & maintenance, which includes parts of the generator that need to be changed and energy consumed in these changes and in the maintenance during the 20 years of operation like it was explained in *Operation & Maintenance* section, because in the last year the wind turbine is still generating electricity.

Offshore wind turbines

For offshore wind turbines, the equation which represents the carbon footprint (CF) during the last year of operation is:

$$CF\ last\ year\ (t\ CO_2) = Decommissioning + \frac{Transport}{2} + \frac{Energy}{20} + \frac{O\&M}{20} \quad \textit{Equation 36}$$

Where:

- Decommissioning: is the CO_2 savings due to the recycling of the materials.

- Transport: is the carbon footprint due to the transport of the materials to the landfill. There are two transport phases, one during the installation and the other one during the decommissioning, like it was explained in the *Transport* section.

- O&M: is the carbon footprint due to the operation & maintenance, which includes parts of the generator that need to be changed during the 20 years of operation like it was explained in *Operation & Maintenance* section, because in the last year the wind turbine is still operational.

- Energy: is the carbon footprint due to the energy consumed in these changes and in the maintenance during the 20 years of operation, because in the last year the wind turbine is still generating electricity.

5.5.4 Carbon footprint evolution per year results

The next table shows the results of applying the method explained above.

Table 5.6. Onshore and offshore cumulative carbon footprint per year

Onshore							
Name	Year 0	Year 1	Year 2	Year 3	…	Year 19	Year 20
Carbon footprint/year (t CO_2)	506.1	3.5	3.5	3.5	…	3.5	-175.3
Cumulative Carbon footprint (t CO_2)	506.1	509.6	513.0	516.5	…	571.9	396.5
Offshore							
Name	Year 0	Year 1	Year 2	Year 3	…	Year 19	Year 20
Carbon footprint/year (t CO_2)	3765.8	27.0	27.0	27.0	…	27.0	-1243.3
Cumulative Carbon footprint (t CO_2)	3765.8	3792.8	3819.8	3846.8		4278.4	3035.1

Figure 5.8 shows the cumulative carbon footprint for an onshore and offshore wind turbine year by year, since it starts working until it is uninstalled. Obviously, the carbon footprint is much higher for offshore wind turbines, since more material is required, the transport distance is greater and more energy is required during the installation and the decommissioning.

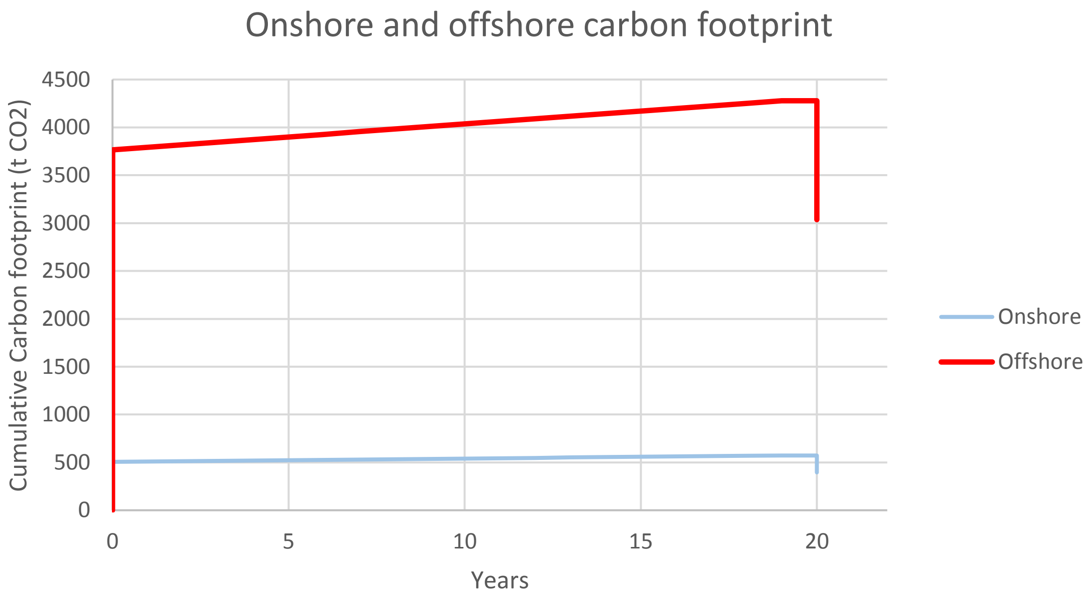

Figure 5.8. Carbon footprint of an onshore and offshore wind turbine year on year

Figure 5.9 shows that carbon footprint evolution for onshore and offshore are really similar. Most of the CO_2 emissions embodied in a wind turbine occur before the wind turbine starts to work. This is because a lot of materials are needed to manufacture turbines, they need to be transported long distances, and machines need a lot of energy to be installed. When a wind turbine starts producing energy, the evolution of the CO_2 embodied is linear and much lower than in the first phase. This is because when wind energy is produced, there are not carbon dioxide emissions, so the cumulative carbon footprint year by year is due to the need to change some wind generator components and the carbon embodied in some machines used to the operation & maintenance of the installation. During the last year, there is a carbon footprint reduction, this is because during the decommissioning, some parts of the wind turbine are recycled, therefore there are CO_2 savings. This savings are around the 33% of the total carbon footprint, so it is really important to recycle wind turbines to reduce the amount of carbon dioxide emissions embodied in them.

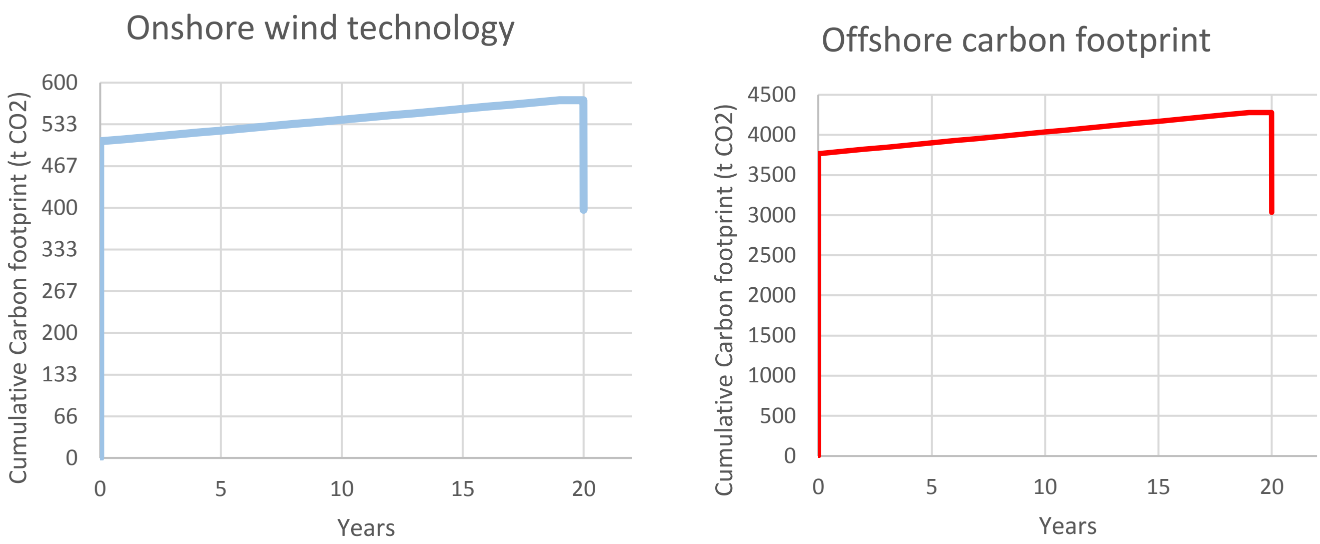

Figure 5.9. Cumulative carbon footprint of an onshore and offshore wind turbine

Other researchers (*(Kaldellis & Apostolou, 2017)* and *(Bonou, Laurent & Olsen, 2016)*) have already estimate the percentage of carbon footprint embodied in the different phases, and their results are essentially the same, where the carbon footprint before wind turbines start working is around the 90%, the operation & maintenance around the 10% and there are important savings if wind turbines are recycled (30%).

5.6. Payback time of carbon dioxide emissions in a wind turbine

Wind turbines do not emit CO_2 while they are producing energy. However, there is an important amount of carbon dioxide emissions embodied in their life cycle like it was already explained. It was shown in *Carbon footprint evolution per year in a wind turbine* section in *Figure 5.9* that the most part of carbon footprint embodied happens when wind turbine is not working yet. Therefore it is really important to know the amount of time happens until turbines start to save CO_2 emissions.

The amount of carbon footprint embodied in an average onshore and offshore wind turbine in the United Kingdom was calculated in the section above (*Carbon footprint evolution per year in a wind turbine*). Moreover it is necessary to estimate the carbon footprint if that wind turbine did not exist and the energy had been produced by another type of technology. It is assumed that all types of technologies would contribute to proporcionate that amount of energy in the same proportion they appear in the electricity generation mix of the United Kingdom in 2016. So the carbon footprint ratio of this distribution in the UK in 2016 is 275 grammes of CO_2/kWh *(Loughran, 2018)*. Then this ratio was multiplied by the amount of energy which average onshore and offshore wind turbines produced in 2016 in the UK like it was shown in *Table 1.2* (1.6 GWh for an onshore and 11.20 GWh for an offshore turbine).

Then, when the graphic of the cumulative carbon footprint due to a wind energy intersects with the cumulative carbon footprint due to the electriciy generation mix, that moment will be the payback time in terms of CO_2 savings.

Figure 5.10 shows that the payback time for an average onshore wind turbine in the United Kingdom is a bit less than one year and two months. After that, all energy generated contribute to reduce the carbon footprint in the UK.

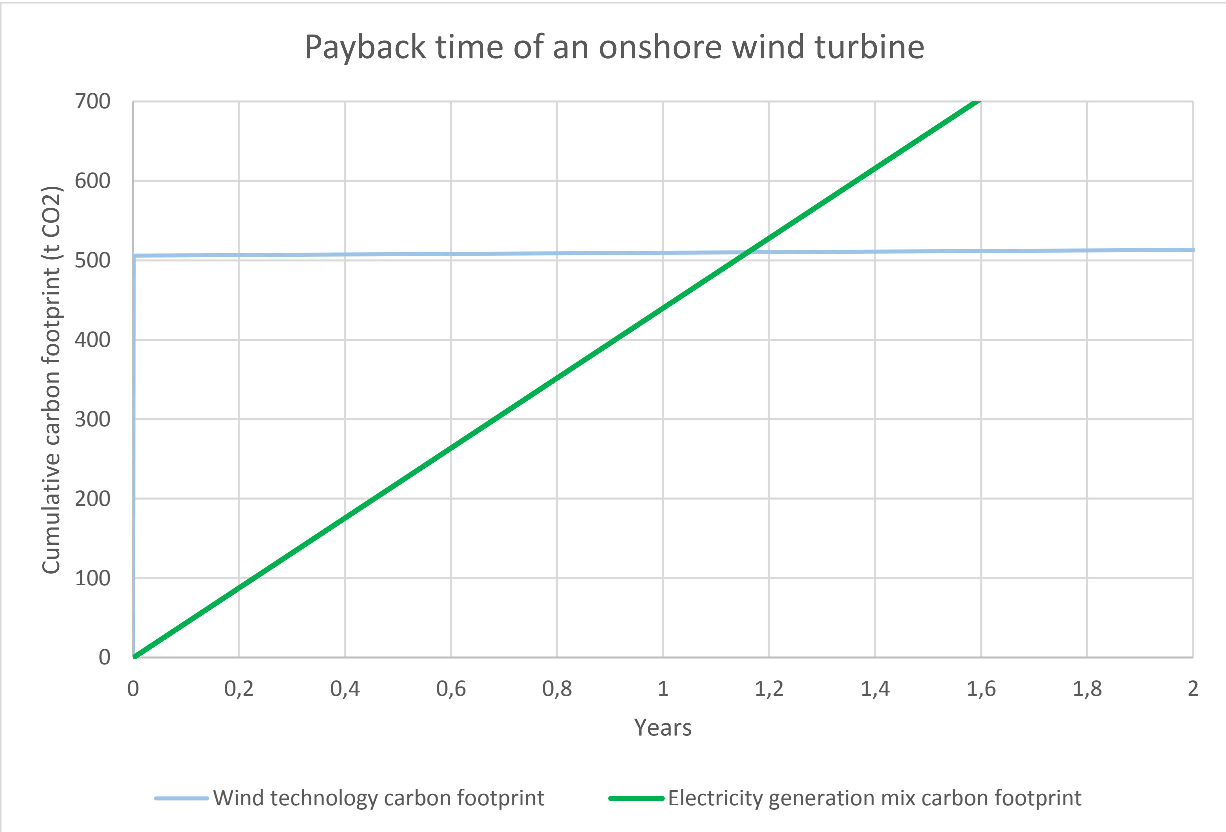

Figure 5.10. Payback time for an onshore wind turbine

Figure 5.11 shows the payback time for an average offshore wind turbine in the United Kingdom is a bit more than one year and two months. After that, all energy generated contributes to reduce the carbon footprint in the UK. Payback time for an offshore wind turbine is greater than for an onshore one, this is because onshore wind turbines are more effective that offshore ones in terms of carbon emissions reduction, which coincide with results showed in *Carbon footprint in the United* Kingdom in *Table 5.4* where the ratio (grammes of CO_2/kWh) shows that onshore wind technology is still more efficient than the offshore one (18,9 against 20,1 gCO_2/kWh).

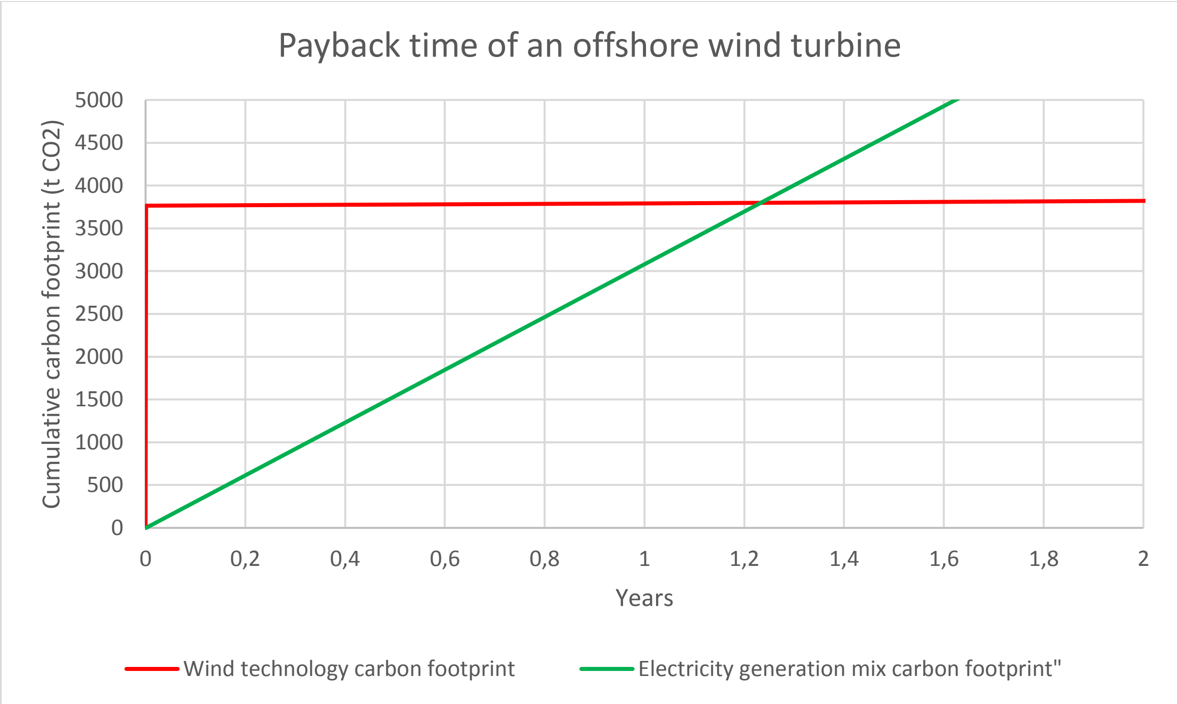

Figure 5.11. Payback time for an offshore wind turbine

Some researchers *(Bonou, Laurent & Olsen, 2016)* have shown that the payback time for onshore and offshore wind turbines is a bit less than one year, but this is because instead of considerating the electricity generation mix in the country, they considerated that the energy produced by the wind turbine would be generated by coal or fossil sources, then the carbon footprint ratio would be much higher (more than 500 gCO_2/kWh), therefore the payback time would decrease.

5.7. Total carbon footprint saving in UK due to the wind energy

It is necessary to compare actual electricity generation mix to one scenario where wind energy never has been developed the United Kingdom. Thus, all CO_2 savings due to the onshore and offshore wind turbines throughout the history can be calculated.

First of all, the ratio grammes of CO_2/kWh (Energy produced) if wind technology had not been developed in the UK has been estimated year on year, like *Table 4.19* shows in *Carbon footprint factor in UK if no wind energy* section. This ratio was used to know the carbon footprint of energy in the United Kingdom due to the mix electricity generation if wind turbines had not been developed.

Then, the installed capacity and the power generated year on year from wind energy was obtained *(Department for Bussines, Energy and Industrial Strategy (1), 2000-2017)*. As no data about the total number of wind turbines per year was found, it was assumed that all onshore turbines have 0.83 MW of installed capacity and 3.61 MW for offshore ones, which correspond with average data from 2016 like it was shown in *Table 1.2*. Then the total number of wind turbines every year and the new wind turbines per year can be estimated like it shows in *Cumulative carbon dioxide emissions saving calculations* section, *Table 7.1* in appendices.

Therefore, if the total number of new turbines per year and the carbon footprint per year for a wind turbine are known, because it was estimated in *Table 5.6* in *Carbon footprint evolution per year results* section, it is really easy to calculate the total CO_2 emissions embodied in all wind turbines in the United Kingdom year by year like it is shown in *Table 7.2* and *Table 7.3* in appendices.

However, if wind energy had not been developed this energy generated by wind turbines must have been produced by another type of technology. It is assumed that all types of technologies would contribute to proporcionate that amount of energy in the same proportion like in the electricity generation mix without considering wind technology. So, to estimate the carbon footprint in this scenerio the ratio grammes of CO_2/kWh, which does not include wind energy, was multiplied by the amount of energy generated by wind technology like it shows in appendices in *Table 7.4* (the ratio before 2000 could not be calculated because no data was found, therefore it is assumed than before 2000 this ratio is constant).

Figure 5.12 shows the difference between an scenario where wind energy was not developed and the actual scenerio where it was. At the beginning, there are no big differences between both scenarios because most of the CO_2 emissions embodied in a wind turbine occur before the wind turbine starts to work. This is because a lot of materials are needed to manufacture turbines, they need to be transported long distances, and machines need a lot of energy to install them. When a wind turbine starts to produce energy, the CO_2 embodied is much lower, as it was explained in *Carbon footprint evolution per year results* section. This is why when years spend the differences between scenarios increase considerably. At the end of 2016 there are more than 79,000,000 tonnes of CO_2 savings due to the wind energy, which is around 86% of savings and the more years spent, the bigger differences there will be.

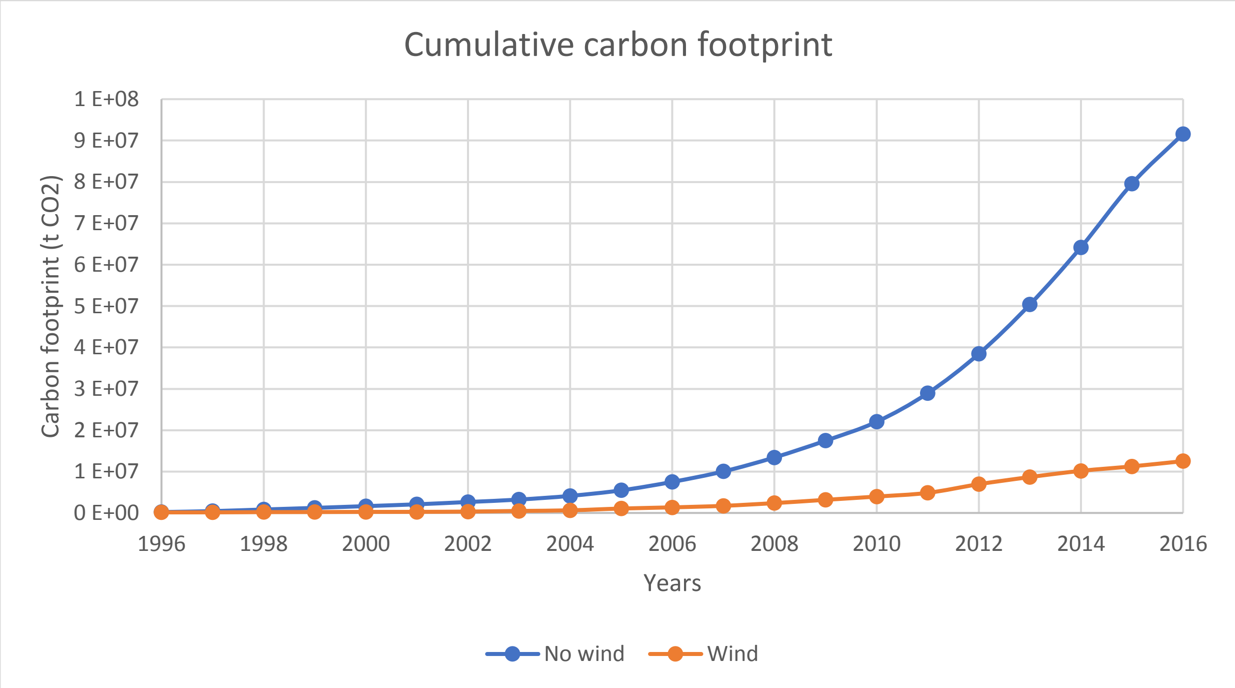

Figure 5.12. Carbon footprint in a scenario where wind energy was not developed and other one where it was

Figure 5.13 shows the difference between an scenario where onshore wind energy was not developed and the actual scenerio where it was. At the beginning, there are not big differences between both scenarios like it was explained above. However, as years go by the differences between scenarios increase considerably due to the fact that wind energy does not emit CO_2 emissions during the operation. At the end of 2016 there are more than 52,000,000 tonnes of CO_2 savings due to the onshore wind energy, which is around 88.5% of savings and the more years spent, the bigger differences there will be.

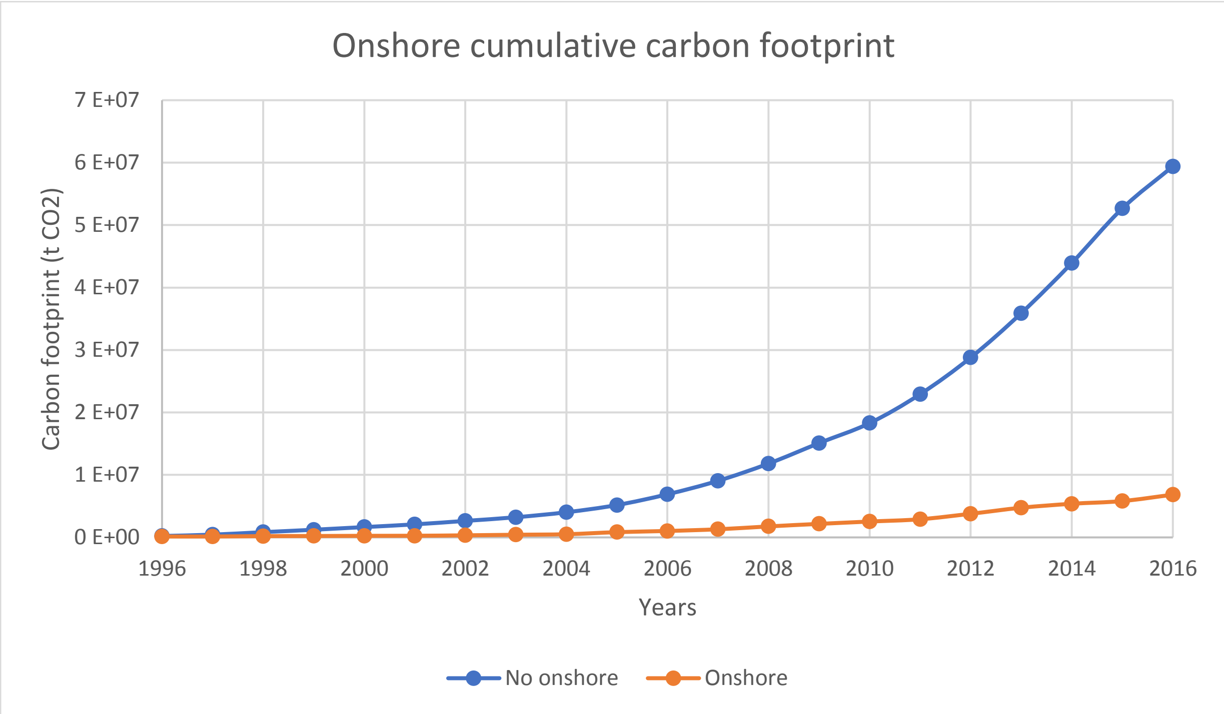

Figure 5.13. Carbon footprint in a scenario where onshore energy was not developed and other one where it was

Figure 5.14 shows the difference between an scenario where offshore wind energy was not developed and the actual scenerio where it was. At the beginning, there are no big differences between both scenarios, as it was explained above. However, as years go by the differences between scenarios increase considerably due to the fact that wind energy does not emit CO_2 emissions during the operation. But, these differences do not increase as fast as onshore ones, and there is even a cannibalization effect during the first years, because the carbon embodied in an offshore wind turbine is much higher than in an onshore one, as it was shown in *Total carbon footprint* section. At the end of 2016 there are more than 26,500,000 tonnes of CO_2 savings due to the offshore wind energy, which is around 82% of savings and the more years spend, the bigger differences there will be. The amount of CO_2 savings due to the offshore wind technology is much less than onshore ones, but this is because offshore technology was developed slowlier than the onshore one at the beginning of 21st century. Although the percentages of savings (88.5% against 82%) shows that onshore wind turbines are more effective that offshore ones in terms of carbon emissions reduction, which coincide with the results showed in *Carbon footprint in the United* Kingdom in *Table 5.4* where the ratio (grammes of CO_2/kWh) show that onshore wind technology is still more efficient than the offshore one (18.9 against 20.1 gCO_2/kWh).

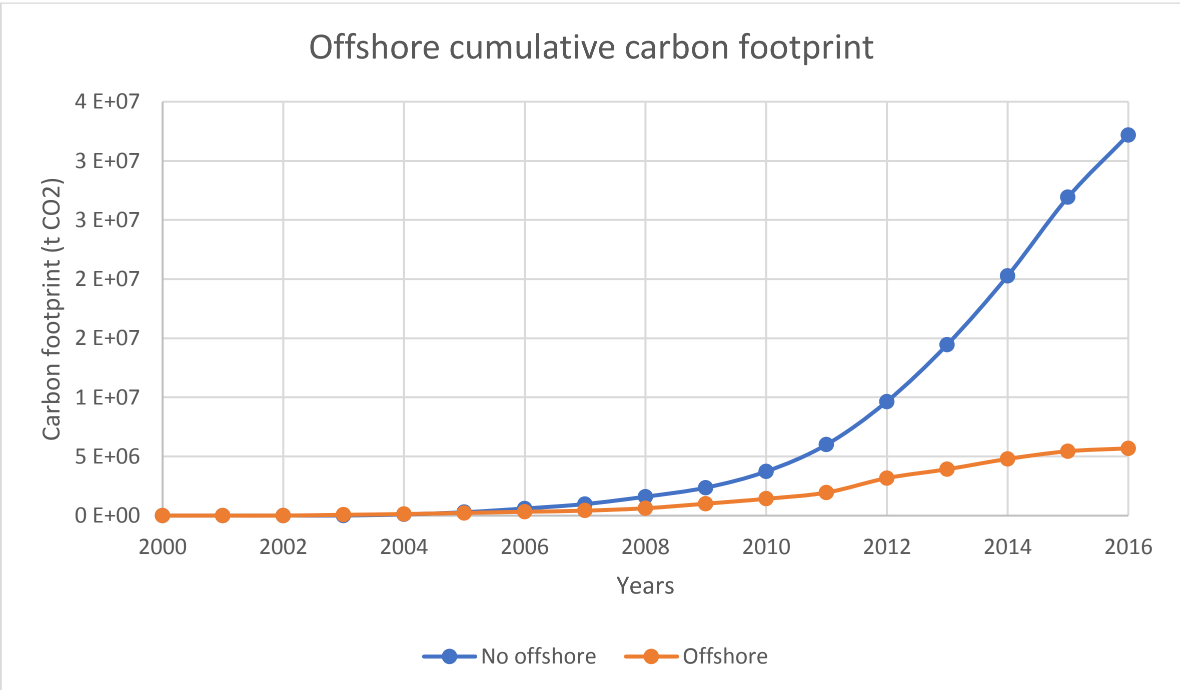

Figure 5.14. Carbon footprint in a scenario where offshore energy was not developed and other one where it was

Other researchers *(Usubiaga et al., 2017)* have done a study like this one, but applicable to all wind turbine in Europe, as it was shown in *Figure 2.3* and *Figure 2.4*. Results are really similar, because onshore technology brings benefits faster than the offshore one, because the carbon footprint of this type of turbines is low. However, for offshore technology in *(Usubiaga et al., 2017)* the research, it is observed a cannibalization effect like it is shown in *Figure 2.4*, however in this dissertation it did not happen, and this is because offshore wind energy was developed slowlier in the United Kingdom where few turbines were installed each year, so the initial carbon footprint impact due to the wind technology, like it was explained in *Carbon footprint evolution per year in a wind turbine* section, was not as big as in the whole Europe, therefore the cannibalization effect was not too big.

5.8. Impact statement

The main problem is that a lot of companies and governments invest a lot of money in renewable energies because it is thought that they do not emit CO_2. Although this is true during the energy generation process, there is a carbon footprint embodied in a wind turbine due to the materials manufacture, transport, installation and maintenance. Therefore, it is tremendously important to calculate the carbon dioxide emissions in the life cycle, thus this way, the exact CO_2 savings due to the use of these technologies will be known, as well as their payback time in terms of contamination and if these technology is really reducing carbon emissions in function of the energetic mix generation of the country. For example, it was thought that solar energy was environmentally friendly *(Usubiaga et al., 2017)*, but almost 15 years of operation are needed to save as much CO_2 during the energetic generation process as the carbon emissions produced during the life cycle. So, considering the cannibalization effect is very important in renewable energies.

This research will study wind turbines because wind energy is the most important renewable energy in Europe, as it is already generating a big amount of energy. Furthermore, a methodology will be developed to calculate the carbon footprint in wind turbines and to compare onshore and offshore technologies in terms of CO_2 emissions per kilowatt of energy generated. In addition, it will provide a method to calculate the payback period in terms of carbon dioxide savings to be aware of the cannibalization effect of wind technology and it will know what operations in the turbine life cycle are more contaminating, in order to try to reduce the emissions in those steps. Apart from these goals, this research will provide a lot of benefits, that being the reason why it should be funded.

This research will benefit the funding body because:

- It will make a difference because this methodology can be shared with clients and consumers.
- It will allow to choose materials to manufacture the generators in a more sustainable way.
- As it will be possible to know what operations emit more CO2, we will be able to analyze how to reduce it.
- Carbon footprint will help improve the brand´s image.
- It will satisfy the consumers demands in terms of environmental efficiency because the information will be reliable.
- It will provide wind more environmentally sustainable wind turbines designs.
- Implanting this methodology and applying it will not imply excessive costs.

But these are only the benefits for the funding body, however this research will bring gains for every living being on Earth, because if CO_2 is reduced, pollution will decrease, life expectancy will increase, health will be improved and illnesses will reduce. Moreover, the ozone hole will not increase as fast, global temperature will not be so high. In consequence the north and south pole will not melt, therefore a lot of species and ecosystems will be saved.

6. CONCLUSIONS

Global warming makes governments worry about carbon dioxide emissions, this is why wind energy has been developed so much these years. Nowadays, any CO_2 level is a reason to worry and should be reduced, it is not enough that wind technology does not contamine while it is producing energy, but it is necessary to reduce as much as possible carbon dioxide emissions in the whole life cycle. So this research tries to determine an accuracy methodology to calculate carbon footprint embodied in a wind turbine in order to compare offshore and onshore wind technologies in the United Kingdom and to know the benefits that wind energy brings in terms of CO_2 savings.

The methodoly developed is the one which considers all carbon dioxide emissions embodied in the whole life cycle of a wind turbine. It includes the carbon footprint due to the manufacture and the transportation of the materials to the location where the wind turbine is placed. Energy consumed during the installation, operation & maintenance, and decommissioning. Finally, the carbon emissions embodied in the transportation to the landfill when the wind turbine is uninstalled. However it is necessary to dock the carbon footprint from the materials which have been recycled.

After calculating the carbon footprint of all wind turbines, offshore wind turbines have more carbon dioxide embodied in the whole life cycle than onshore ones. This is because more materials are needed to manufacture them and transport distances that are longer as well. Moreover, if the carbon footprint is represented as a function of the installed capacity, it was observed that for onshore wind turbines, it has a logarithmic trend, while in offshore wind turbines, it has a linear trend like it was shown in *Figure 5.2* and *Figure 5.3*. Therefore, a logarithmic and a linear equation could be developed in order to calculate the carbon footprint of onshore and offshore wind turbines from the installed capacity on an easy way.

Using the ratio carbon footprint/ installed capacity, it was calculated which power rating is more efficient in terms of CO_2 savings for turbines of the same technology (onshore or offshore). It was shown, in case of onshore wind turbines, that the more installed capacity the wind turbine has, the more efficient it is in terms of CO_2 savings. However, there are not very big onshore wind turbines because there are some limitations. In case of offshore wind turbines, the less the installed capacity is, the more efficient the turbine is. But there are few turbines with little installed capacity, since there are not economically viable, as it was shown in *Figure 5.6*.

Moreover, it was known that most of the carbon footprint of onshore and offshore wind turbines is due to the manufacture of the materials, around an 80%. And the big differences between onshore and offshore technologies is the transport phase because the carbon dioxide emissions embodied in them of offshore turbines is greater than for onshore ones. This is because, more materials and longer distances are needed to get them to their instalation location. Furthermore, if wind turbines are recycled more than 30% of carbon footprint is saved, so it is really important to recycle them, as it was shown in *Figure 5.7*.

It was calculated that the total amount of carbon footprint in the United Kigdom due to the onshore wind turbines is almost 8,000,000 tonnes of CO_2, while for offshore ones is more than 6,500,000 tonnes of CO_2. Moreover, it was shown that the ratio carbon footprint/energy generated (grammes of CO_2/kWh) in onshore technology is 18.9 gCO_2/kWh and 20.1 gCO_2/kWh in offshore one. So it was shown that onshore wind turbines are more efficient in terms of CO_2 savings than offshore ones in the United Kingdom, however both are much more efficient than the electriciy generation mix ratio which is 275 gCO_2/kWh. So wind technology brings important benefits in reducing carbon footprint like it was shown in *Table 5.4*.

Furthermore, it was known that most of the carbon footprint embodied in a wind turbine is produced before it starts working because of the amount of materials needed, the long transport distance and the energy needed to install it. Once it starts to produce energy, the carbon footprint is lower because when wind energy is produced, there are not carbon dioxide emissions, just the carbon dioxide embodied in some wind generator components which needs to be replaced and the energy used during the operation & maintenance. During the last year, if the wind turbine is recycled, there is an important amount of carbon footprint saved, as it was shown in *Figure 5.9*.

It was estimated that the payback time in terms of carbon emissions savings is a bit less than one year and two months for UK onshore turbines and a bit more for offshore ones. So it was shown again that onshore technology is better to reduce the carbon footprint than the offshore one like it was shown in *Figure 5.10* and *Figure 5.11*. However, the time needed in both technologies until wind energy starts to bring net environmental benefits in the United Kingdom is little.

Finally, it was estimated the total carbon dioxide emissions savings in the United Kingdom due to the wind technology and more than 79,000,000 tonnes of CO_2 have been saved. At the beginning, CO_2 savings are not great because a lot of materials are needed to manufacture turbines, they need to be transported long distances, and machines need a lot of energy to installed them. However, when wind turbines start to produce energy, the CO_2 embodied in this phase is much lower, this is why as years go by the CO_2 savings increase considerably due to the wind energy. This increasement is faster in onshore wind energy than in the offshore one due to the fact that carbon footprint is much less, as it was shown in *Figure 5.13* and *Figure 5.14*.

6.1. Research limitations

There have been different problems to calculate the total carbon footprint for a wind turbine, since a lot of researchers only include CO_2 emissions due to the materials and other phases are not included, this is why those phases have been estimated, as it was explained above.

Moreover, not all materials that are used to manufacture a wind turbine, are included, although this is not too important to calculate the carbon footprint due to the materials, because the more contaminating materials are always included in all papers, it is really important to calculate the carbon dioxide emissions in the transport phase because the whole weight of the materials is not included.

The best would have been to analyze real wind turbines projects in order to get more accurate results, considering all materials, energy from all machines used, all transport vehicles and trips needed, all machines and wind generator components changed during the operation & maintenance, and finally all materials recycled from the wind turbine, instead of analyzing other research works.

However, although this results are not 100% accurate, a methodology to calculate the total carbon footprint for wind turbines was created, since all phases are considered.

When the ratio carbon footprint/energy produced was estimated for an scenario where wind energy has never been developed, no data was found to calculate this ratio before 2000, so it was considered that this ratio was constant before that year.

Moreover, when the carbon footprint and the cumulative carbon dioxide emissions savings were calculated for the United Kingdom, the average installed capacity of all turbines was considerated to do the calculations, instead of considering the real power ratings of all wind turbines, since these data was not found.

6.2. Recommendations

It is recommended to repeat this methodology with real wind turbines projects instead of using other researchers' investigations and when the total carbon footprint in one country is calculated it would be better to use the installed capacity of all wind turbines in the country, instead of using the average values.

Moreover, it is also recommended to add new wind turbines carbon footprint to the graphs (*Figure 5.2* and *Figure 5.3*) where the carbon footprint is represented as a function of the installed capacity. So, accurate equations could be achieved.

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7. *APPENDICES*

7.1. Carbon footprint for onshore wind turbines

7.1.1 (Ardente et al., 2008)

Name	Capacity (MW)	Kg CO_2
(Ardente et al., 2008)	0.66	503446

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	66434	kg	2.75	182694	
Cast iron	6001	kg	1.91	11462	
Glass reinforced plastics	4950	kg	8.10	40095	
Copper	924	kg	3.83	3539	
Paints	389	kg	3.56	1385	
Lubricant oils	111	kg	9.95	1106	
Aluminium	85	kg	11.50	978	
PVC	65	kg	2.41	157	
Bronze	5	kg	4.10	21	
Aggregate quarrying	1973455	kg	0.01	9867	
Local soils and stones	939409	kg	0.06	52607	
Steel	11139	kg	2.75	30632	
Polypropylene	10	kg	5.03	53	
HDPE	1035	kg	1.60	1656	
Polybutadiene	467	kg	4.02	1879	
Aluminium	754	kg	11.50	8666	
Copper	263	kg	3.83	1007	
PVC	1721	kg	2.41	4148	
Sand	254753	kg	0.01	1274	
Concrete	372480	kg	0.13	48422	
Total				401646	80%
Energy					
Water	133333	kg	0.00	0	
Diesel	7147	L	2.61	18653	
Gasoline	2227	L	2.38	5300	
Electricity	22000	kWh	0.275	6050	
Total				30003	6%
Operation & Maintenance					
Electricity	44267	kWh	0.275	12173	
Water	116802	kg	0.00	0	

Gasoline	1547	kg	3.18	4920	
15% of wind generator changed				36148	
Total				53241	11%
Transport					
Diesel	371121	tkm	0.05	18556	4%
Decommissioning phase					
90% of metal from the generator				-142825	-28%
Total				503446	
Total (if recycled)				360621	

7.1.2 (Bonou, Laurent & Olsen, 2016)

Name	Capacity (MW)	Kg CO_2
(Bonou, Laurent & Olsen, 2016)	2.75	1155572

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Concrete	649740	kg	0.13	84466	
Steel	182962.5	kg	2.75	503147	
Iron	16065	kg	1.91	30684	
Epoxy	10710	kg	5.7	61047	
Glass Fibre	8925	kg	8.1	72293	
Plastics	7140	kg	2.53	18064	
Aluminium	6247.5	kg	11.5	71846	
Cooper	6247.5	kg	3.83	23928	
Wood	1785	kg	0	0	
Total				865475	75%
Energy					
Water	555555	kg	0	0	
Diesel	29778	L	2.61	77720	
Gasoline	9279	L	2.38	22083	
Electricity	91667	kWh	0.275	25208	
Total				125011	11%
Operation & Maintenance					
Energy	184444	kWh	0.275	50722	
Water	486677	kg	0	0	
Gasoline	6446	kg	3.18	20498	
15% of wind generator changed				77893	
Total				149113	13%
Transport					
Diesel	319446	tkm	0.05	15972	1%
Decommissioning phase					

90% of metal from the generator	-376252	-33%
Total	1155572	
Total (if recycled)	779320	

7.1.3 (Crawford, 2009)

Name	Capacity (MW)	Kg CO_2
(Crawford, 2009) (1)	0.85	521817

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Concrete	480000	kg	0.13	62400	
Steel	109244	kg	2.75	300421	
Paint	930	kg	3.56	3311	
Copper	1029	kg	3.83	3941	
Aluminium	599	kg	11.5	6889	
Plastic	180	kg	2.53	455	
Fibre glass	3010	kg	8.1	24381	
Epoxy	2010	kg	5.7	11457	
Total				413255	79%
Energy					
Water	171717	kg	0	0	
Diesel	9204	L	2.61	24023	
Gasoline	2868	L	2.38	6826	
Electricity	28333	kWh	0.275	7792	
Total				38640	7%
Operation & Maintenance					
Energy	57010	kWh	0.275	15678	
Water	150427	kg	0	0	
Gasoline	1992	kg	3.18	6336	
15% of wind generator changed				37193	
Total				59207	11%
Transport					
Diesel	214324	tkm	0.05	10716	2%
Decommissioning phase					
90% of metal from the generator				-186003	-36%
Total				521817	
Total (if recycled)				335814	

7.1.4 (Dones et al., 2007)

Name	Capacity (MW)	Kg CO_2
(Dones et al., 2007)	0.8	636099

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	69375	kg	2.75	190781	
Reinforced steel	42560	kg	2.75	117040	
Concrete	459000	kg	0.13	59670	
Epoxy resine	360	kg	5.7	2052	
Glass fibre reindorced plasics	9661	kg	8.1	78254	
Chromium steel	14526	kg	2.75	39947	
Cast iron	6479	kg	1.91	12375	
Steel, low alloyed	3685	kg	2.75	10134	
Rubber	100	kg	3.18	318	
Aluminium	207	kg	11.5	2381	
Copper	242	kg	3.83	927	
Lubricant	58,8	kg	9.95	585	
Copper	1217	kg	3.83	4661	
HDPE	594	kg	1.6	950	
PP	20	kg	3.9	78	
PVC	428	kg	2.41	1031	
Total				521184	82%
Energy					
Water	161616	kg	0	0	
Diesel	8663	L	2.61	22609	
Gasoline	2699	L	2.38	6424	
Electricity	26667	kWh	0.275	7333	
Total				36367	6%
Operation & Maintenance					
Energy	53657	kWh	0.275	14756	
Water	141579	kg	0	0	
Gasoline	1875	kg	3.18	5963	
15% of wind generator changed				46907	
Total				67625	11%
Transport					
Diesel	218456	tkm	0.05	10923	2%
Decommissioning phase					
90% of metal from the generator				-226039	-36%
Total				636099	
Total (if recycled)				410060	

7.1.5 (Crawford, 2009)

Name	Capacity (MW)	Kg CO_2
(Crawford, 2009) (2)	3	1436473

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Concrete	1140000	kg	0.13	148200	
Steel	275690	kg	2.75	758148	
Paint	1240	kg	3.56	4414	
Copper	3991	kg	3.83	15286	
Aluminium	2311	kg	11.5	26577	
Plastic	700	kg	2.53	1771	
Fibre glass	12040	kg	8.1	97524	
Epoxy	8030	kg	5.7	45771	
Total				1097690	76%
Energy					
Water	606060	kg	0	0	
Diesel	32485	L	2.61	84785	
Gasoline	10122	L	2.38	24090	
Electricity	100000	kWh	0.275	27500	
Total				136376	9%
Operation & Maintenance					
Energy	201212	kWh	0.275	55333	
Water	530920	kg	0	0	
Gasoline	7032	kg	3.18	22362	
15% of wind generator changed				98792	
Total				176487	12%
Transport					
Diesel	518397	tkm	0.05	25920	2%
Decommissioning phase					
90% of metal from the generator				-478086	-33%
Total				1436473	
Total (if recycled)				958387	

7.1.6 (Martínez et al., 2009)

Name	Capacity (MW)	Kg CO_2
(Martínez et al., 2009)	2	1090505

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Resin	13086	kg	5.7	74590	
Steel	179690	kg	2.75	494148	
Fibre glass	8724	kg	8.1	70664	
Cast iron	14000	kg	1.91	26740	
Concrete	700000	kg	0.13	91000	
Iron	43500	kg	1.91	83085	
Silica	344	kg	0.13	45	
Copper	3500	kg	3.83	13405	
Total				853677	78%
Energy					
Water	404040	kg	0	0	
Diesel	21657	L	2.61	56524	
Gasoline	6748	L	2.38	16060	
Electricity	66667	kWh	0.275	18333	
Total				90917	8%
Operation & Maintenance					
Energy	134141	kWh	0.275	36889	
Water	353947	kg	0	0	
Gasoline	4688	kg	3.18	14908	
15% of wind generator changed				76831	
Total				128628	12%
Transport					
Diesel	345661	tkm	0.05	17283	2%
Decommissioning phase					
90% of metal from the generator				-368945	-34%
Total				1090505	
Total (if recycled)				721560	

7.1.7 (Oebels & Pacca, 2013)

Name	Capacity (MW)	Kg CO_2
(Oebels & Pacca, 2013)	1,5	938376

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Fiber glass	13500	kg	8.1	109350	
Epoxy resin	6190	kg	5.7	35283	
Steel	101060	kg	2.75	277915	
Paint	1030	kg	3.56	3667	
Cast iron	26630	kg	1.91	50863	
Engineering steel	13180	kg	2.75	36245	
Stainless steel	7090	kg	6.15	43604	
Copper	4410	kg	3.83	16890	
Plastic	4550	kg	2.53	11512	
Aluminium	5290	kg	11.5	60835	
Electronics	270	kg	0	0	
Oil	270	kg	9.95	2687	
Concrete	756660	kg	0.13	98366	
Total				747216	80%
Energy					
Water	303030	kg	0	0	
Diesel	16242	L	2.61	42393	
Gasoline	5061	L	2.38	12045	
Electricity	50000	kWh	0.275	13750	
Total				78838	7%
Operation & Maintenance					
Energy	100606	kWh	0.275	27667	
Water	265460	kg	0	0	
Gasoline	3516	kg	3.18	11181	
15% of wind generator changed				67249	
Total				106097	11%
Transport					
Diesel	337507	tkm	0.05	16875	2%
Decommissioning phase					
90% of metal from the generator				-326999	-35%
Total				938376	
Total (if recycled)				611377	

7.1.8 (Schleisner, 2000)

Name	Capacity (MW)	Kg CO_2
(Schleisner, 2000)	0,5	298582

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	52700	kg	2.75	144925	
Aluminium	1400	kg	11.5	16100	
Copper	350	kg	3.83	1340,5	
Sand	2100	kg	0.005	10.5	
Glass	1100	kg	0.85	935	
Plast (polyester and epoxy)	2000	kg	5.7	11400	
Oil Products	100	kg	9.95	995	
Others	700	kg	0	0	
Reinforced iron	12000	kg	1.91	22920	
Concrete	282500	kg	0.13	36725	
Copper	0	kg	3.83	0	
Lead	0	kg	2.61	0	
Steel	0	kg	2.75	0	
PEX	0	kg	1.94	0	
Total				235351	79%
Energy					
Water	101010	kg	0	0	
Diesel	5414	L	2.61	14131	
Gasoline	1687	L	2.38	4015	
Electricity	16667	kWh	0.275	4583	
Total				22729	8%
Operation & Maintenance					
Energy	33535	kWh	0.275	9222	
Water	88487	kg	0	0	
Gasoline	1172	kg	3.18	3727	
15% of wind generator changed				21182	
Total				34131	11%
Transport					
Diesel	127427	tkm	0.05	6371	2%
Decommissioning phase					
90% of metal from the generator				-110727	-37%
Total				298582	
Total (if recycled)				187856	

7.1.9 (Yang & Chen, 2013)

Name	Capacity (MW)	Kg CO_2
(Yang & Chen, 2013)	1.5	1029551

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	6200	kg	2.75	17050	
Fiber glass	3900	kg	8.1	31590	
Epoxy	2600	kg	5.7	14820	
Steel	34560	kg	2.75	95040	
Copper	8640	kg	3.83	33091	
Steel	13500	kg	2.75	37125	
Aluminium	500	kg	11.5	5750	
Glass	350	kg	0.85	298	
Polyester	300	kg	2.53	759	
Steel	129000	kg	2.75	354750	
Concrete	1005685	kg	0.13	130739	
Steel	38130	kg	2.75	104858	
Total				825869	80%
Energy					
Water	303030	kg	0	0	
Diesel	16242	L	2.61	42393	
Gasoline	5061	L	2.38	12045	
Electricity	50000	kWh	0.275	13750	
Total				68188	7%
Operation & Maintenance					
Energy	100606	kWh	0.275	27667	
Water	265460	kg	0	0	
Gasoline	3516	kg	3.18	11181	
15% of wind generator changed				74328	
Total				113176	11%
Transport					
Diesel	446368	tkm	0.05	22318	2%
Decommissioning phase					
90% of metal from the generator				-387044	-38%
Total				1029551	
Total (if recycled)				642507	

7.2. Carbon footprint for onshore wind turbines

7.2.1 (Bonou, Laurent & Olsen, 2016)

Name	Capacity (MW)	Kg CO_2
(Bonou, Laurent & Olsen, 2016)	5	6274458

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	1295750	kg	2.75	3563313	
Iron	113600	kg	1.91	216976	
Concrete	83425	kg	0.13	10845	
Plastics	63900	kg	2.53	161667	
Epoxy	42600	kg	5.7	242820	
Glass Fibre	40825	kg	8.1	330683	
Aluminium	35500	kg	11.5	408250	
Copper	24850	kg	3.83	95176	
Lead	17750	kg	2.61	46328	
Total				5076056	81%
Energy					
Electricity	177000	kWh	0.275	48675	
Oil	22600	L	2.96	66896	
Diesel	922	MJ	0.0736	68	
Electricity from oil	470	Kwh	0.6	282	
Total				115921	2%
Operation & Maintenance					
15% of wind generator changed				616741	10%
Transport					
Truck transport	812709	tkm	0.05	40635	
Transport barge	3341899	tkm	0.007	23393	
Train transport	539515	tkm	0.018	9711	
Transport helicopter fuel	140000	kg	2.8	392000	
Total				465740	7%
Decommissioning phase					
90% of metal from the generator				-2220677	-35%
Total				6274458	
Total (if recycled)				4053781	

7.2.2 (Dolan, 2007)

Name	Capacity (MW)	Kg CO_2
(Dolan, 2007)	1.8	2218536

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	583767	kg	2.75	1605359	
Concrete	1000	kg	0.13	130	
Copper	4233	kg	3.83	16212	
Glass reinforced epoxy (GRE)	21000	kg	8.1	170100	
Total				1791802	81%
Energy					
Electricity	63720	kWh	0.275	17523	
Oil	8136	L	2.96	24083	
Diesel	331,92	MJ	0.0736	24	
Electricity from oil	169,2	KWh	0.6	102	
Total				41732	2%
Operation & Maintenance					
15% of wind generator changed				217704	10%
Transport					
Truck transport	288530	Tkm	0.05	14427	
Transport barge	1186450	Tkm	0.007	8305	
Train transport	191540	tkm	0.018	3448	
Transport helicopter fuel	50400	kg	2.8	141120	
Total				167299	8%
Decommissioning phase					
90% of metal from the generator				-840623	-38%
Total				2218536	
Total (if recycled)				1377914	

7.2.3 (Dones et al., 2007)

Name	Capacity (MW)	Kg CO_2
(Dones et al., 2007)	2	1633282

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Reinforced steel	80000	kg	2.75	220000	
Concrete	120000	kg	0.13	15600	
Steel	113210	kg	2.75	311328	
Epoxy resine	547	kg	5.7	3118	
Glass fibre reinforced plastics	40938	kg	8.1	331598	
Chromium steel	60643	kg	2.75	166768	
Cast iron	33866	kg	1.91	64684	
Steel, low alloyed	15050	kg	2.75	41388	
Rubber	100	kg	3.18	318	
Aluminium	845	kg	11.5	9718	
Copper	986	kg	3.83	3776	
Lubricant	150	kg	9.95	1493	
Copper	3900	kg	3.83	14937	
Lead	7575	kg	2.61	19771	
Steel, low alloyed	8766	kg	2.75	24107	
PVC	3500	kg	2.41	8435	
Total				1237037	76%
Energy					
Electricity	70800	kWh	0.275	19470	
Oil	9040	L	2.96	26758	
Diesel	368,8	MJ	0.0736	27	
Electricity from oil	188	Kwh	0.6	113	
Total				46368	3%
Operation & Maintenance					
15% of wind generator changed				150300	9%
Transport					
Truck transport	84783	tkm	0.05	84783	
Transport barge	347464	tkm	0.007	2432	
Train transport	56359	tkm	0.018	56359	
Transport helicopter fuel	56000	kg	2.8	56003	
Total				199577	12%
Decommissioning phase					
90% of metal from the generator				-431619	-26%
Total				1633282	
Total (if recycled)				1201663	

7.2.4 (Reimers, Özdirik & Kaltschmitt, 2014)

Name	Capacity (MW)	Kg CO_2
(Reimers, Özdirik & Kaltschmitt, 2014)	5	5858993

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Glass fibre	37000	kg	8.1	299700	
Resin	32000	kg	5.7	182400	
Steel	120000	kg	2.75	330000	
High-grade steel	14000	kg	2.75	38500	
Cast iron	208000	kg	1.91	397280	
Mild steel	1043000	kg	2.75	2868250	
Stainless steel	17000	kg	6.15	104550	
Copper	48000	kg	3.83	183840	
Aluminium	10000	kg	11.5	115000	
Lead	0	kg	2.61	0	
Plastics	66000	kg	2.53	166980	
Zinc	2000	kg	3.86	7720	
Alcydresin	2000	kg	5.7	11400	
Concrete	27000	kg	0.13	3510	
Total				4709130	80%
Energy					
Electricity	177000	kWh	0.275	48675	
Oil	22600	L	2.96	66896	
Diesel	922	MJ	0.0736	68	
Electricity from oil	470	Kwh	0.6	282	
Total				115921	2%
Operation & Maintenance					
15% of wind generator changed				572159	10%
Transport					
Truck transport	769098	tkm	0.05	38455	
Transport barge	3162570	tkm	0.007	22138	
Train transport	510564	tkm	0.018	9190	
Transport helicopter fuel	140000	kg	2.8	392000	
Total				461783	8%
Decommissioning phase					
90% of metal from the generator				-2092999	-36%
Total				5858993	
Total (if recycled)				3765995	

7.2.5 (Schleisner, 2000)

Name	Capacity (MW)	Kg CO_2
(Schleisner, 2000)	0.5	426098

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel	52700	kg	2.75	144925	
Aluminium	1400	kg	11.5	16100	
Copper	350	kg	3.83	1341	
Sand	2100	kg	0.005	11	
Glass	1100	kg	0.85	935	
Plast (Polyester and epoxy)	2000	kg	5.7	11400	
Oil products	100	kg	9.95	995	
Others	700	kg	0	0	
Reinforced iron	24000	kg	1.91	45840	
Concrete	565000	kg	0.13	73450	
Copper	2580	kg	3.83	9881	
Lead	3360	kg	2.61	8770	
Steel	3900	kg	2.75	10725	
PEX	540	kg	1.94	1048	
Total				325420	76%
Energy					
Electricity	17700	kWh	0.275	4868	
Oil	2260	L	2.96	6690	
Diesel	92,2	MJ	0.0736	7	
Electricity from oil	47	Kwh	0.6	28	
Total				11592	3%
Operation & Maintenance					
15% of wind generator changed				39538	9%
Transport					
Truck transport	114151	tkm	0.05	5708	
Transport barge	467819	tkm	0.007	3275	
Train transport	75880	tkm	0.018	1366	
Transport helicopter fuel	14000	kg	2.8	39200	
Total				49548	12%
Decommissioning phase					
90% of metal from the generator				-118616	-28%
Total				426098	
Total (if recycled)				307482	

7.2.6 (Weinzettel et al., 2009)

Name	Capacity (MW)	Kg CO_2
(Weinzettel et al., 2009)	5	7289085

Name	Amount	Unit	kg CO_2/unit	Total Kg CO_2	
Material					
Steel, low alloyed	1410000	kg	2.75	3877500	
Steel, high alloyed	5250	kg	2.75	14438	
Gravel	3230000	kg	0.017	54910	
Copper	58500	kg	3.83	224055	
Lubricant oil	75100	kg	9.95	747245	
Aluminium	2250	kg	11.5	25875	
Chromium steel	135000	kg	2.75	371250	
Glass fiber	52100	kg	8.1	422010	
Lead	12900	kg	2.61	33669	
Polyethylene	14500	kg	1.94	28130	
Cast iron	69100	kg	1.91	131981	
Polyvinyl Chloride	9220	kg	2.41	22220	
Electro steel	4750	kg	2.75	13063	
Epoxy resin	1440	kg	5.7	8208	
Wood	360	kg	0	0	
Synthetic rubber	263	kg	4.02	1057	
Ceramics	53,9	kg	0.65	35	
Tin	1,31	kg	13.7	18	
Total				5975663	82%
Energy					
Electricity	177000	kWh	0.275	48675	
Oil	22600	L	2.96	66896	
Diesel	922	MJ	0.0736	68	
Electricity from oil	470	Kwh	0.6	282	
Total				115921	2%
Operation & Maintenance					
15% of wind generator changed				726043	10%
Transport					
Truck transport	876000	tkm	0.05	43800	
Transport barge	3600000	tkm	0.007	25200	
Train transport	581000	tkm	0.018	10458	
Transport helicopter fuel	140000	kg	2.8	392000	
Total				471458	6%
Decommissioning phase					
90% of metal from the generator				-2414791	-33%
Total				7289085	

Total (if recycled)	4874295

7.3. Carbon footprint per kilowatt without considering wind energy

2016	Total energy = 3.36439 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	3.10%	10429578000	600	6.25775E+12
Coal	9.00%	30279420000	200	6.05588E+12
Gas	42.00%	1.41304E+11	450	6.35868E+13
Nuclear	21.00%	70651980000	30	2.11956E+12
Solar	3.19%	10715550300	55	5.89355E+11
Landfill gas	1.47%	4945638600	170	8.40759E+11
Bioenergy	7.35%	24728193000	240	5.93477E+12
Hydro	1.47%	4945638600	8	39565108800
Wind energy	11.03%	-	-	-
			Total	8.54244E+13
			gCO2/kWh	286.6591589

2015	Total energy = 3.36356 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	2.80%	9417968000	600	5.65078E+12
Coal	22.00%	73998320000	800	5.91987E+13
Gas	30.00%	1.00907E+11	400	4.03627E+13
Nuclear	21.00%	70634760000	20	1.4127E+12
Solar	2.25%	7568010000	55	4.16241E+11
Landfill gas	1.45%	4877162000	170	8.29118E+11
Bioenergy	7.29%	24520352400	240	5.88488E+12
Hydro	1.87%	6289857200	8	50318857600
Wind energy	11.98%	40295448800	-	-
			Total	1.13805E+14
			gCO2/kWh	381.6242951

2014	Total energy = 3.36043 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	2.60%	8737118000	600	5.24227E+12
Coal	30.00%	1.00813E+11	800	8.06503E+13
Gas	30.00%	1.00813E+11	400	4.03252E+13
Nuclear	19.00%	63848170000	20	1.27696E+12
Solar	1.21%	4066120300	55	2.23637E+11
Landfill gas	1.50%	5040645000	170	8.5691E+11
Bioenergy	5.25%	17642257500	240	4.23414E+12
Hydro	1.75%	5880752500	8	47046020000
Wind energy	9.53%	32024897900	-	-
			Total	1.32856E+14
			gCO2/kWh	432.9816011

2013	Total energy = 3.56253 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	2.40%	8550072000	600	5.13004E+12
Coal	26.00%	92625780000	800	7.41006E+13
Gas	27.00%	96188310000	400	3.84753E+13
Nuclear	20.00%	71250600000	20	1.42501E+12
Solar	0.57%	2030642100	55	1.11685E+11
Landfill gas	1.46%	5201293800	170	8.8422E+11
Bioenergy	3.74%	13323862200	240	3.19773E+12
Hydro	1.32%	4702539600	8	37620316800
Wind energy	7.98%	-	-	-
			Total	1.23362E+14
			gCO2/kWh	419.7807007

2012	Total energy = 3.60869 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	2.50%	9021725000	600	5.41304E+12
Coal	39.00%	1,40739E+11	800	1.12591E+14
Gas	28.00%	1.01043E+11	400	4.04173E+13
Nuclear	19.00%	68565110000	20	1.3713E+12
Solar	0.33%	1187259010	55	65299245550
Landfill gas	1.43%	5160426700	170	8.77273E+11
Bioenergy	2.78%	10032158200	240	2.40772E+12
Hydro	1.32%	4763470800	8	38107766400
Wind energy	5.40%	-	-	-
			Total	1.63181E+14
			gCO2/kWh	479.2224907

2011	Total energy = 3.64897 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	2.50%	9122425000	600	5.47346E+12
Coal	30.00%	1.09469E+11	800	8.75753E+13
Gas	40.00%	1.45959E+11	400	5.83835E+13
Nuclear	19.00%	69330430000	20	1.38661E+12
Solar	0.07%	251778930	55	13847841150
Landfill gas	1.36%	4962599200	170	8.43642E+11
Bioenergy	2.19%	7991244300	240	1.9179E+12
Hydro	1.56%	5692393200	8	45539145600
Wind energy	4.25%	-	-	-
			Total	1.5564E+14
			gCO2/kWh	441.1824181

2010	Total energy = 3.77977 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	1.00%	3779770000	600	2.26786E+12
Coal	28.00%	1.05834E+11	800	8.46668E+13
Gas	47.00%	1.77649E+11	400	7.10597E+13
Nuclear	16.00%	60476320000	20	1.20953E+12
Solar	0.00%	0	55	0
Landfill gas	1.33%	5027094100	170	8.54606E+11
Bioenergy	1.82%	6879181400	240	1.651E+12
Hydro	0.95%	3602120810	8	28816966480
Wind energy	2.69%	-	-	-
			Total	1.61738E+14
			gCO2/kWh	445.2569014

2009	Total energy = 3.71978 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	1.00%	3719780000	600	2.23187E+12
Coal	28.00%	1.04154E+11	800	8.33231E+13
Gas	45.00%	1.6739E+11	400	6.6956E+13
Nuclear	18.00%	66956040000	20	1.33912E+12
Solar	0.00%	0	55	0
Landfill gas	1.33%	4947307400	170	8.41042E+11
Bioenergy	1.53%	5691263400	240	1.3659E+12
Hydro	1.41%	5244889800	8	41959118400
Wind energy	2.50%	-	-	-
			Total	1.56099E+14
			gCO2/kWh	435.9050587

2008	Total energy = 3.85560 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	6.00%	23133600000	600	1.38802E+13
Coal	31.00%	1,19524E+11	800	9.56189E+13
Gas	46.00%	1,77358E+11	400	7.0943E+13
Nuclear	13.00%	50122800000	20	1.00246E+12
Solar	0.00%	0	55	0
Landfill gas	1.23%	4742388000	170	8.06206E+11
Bioenergy	1.18%	4549608000	240	1.09191E+12
Hydro	1.34%	5166504000	8	41332032000
Wind energy	1.80%	-	-	-
			Total	1.83384E+14
			gCO2/kWh	476.8222556

2007	Total energy = 3.92597 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	5.50%	21592835000	600	1.29557E+13
Coal	34.00%	1.33483E+11	800	1.06786E+14
Gas	43.00%	1.68817E+11	400	6.75267E+13
Nuclear	15.00%	58889550000	20	1.17779E+12
Solar	0.00%	0	55	0
Landfill gas	1.19%	4671904300	170	7.94224E+11
Bioenergy	1.18%	4632644600	240	1.11183E+12
Hydro	1.30%	5103761000	8	40830088000
Wind energy	1.34%	-	-	-
			Total	1.90393E+14
			gCO2/kWh	479.350598

2006	Total energy = 3.94474 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	5.50%	21696070000	600	1.30176E+13
Coal	37.50%	1.47928E+11	800	1.18342E+14
Gas	36.00%	1.42011E+11	400	5.68043E+13
Nuclear	18.00%	71005320000	20	1.42011E+12
Solar	0.00%	0	55	0
Landfill gas	1.12%	4418108800	170	7.51078E+11
Bioenergy	1.23%	4852030200	240	1.16449E+12
Hydro	1.17%	4615345800	8	36922766400
Wind energy	1.07%	-	-	-
			Total	1.91537E+14
			gCO2/kWh	483.0378034

2005	Total energy = 3.97595 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	5.00%	19879750000	600	1.19279E+13
Coal	33.50%	1.33194E+11	800	1.06555E+14
Gas	39.00%	1.55062E+11	400	6.20248E+13
Nuclear	19.50%	77531025000	20	1.55062E+12
Solar	0.00%	0	55	0
Landfill gas	1.08%	4294026000	170	7.29984E+11
Bioenergy	1.20%	4771140000	240	1.14507E+12
Hydro	1.25%	4969937500	8	39759500000
Wind energy	0.73%	-	-	-
			Total	1.83974E+14
			gCO2/kWh	460.2765344

2004	Total energy = 3.92979 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	4.50%	17684055000	600	1.06104E+13
Coal	33.00%	1.29683E+11	800	1.03746E+14
Gas	40.00%	1.57192E+11	400	6.28766E+13
Nuclear	19.00%	74666010000	20	1.49332E+12
Solar	0.00%	0	55	0
Landfill gas	1.02%	4008385800	170	6.81426E+11
Bioenergy	0.84%	3301023600	240	7.92246E+11
Hydro	1.25%	4912237500	8	39297900000
Wind energy	0.49%	-	-	-
			Total	1.8024E+14
			gCO2/kWh	460.4457384

2003	Total energy = 3.95886 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	4.00%	15835440000	600	9.50126E+12
Coal	35.00%	1.3856E+11	800	1.10848E+14
Gas	38.00%	1.50437E+11	400	6.01747E+13
Nuclear	22.00%	87094920000	20	1.7419E+12
Solar	0.00%	0	55	0
Landfill gas	0.83%	3273977220	170	5.56576E+11
Bioenergy	0.72%	2834543760	240	6.80291E+11
Hydro	0.82%	3226470900	8	25811767200
Wind energy	0.32%	-	-	-
			Total	1.83529E+14
			gCO2/kWh	457.3783027

2002	Total energy = 3.84594 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	4.00%	15383760000	600	9.23026E+12
Coal	32.00%	1.2307E+11	800	9.84561E+13
Gas	39.00%	1.49992E+11	400	5.99967E+13
Nuclear	22.00%	84610680000	20	1.69221E+12
Solar	0.00%	0	55	0
Landfill gas	0.70%	2680620180	170	4.55705E+11
Bioenergy	0.62%	2399866560	240	5.75968E+11
Hydro	1.24%	4768965600	8	38151724800
Wind energy	0.32%	-	-	-
			Total	1.70445E+14
			gCO2/kWh	445.1358464

2001	Total energy = 3.82356 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	3.50%	13382460000	600	8.02948E+12
Coal	33.50%	1.28089E+11	800	1.02471E+14
Gas	37.00%	1.41472E+11	400	5.65887E+13
Nuclear	22.00%	84118320000	20	1.68237E+12
Solar	0.00%	0	55	0
Landfill gas	0.66%	2523549600	170	4.29003E+11
Bioenergy	0.53%	2018839680	240	4.84522E+11
Hydro	1.06%	4052973600	8	32423788800
Wind energy	0.25%	-	-	-
			Total	1.69718E+14
			gCO2/kWh	451.7893494

2000	Total energy = 3.74374 E+11 kW			
Type of energy	Percentage	Energy Produced (kWh)	Footprint (g CO2/KWh)	g CO2
Fuels	4.00%	14974960000	600	8.98498E+12
Coal	33.00%	1.23543E+11	800	9.88347E+13
Gas	39.00%	1.46006E+11	400	5.84023E+13
Nuclear	21.00%	78618540000	20	1.57237E+12
Solar	0.00%	0	55	0
Landfill gas	0.58%	2171369200	170	3.69133E+11
Bioenergy	0.45%	1692170480	240	4.06121E+11
Hydro	1.36%	5091486400	8	40731891200
Wind energy	0.25%	-	-	-
			Total	1.6861E+14
			gCO2/kWh	453.1346587

7.4. Cumulative carbon dioxide emissions saving calculations

Table 7.1. Total installed capacity, number of turbines, new turbines and energy generated year on year

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Onshore																					
Total installed capacity (MW)	237.7	237.7	331.3	357	408	423.4	530.6	678.4	809.4	1351.2	1650.7	2083	2824	3468	4060	4629	6035	7586	8573	9222	10923
Total number of turbines	286	286	399	430	492	510	639	817	975	1628	1989	2510	3402	4178	4892	5577	7271	9140	10329	11111	13160
New turbines per year	286	0	113	31	61	19	129	178	158	653	361	521	893	776	713	686	1694	1869	1189	782	2049
Power generated (GWh)	488	488	877	850	945	960	1251	1276	1736	2501	3574	4491	5788	7529	7182	10503	12244	16925	18555	22895	20962
Offshore																					
Total installed capacity (MW)	0	0	0	0	3.8	3.8	3.8	63.8	123.8	213.8	303.8	394	586	951	1341	1838	2995	3696	4501	5093	5293
Total number of turbines	0	0	0	0	1	1	1	18	34	59	84	109	162	263	371	509	830	1024	1247	1411	1466
New turbines per year	0	0	0	0	1	0	0	17	17	25	25	25	53	101	108	138	320	194	223	164	55
Power generated (GWh)	0	0	0	0	1	5	5	10	199	403	651	783	1305	1754	3073	5149	7603	11472	13405	17423	16406

Table 7.2. Cumulative carbon footprint in United Kingdom due to the onshore wind energy year on year

		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
	Onshore																					
1996	CF/turbine (tCO2)	506	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	-175
	New turbines	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286	286
	Total CF (tCO2)	144745	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	990	-50136
1997	CF/turbine (tCO2)		506	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	CF/turbine (tCO2)			506	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines			113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113
	Total CF (tCO2)			57189	391	391	391	391	391	391	391	391	391	391	391	391	391	391	391	391	391	391
1999	CF/turbine (tCO2)				506	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines				31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
	Total CF (tCO2)				15689	107	107	107	107	107	107	107	107	107	107	107	107	107	107	107	107	107
2000	CF/turbine (tCO2)					506	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines					61	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61
	Total CF (tCO2)					30872	211	211	211	211	211	211	211	211	211	211	211	211	211	211	211	211
2001	CF/turbine (tCO2)						506	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines						19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
	Total CF (tCO2)						9616	66	66	66	66	66	66	66	66	66	66	66	66	66	66	66
2002	CF/turbine (tCO2)							506	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines							129	129	129	129	129	129	129	129	129	129	129	129	129	129	129
	Total CF (tCO2)							65287	447	447	447	447	447	447	447	447	447	447	447	447	447	447
2003	CF/turbine (tCO2)								506	3	3	3	3	3	3	3	3	3	3	3	3	3

	New turbines								178	178	178	178	178	178	178	178	178	178	178	178	178	178
	Total CF (tCO2)								90086	616	616	616	616	616	616	616	616	616	616	616	616	616
2004	CF/turbine (tCO2)									506	3	3	3	3	3	3	3	3	3	3	3	3
	New turbines									158	158	158	158	158	158	158	158	158	158	158	158	158
	Total CF (tCO2)									79964	547	547	547	547	547	547	547	547	547	547	547	547
2005	CF/turbine (tCO2)										506	3	3	3	3	3	3	3	3	3	3	3
	New turbines										653	653	653	653	653	653	653	653	653	653	653	653
	Total CF (tCO2)										330483	2260	2260	2260	2260	2260	2260	2260	2260	2260	2260	2260
2006	CF/turbine (tCO2)											506	3	3	3	3	3	3	3	3	3	3
	New turbines											361	361	361	361	361	361	361	361	361	361	361
	Total CF (tCO2)											182702	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250
2007	CF/turbine (tCO2)												506	3	3	3	3	3	3	3	3	3
	New turbines												521	521	521	521	521	521	521	521	521	521
	Total CF (tCO2)												263678	1803	1803	1803	1803	1803	1803	1803	1803	1803
2008	CF/turbine (tCO2)													506	3	3	3	3	3	3	3	3
	New turbines													893	893	893	893	893	893	893	893	893
	Total CF (tCO2)													451947	3091	3091	3091	3091	3091	3091	3091	3091
2009	CF/turbine (tCO2)														506	3	3	3	3	3	3	3
	New turbines														776	776	776	776	776	776	776	776
	Total CF (tCO2)														392733	2686	2686	2686	2686	2686	2686	2686
2010	CF/turbine (tCO2)															506	3	3	3	3	3	3
	New turbines															713	713	713	713	713	713	713
	Total CF (tCO2)															360849	2468	2468	2468	2468	2468	2468
2011	CF/turbine (tCO2)																506	3	3	3	3	3
	New turbines																686	686	686	686	686	686
	Total CF (tCO2)																347184	2375	2375	2375	2375	2375
2012	CF/turbine (tCO2)																	506	3	3	3	3
	New turbines																	1694	1694	1694	1694	1694
	Total CF (tCO2)																	857333	5864	5864	5864	5864
2013	CF/turbine (tCO2)																		506	3	3	3
	New turbines																		1869	1869	1869	1869
	Total CF (tCO2)																		945900	6469	6469	6469
2014	CF/turbine (tCO2)																			506	3	3
	New turbines																			1189	1189	1189
	Total CF (tCO2)																			601753	4116	4116
2015	CF/turbine (tCO2)																				506	3
	New turbines																				782	782
	Total CF (tCO2)																				395770	2707
2016	CF/turbine (tCO2)																					506
	New turbines																					2049

	Total CF (tCO2)																				1036998
Total CF by year (tCO2)		144745	990	58179	17070	32360	11315	67052	92298	82792	333858	188337	270563	460635	404512	375314	364117	876640	971071	633393	431526	1024335
Cumulative CF (tCO2)		144745	145734	203914	220984	253344	264660	331712	424009	506801	840659	1028996	1299559	1760194	2164706	2540020	2904138	3780778	4751849	5385242	5816768	6841104

Table 7.3.Cumulative carbon footprint in United Kingdom due to the offshore wind energy year on year

		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
	Offshore																					
1996	CF/turbine (tCO2)	3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	-1243
	New turbines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	CF/turbine (tCO2)		3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	CF/turbine (tCO2)			3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	CF/turbine (tCO2)				3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	CF/turbine (tCO2)					3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines					1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Total CF (tCO2)					3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
2001	CF/turbine (tCO2)						3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	CF/turbine (tCO2)							3766	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total CF (tCO2)							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	CF/turbine (tCO2)								3766	27	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines								17	17	17	17	17	17	17	17	17	17	17	17	17	17
	Total CF (tCO2)								64019	459	459	459	459	459	459	459	459	459	459	459	459	459
2004	CF/turbine (tCO2)									3766	27	27	27	27	27	27	27	27	27	27	27	27
	New turbines									17	17	17	17	17	17	17	17	17	17	17	17	17
	Total CF (tCO2)									64019	459	459	459	459	459	459	459	459	459	459	459	459
2005	CF/turbine (tCO2)										3766	27	27	27	27	27	27	27	27	27	27	27
	New turbines										25	25	25	25	25	25	25	25	25	25	25	25
	Total CF (tCO2)										94145	674	674	674	674	674	674	674	674	674	674	674
2006	CF/turbine (tCO2)											3766	27	27	27	27	27	27	27	27	27	27
	New turbines											25	25	25	25	25	25	25	25	25	25	25
	Total CF (tCO2)											94145	674	674	674	674	674	674	674	674	674	674

	CF/turbine (tCO2)												3766	27	27	27	27	27	27	27	27	27
2007	New turbines												25	25	25	25	25	25	25	25	25	25
	Total CF (tCO2)												94145	674	674	674	674	674	674	674	674	674
	CF/turbine (tCO2)													3766	27	27	27	27	27	27	27	27
2008	New turbines													53	53	53	53	53	53	53	53	53
	Total CF (tCO2)													199588	1430	1430	1430	1430	1430	1430	1430	1430
	CF/turbine (tCO2)														3766	27	27	27	27	27	27	27
2009	New turbines														101	101	101	101	101	101	101	101
	Total CF (tCO2)														380348	2725	2725	2725	2725	2725	2725	2725
	CF/turbine (tCO2)															3766	27	27	27	27	27	27
2010	New turbines															108	108	108	108	108	108	108
	Total CF (tCO2)															406708	2914	2914	2914	2914	2914	2914
	CF/turbine (tCO2)																3766	27	27	27	27	27
2011	New turbines																138	138	138	138	138	138
	Total CF (tCO2)																519683	3723	3723	3723	3723	3723
	CF/turbine (tCO2)																	3766	27	27	27	27
2012	New turbines																	320	320	320	320	320
	Total CF (tCO2)																	1205062	8633	8633	8633	8633
	CF/turbine (tCO2)																		3766	27	27	27
2013	New turbines																		194	194	194	194
	Total CF (tCO2)																		730569	5234	5234	5234
	CF/turbine (tCO2)																			3766	27	27
2014	New turbines																			223	223	223
	Total CF (tCO2)																			839778	6016	6016
	CF/turbine (tCO2)																				3766	27
2015	New turbines																				164	164
	Total CF (tCO2)																				617594	4425
	CF/turbine (tCO2)																					3766
2016	New turbines																					55
	Total CF (tCO2)																					207120
Total CF by year (tCO2)		0	0	0	0	3766	27	27	64046	64505	95090	95764	96439	202556	384745	413831	529719	1218821	752961	867404	651237	245187
Cumulative CF (tCO2)		0	0	0	0	3766	3793	3820	67866	132370	227460	323224	419663	622219	1006964	1420795	1950514	3169336	3922297	4789701	5440938	5686126

Table 7.4. Cumulative carbon footprint if wind energy would have not been developed

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Power generated (GWh) onshore	488	488	877	850	945	960	1251	1276	1736	2501	3574	4491	5788	7529	7182	10503	12244	16925	18555	22895	20962
Power generated (GWh) offshore	0	0	0	0	1	5	5	10	199	403	651	783	1305	1754	3073	5149	7603	11472	13405	17423	16406
Ratio (t CO_2/GWh)	453,13	453,13	453,13	453,13	453,13	451,79	445,14	457,38	460,44	460,28	483,04	479,35	476,82	435,91	445,26	441,18	479,22	419,78	432,98	381,62	321,54
CF by year (tCO2) onshore	221127,44	221127	397395	385160,5	428207,85	433718,4	556870	583616,9	799324	1151160	1726385	2152761	2759834	3281966,39	3197857,3	4633714	5867569,7	7104776,5	8033943,9	8737189,9	6740121,48
Cumulative CF (tCO2) onshore	221127,44	442255	839650	1224810	1653018,24	2086737	2643607	3227224	4026548	5177708	6904093	9056854	11816688	15098654,14	18296511	22930225	28797795	35902571	43936515	52673705	59413826,46
CF by year (tCO2) offshore	0	0	0	0	453,13	2258,95	2225,7	4573,8	91627,6	185492,8	314459	375331,1	622250,1	764586,14	1368284	2271636	3643509,7	4815716,2	5804096,9	6648965,3	5275185,24
Total Cumulative CF (tCO2) offshore	0	0	0	0	453,13	2712,08	4937,78	9511,58	101139	286632	601091	976422,1	1598672	2363258,31	3731542,3	6003178	9646687,8	14462404	20266501	26915466	32190651,33
Total CF by year (tCO2)	221127,44	221127	397395	385160,5	428660,98	435977,4	559096	588190,7	890951	1336653	2040844	2528092	3382084	4046552,53	4566141,3	6905349	9511079,3	11920493	13838041	15386155	12015306,72
Cumulative CF (tCO2)	221127,44	442255	839650	1224810	1653471,37	2089449	2648545	3236735	4127687	5464340	7505184	10033276	13415360	17461912,45	22028054	28933403	38444482	50364975	64203016	79589171	91604477,79